

An Evaluation of the Ongoing Impacts of Sand Mining at the CEMEX Lapis Sand Plant in Marina, California on the Southern Monterey Bay Shoreline

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Purpose and Overview: The City of Marina commissioned this report to assist in its management and decision-making for coastal property and resources within the City's jurisdiction. Consistent with that purpose, this report provides a review and synthesis of available documentary information and scientific literature addressing the impact of current sand mining activities within southern Monterey Bay. To assist in preparation of this report, in March 2017, the author visited the Lapis Sand Mine, the site of current beach sand mining activities in the City of Marina. It is my understanding that the Lapis Sand Mine is the only coastal mining activity in Monterey County at this time, and that other sand mining operations that previously operated along the Monterey Bay shoreline ceased operations in the late 1980s. Accordingly, all references to ongoing beach sand mining in this report are to the Lapis Sand Mining operation in the City of Marina.

This report is intended for an informed lay audience and, in particular, for City of Marina officials seeking to base coastal management decisions on the best available science. It provides a distillation of the most relevant facts and science related to the basic question: "Are sand mining activities at the Lapis Sand Mine (Figure 1) impacting the sediment budget and shoreline change rates in the vicinity of the mine?" Based on my review of the available information, data, and scientific literature, I conclude that beach sand extraction by the Lapis Sand Mine constitutes a significant source of sand loss from the southern Monterey Bay central littoral cell and, as a result, is causing or contributing to significant adverse effects on coastal property, resources, and uses.

The portions of southern Monterey Bay shoreline have the highest erosion rates in the state. None of the documents reviewed for this report can offer any explanation for these anomalously high erosion rates beyond the sand extraction from the littoral zone at the Lapis Mine. The overwhelming evidence leads me to conclude that continued sand mining activities have led to a substantial sand deficit in southern Monterey Bay. This sand deficit is driving these anomalously high rates of coastal erosion. In order to grapple with the serious erosion problems in southern Monterey Bay, I recommend that the

City of Marina pursue options to stop beach sand mining activities at the Lapis facility.



Figure 1. Aerial view of the Lapis Sand Plant, Marina, CA.

Introduction: Sand is to beaches and shorelines, as water is to western urbanization and agriculture. Sand moves between sources and temporary sinks. Preserving this sand and its movement is the key to maintaining the broad coastal economy, providing storm protection to infrastructure and shoreline development, ensuring recreational use of a state’s beaches, and protecting coastal ecosystems. This free movement of sand between sources and sinks is commonly referred to as the **Sand Sharing System**. Many legislative and rule-making bodies have codified the importance of the Sand Sharing System.¹

¹ For example, the State of Georgia Code § 12-5-231 (2015) reads:

The General Assembly finds and declares that coastal sand dunes, beaches, sandbars, and shoals comprise a vital natural resource system, known as the sand-sharing system, which acts as a buffer to protect real and personal property and natural resources from the damaging effects of floods, winds, tides, and erosion. . . . The General Assembly further finds that this sand-sharing system is a vital area of the state and is essential to maintain the health, safety, and welfare of all the citizens of the state. . . . It is declared to be a policy of this state and the intent of this part to protect this vital natural resource system by allowing only activities and alterations of the sand dunes and beaches which are considered to be in the best interest of the state and which do not substantially impair the values and functions of the sand-sharing system and by authorizing the local units of government of the State of Georgia to regulate activities and alterations of the ocean sand dunes and beaches

This Sand Sharing System is based on the uncontroversial, science-based concept that sand is constantly being exchanged from one coastal feature to another: from dunes to the beach, from one stretch of shoreline to the next, from the beach to the nearshore sand bars. Removal of sand from the system will impact all portions of the system eventually.

The Sand Sharing System can be described by the development of a sediment budget. Sediment (sand) budgets are important tools in understanding regional sand supply, loss, and movement. Best and Griggs, 1991; Rosati, 2005. A sand budget itemizes and quantifies the sources (inputs), sinks (outputs), and movement of the sand within a littoral cell. A littoral cell is a relatively self-contained section of coast where the sand circulates, i.e. “a defined length of shoreline along which the cycle of sediment erosion, transportation, and deposition is essentially self-contained.” Philip Williams & Associates, 2008 at 21. Littoral cells are separated from each other by features that block the exchange of sand, like a rocky headland. The south Monterey Bay shoreline has been divided into sub-cells, which are essentially delineated by differing sand transport directions (shown in Figure 2). Patsch and Griggs, 2007. The Lapis Mine sits approximately in the middle of the Central sub-cell, stretching from the Salinas River to Sand City in the south. The basic sources and sinks within this sub-cell are listed in Table 1.

Numerous researchers have quantified the sediment movement within the southern Monterey Bay littoral cell. The sediment budgets in these studies vary depending on the area within Monterey Bay they are considering and the type of sediment being quantified (e.g. beach sand vs. all sediment). Patsch and Griggs, 2007; Jones and Griggs, 1985; Smith, 2005; Philip Williams & Associates et al., 2008; Thornton, 2016. However, all of the studies conclude that sand mining removes a significant amount of sand from the sand budget and is contributing to shoreline erosion.

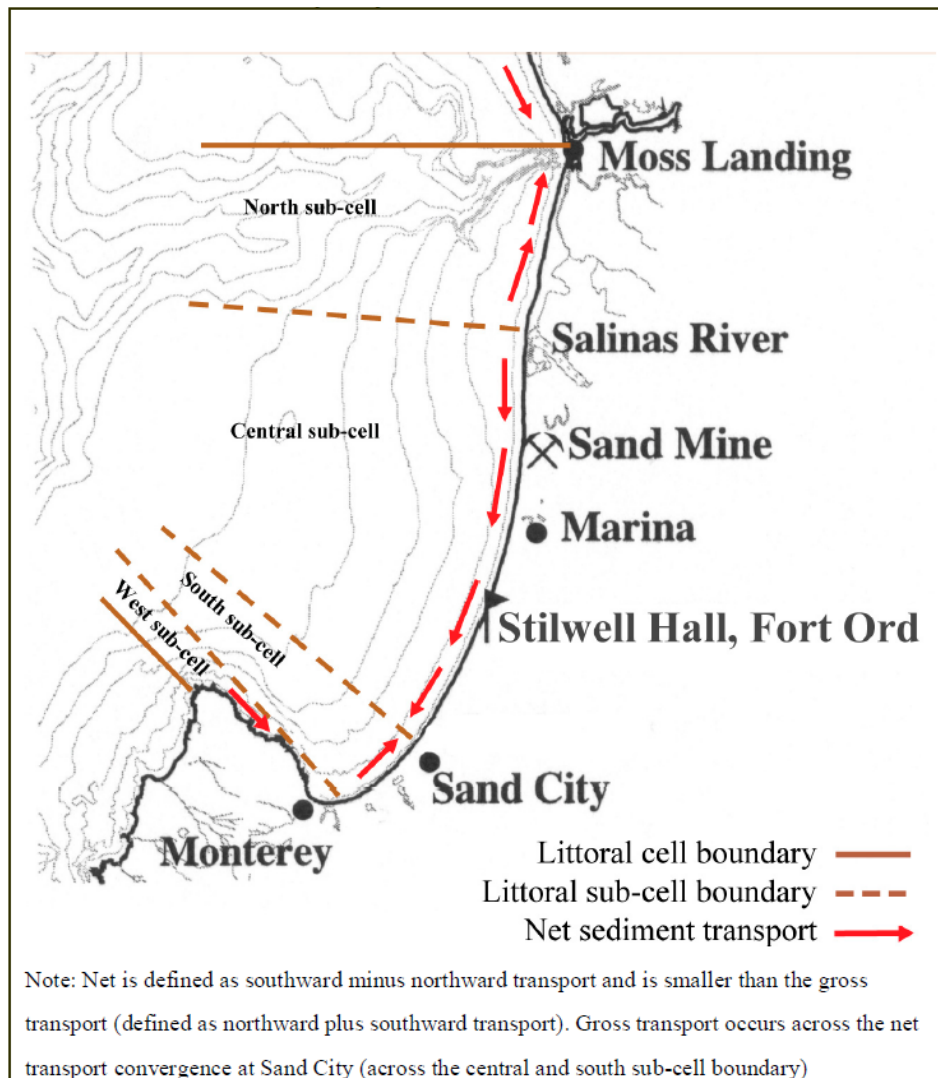


Figure 2. Southern Monterey Bay Littoral Sub-Cells and Net Sediment Transport. Source: Figure 12 from Philip Williams & Associates et al. (2008).

The most recent sediment budget for the Central sub-cell was presented by Thornton (2016) and is summarized in Table 1. It is significant that these data are presented in the peer-reviewed scientific journal, *Marine Geology*. This offers a high level of confidence in the data quality. This sand budget is useful because it is focused on the Central sub-cell and considers only beach compatible sand.

Thornton's recent sediment budget indicates that the biggest source of sand in the southern Monterey Bay is from dune erosion. However, only about 25% of the dune sand is coarse enough to stay on the beach; the remaining 75% of the finer grained sand ends up being transported offshore (or blown back into the dunes). Thornton, 2016. Because CEMEX mines the coarse beach sand tracked in his budget,

Thornton's 2016 budget is the most appropriate sediment budget to use for the purposes of determining the sources and sinks of the sand that feed the beaches in the City of Marina.²

Table 1. Sand budget for SMB central sub-cell.³ Values in m³/year × 10³. Uncertainties are presented with the values. Source: Table 2 from Thornton (2016).

	1940–1989	1989–2011
Mean recession (m)	– 1.0	– 1.3
Dune erosion	190	155
Dune erosion × compatibility factor, 0.25	48 ± 5	39 ± 4
Beach erosion	105 ± 9	127 ± 11
River input	56 ± 6	34 ± 3
Littoral transport in from south	20 ± 4	10 ± 2
Littoral transport in from south × 0.29	6 ± 2	3 ± 1
Sand mining	– 174 ± 43	– 205 ± 50
Residuals	41 ± 69	– 2 ± 71

Dunes contribute an estimated sand volume of 155,000 cubic meters/year to the littoral system. Thornton 2016. There is also a small sediment input to the Central sub-cell system from the Salinas River that has decreased through time.⁴ The sand input to the Central sub-cell from riverine sources is relatively modest – about 34,000 cubic meters/year – because most sand from the Salinas River is transported north.⁵ Thornton, 2016; Patsch and Griggs, 2007.

² Only sand with a grain size greater than .25 mm typically stays on the beach. Thornton, 2016. This coarse beach size sand is the type of sand that CEMEX mines. Thornton, 2016. Therefore, other broader sediment budgets showing large amounts of sand being lost offshore are not relevant to the analysis of impacts from sand mining. See, e.g., Philip Williams & Associates et al., 2008 at 46.

³ Beach sand budgets were calculated for two time periods to examine the impact of sand mining: “The first budget is calculated from 1940 to 1989 during the time of intensive drag-line sand mining of the surf zone focused on the south end of the littoral cell. The second budget is calculated from 1989 to 2011 after all the drag-line mines were closed leaving only a dredge pond mining operation at the north end of the littoral cell.” Thornton, 2016.

⁴ Two dams, built in 1941 and 1961, are estimated to have reduced the total annual sediment input from the Salinas river by 33%. Willis and Griggs, 2003. However, this does not have a major impact on the Central sub-cell sand budget since most of the sand from the Salinas is “is driven northward by the dominant littoral drift” and is eventually carried into the Monterey Submarine Canyon. Patsch and Griggs, 2007.

⁵ Other studies estimate an even lower volume of sediment – less than 8,000 cubic meters – traveling south from the Salinas river. Philip Williams & Associates et al., 2008.

Sand within this cell moves from dunes to the beach as the shoreline recedes. It also moves back and forth along the shore by waves (this is known as longshore sediment transport or littoral drift). But, for the most part, the sand remains in the cell as a part of the Sand Sharing System, maintaining a balance that stabilizes the shoreline and the beaches. If there is a balance between sand entering and leaving the beach, then the shoreline position will remain stable. If there is a deficit of sand entering the beach, the shoreline will move landward, or erode. Sand mining that removes sand from this active system becomes a permanent sink— taking away sand that will never return. Thornton (2016) finds that sand mining is the only significant sink (or loss) of beach size sand in the sand budget for this sub-cell.

Impacts of sand mining: There is no scientific dispute that removing sand from the active Sand Sharing System will decrease the amount of sand available for building and maintaining beaches. The question for setting policy direction is whether such removal is significant enough to have a long-term effect on shoreline position, beach volume, and beach/dune erosion. The first step in understanding the potential impact of the sand removal at the Lapis Mine is to determine if the sand is actually being removed from the active Sand Sharing System (from the littoral zone).

All of the available evidence shows that sand is being removed from the littoral zone. The dredging activity relies on a suction dredge operating in an artificial lagoon immediately adjacent to the beach. The lagoon is filled during coincident high tides and large waves, and the sand is removed by the dredge for processing. The sand filling the lagoon comes directly from the beach and nearshore immediately in front of the mine (Figure 3). The lagoon also traps sand that is moving in either direction along the beach. During a site visit by the author in 2017, recent storm waves had clearly reached well past the seaward portion of the lagoon (Figure 4). The visible wrack line was across the footprint of the lagoon. It is clear that the sand repeatedly filling the lagoon could not be coming from anywhere else other than the adjacent beaches and nearshore. Numerous peer-reviewed papers examining the sediment budget of southern Monterey Bay support the conclusion that the sand being removed at the Lapis Mine is coming from the local Sand Sharing System; and thus, it is a permanent, annual sink (deficit) in the littoral cell sand budget. Patsch and Griggs, 2007; Jones and Griggs, 1985; Smith, 2005; Philip Williams & Associates et al., 2008; Thornton, 2016.



Figure 3. Image of the sand mining operations at the CEMEX Lapis Mine. Note the fact that waves are pouring over the berm and into the lagoon. Effectively, the mining here is occurring in the active surf zone. Photo credit: Gary Griggs



Figure 4. In a March 2017 visit to the site, the author noted that the lagoon had been filled by storm waves and heavy equipment. The high tide wrack lines crossed the tracks of the equipment and the outer edge of the lagoon footprint.

The Lapis Sand Mine has not provided current extraction volumes to the City of Marina, nor publicly shared annual extraction information. Thornton (2016) estimated the sand removal to be approximately 205,000 cubic meters per year based on a CEMEX Annual Report from 2000. The Coastal Regional Sediment Management Plan for Southern Monterey Bay (Philip Williams & Associates et al., 2008) used an estimate of around 153,000 cubic meters per year. Both numbers represent a significant removal of sand from the littoral cell. It is important to keep in mind that these numbers represent average, annual removal. It is likely that the sand volume mined each year has fluctuated from slightly below to above this average rate range. As Table 1 indicates, the total sand volume exchanged annually in the sub-cell is estimated at approximately 326,000 cubic meters per year. Therefore, sand mining at the Lapis site is removing approximately 47% to 63% of the local sand budget.

To put these numbers in perspective, the Lapis mining operation is removing somewhere around 750,000 to just over 1 million cubic meters of sand every five years. This is the equivalent of a large beach nourishment project for many beaches in the United States. For example, a proposed U.S. Army Corps of Engineers beach nourishment project along an eroding stretch of the Southern California coast would (1) initially place 260,000 cubic meters of replacement sand on the Encinitas beach, with 168,000 cubic meters of replacement sand added every five years and (2) initially place 535,000 cubic meters of sand along Solana Beach, with planned renourishment of 221,000 cubic meters every ten years.⁶ The projected cost for this project is \$165 million, with annual costs of over \$3.5 million.⁷ Given the costs of such projects, it is difficult, from a public policy perspective, to justify a similar beach nourishment effort along the similarly erosive southern Monterey Bay coast when the Lapis Sand Mine will quickly offset any replenishment benefits by sand removal for commercial profit.

Evidence of impact: Removal of sand at these volumes, over the long term, from a relatively closed littoral cell necessarily causes a negative impact on the coastal systems within that cell. Because the longshore sediment transport rates in southern Monterey Bay are small (on the order of 10,000 to 20,000 cubic meters per year) relative to the amount of material being removed annually at the Lapis

⁶ See U.S Army Corps of Engineers Project Description (numbers converted from cu yards to cu meters): <http://www.spl.usace.army.mil/Missions/Civil-Works/Projects-Studies/Solana-Encinitas-Shoreline-Study/>.

⁷ Cost estimates are the most recent numbers in the media from December 2016: <http://www.thecoastnews.com/2016/12/15/federal-funding-for-50-year-sand-project-approved/>.

Sand Mine, the greatest sand deficit will be closest to the mine, within the municipality of Marina (Figure 5). Thornton, 2017; Philip Williams & Associates et al., 2008.



Figure 5. Typical section of rapidly eroding shoreline with the City of Marina.

A comprehensive evaluation of coastal erosion rates for the State of California conducted by the United States Geological Survey (Hapke et al., 2006) shows that the Central sub-cell has the highest erosion rates in the state (Figure 6).⁸ Hapke et al. (2006) and other studies looking at long-term average erosion rates show that erosion rates have increased dramatically over the last century in the southern Monterey Bay. This is illustrated by how much higher recent erosion rates are than long-term erosion rates. For Marina State Beach, Hapke et al. (2006) calculated an average erosion rate from 1910-2002 of 1.4 to 2.0 ft/yr and from 1970 to 2002 of 3.1 to 5.2 ft/year.⁹ Other studies support the increasing trend

⁸ Hapke et al. (2006) calculated an average erosion rate from 1970 to 2002 of 4.0 ft/year for southern Monterey Bay between the Salinas River and Monterey. Thornton et al., 2006 estimated approximately 3.0ft/year of erosion from 1985 to 2005. Smith (2005) calculated erosion rates in southern Monterey Bay at 1m/yr (3.28 ft/yr).

⁹ These results are broadly consistent with the erosion rate results in Thornton et al. (2006). Thornton et al., (2006) estimated approximately 1.0 ft/year of erosion in Marina from 1940-1985 and 4.7 ft/year of erosion in Marina from 1985 to 2005.

in erosion rates in southern Monterey Bay over the past century. Thornton, 2006; Jones and Griggs, 1985. The difference between the long-term erosion rates (which include a period of time before sand mining and older mining methods before the suction dredge) and the short-term erosion rates (including only the period of modern mining with current sand extraction amounts) in Hapke et al. 2006 is significant: it demonstrates that the impact of current sand mining practices on local shorelines has been an increase in the rate of erosion.

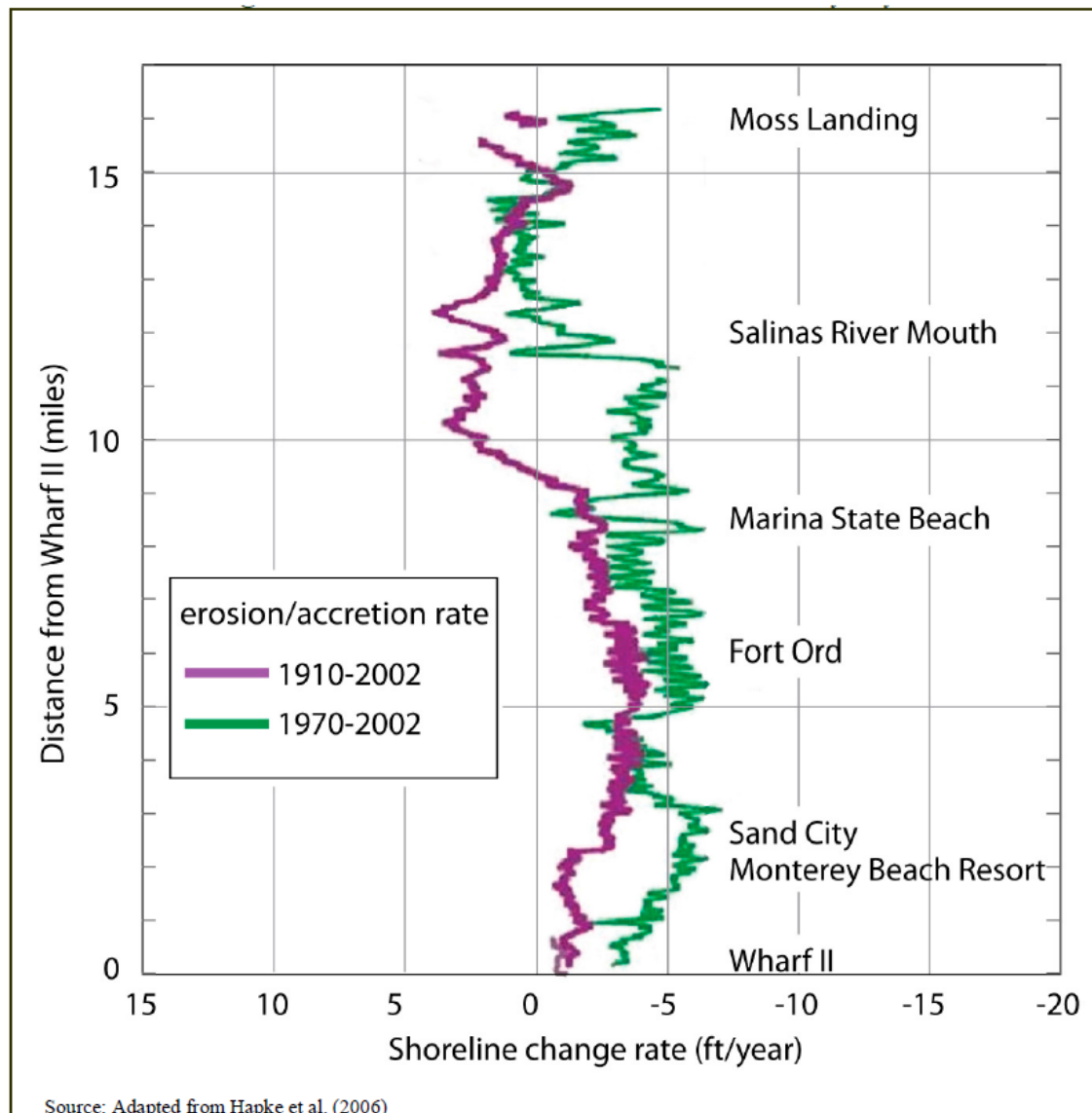


Figure 6. Dune Erosion Rates in Southern Monterey Bay. Source: Figure 18 from Philip Williams & Associates et al. (2008).

None of the documents reviewed for this report can offer any explanation for these anomalously high erosion rates beyond the sand extraction from the littoral zone at the Lapis Mine. The overwhelming evidence leads me to conclude that continued sand mining activities have led to a substantial sand deficit in southern Monterey Bay. This sand deficit is driving high rates of coastal erosion.

Coastal management implications and recommendations: In the vast majority of coastal communities in the continental United States, rising sea level is the primary driver of long-term coastal erosion. In those localities, managers have little choice but to accept the fact that halting global sea-level rise is not a problem they can tackle alone. Coastal management, therefore, becomes an exercise in planned adaptation and perhaps some degree of shoreline stabilization— typically with beach nourishment as a key component.

In southern Monterey Bay, municipalities and coastal managers are confronted with a unique complicating factor for the development of any sediment management plan (e.g. Philip Williams & Associates et al., 2008) or erosion mitigation plan (e.g. ESA PWA, 2012). Coastal erosion is being exacerbated by (at best) or driven by (at worst) the direct and intentional removal of sand from the Sand Sharing System.

Given the costs and other significant disadvantages of long-term beach nourishment programs, coastal managers can best serve the public interest by first attempting to eliminate sand sinks that are contributing to coastal erosion. In southern Monterey County, the Lapis Sand Mine is a substantial sand sink that is removing roughly 50 percent or more from the littoral system sand budget and, therefore, is a significant source of the coastal erosion that is negatively affecting coastal property, resources, and uses. Mitigating this ongoing erosion with hard structures (seawalls, revetments, and other coastal armoring) is not a sound policy response to the problem, as seawalls and groins will also directly interfere with the Sand Sharing System and create additional sand deficits. Before municipalities and regional managers can meaningfully implement any serious, comprehensive, long-term coastal planning, they will have to deal with the harmful sand deficit caused by the Lapis Sand Mine. Based on my review of the available information and literature and my professional expertise, I recommend that the City of Marina pursue options for halting the beach sand mining activities at the Lapis facility.

About the Author

Robert S. Young is the Director of the Program for the Study of Developed Shorelines, a joint Duke University/Western Carolina University venture. He is also a Professor of Geology at Western Carolina University and a licensed professional geologist in three states (FL, NC, SC). The Program for the Study of Developed Shorelines (PSDS) is a research and policy outreach center serving the global coastal community. The primary mission of PSDS is to conduct scientific research into coastal processes and to translate that science into management and policy recommendations through a variety of professional and public outreach mechanisms. The Program specializes in evaluating the design and implementation of coastal engineering projects. In California, Dr. Young is the Principal Investigator of a National Park Service project to map the vulnerability of every building, road, and facility in the state's National Parks.

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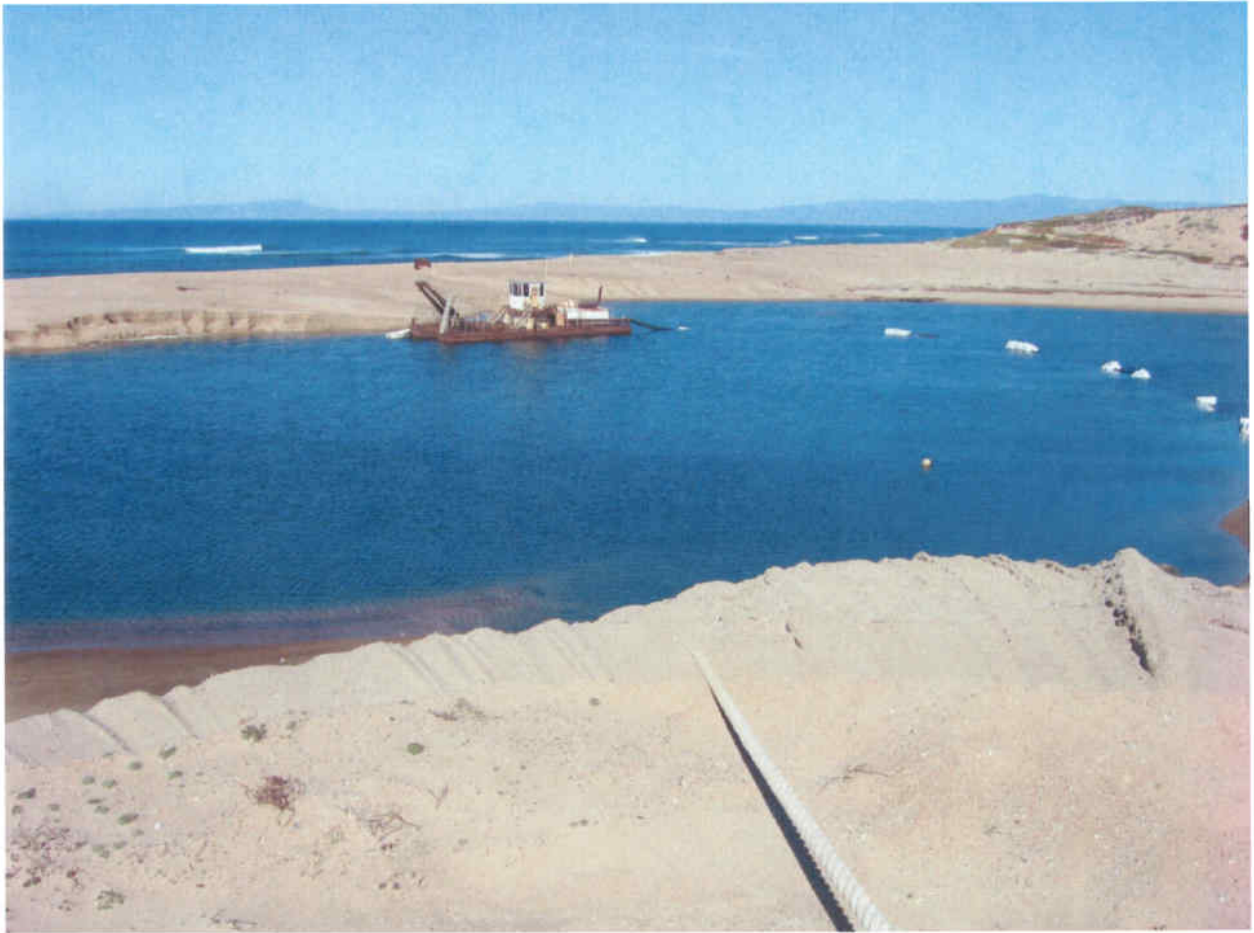
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2012 SMARA MINE INSPECTION
CEMEX Lapis Sand Plant
CA MINE ID No. 91-27-0006
City of Marina, California
January 17, 2013



Prepared for:
State Mining and Geology Board
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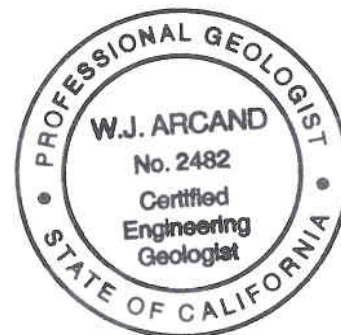
City of Marina, California

January 17, 2013

Prepared by:


Will J. Arcand
CEG No. 2482


Date



NOTE: Inquiries regarding the preparation or contents of this report should be made directly to the State Mining and Geology Board.

**2012 SMARA Mine Inspection
CEMEX Lapis Sand Plant
CA Mine ID No. 91-27-0006
City of Marina, California**

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March 7, 2013

State Mining and Geology Board
801 K Street, Suite 2015
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Subject: 2012 SMARA Mine Inspection
CEMEX Lapis Sand Plant
CA Mine ID No. 91-27-0006
City of Marina, Monterey County, California

Presented herein is the 2012 Surface Mining and Reclamation Act (SMARA) Mine Inspection report for the CEMEX Lapis Sand Plant (CA Mine ID No. 91-27-0006) located within the jurisdiction of the City of Marina, in Monterey County, California. SMARA requires that each surface mining operation in the State undergo a physical site inspection at least once each calendar year (Public Resources Code (PRC) Section 2774(b)). The inspection is performed to determine whether the surface mining operation is in compliance with its approved reclamation plan and SMARA.

The SMARA inspection was performed by Mr. Will Arcand, Senior Engineering Geologist with the State Mining and Geology Board (SMGB) on January 17, 2013. Mr. Ron Wilson, representing CEMEX, accompanied Mr. Arcand during conduct of the mine inspection.

The scope of work included review of files maintained by the Office of Mine Reclamation (OMR) and the SMGB, conduct of an on-site inspection, preparation of the mine inspection report contained herein, and subsequent presentation of salient points to the SMGB at their scheduled meeting. A copy of the 2011 Mining Operation Annual Report as submitted by the operator is provided in Attachment A. The 2012 Surface Mining Inspection Report as prepared by the inspector is provided in Attachment B. Annotated site photographs are provided in Attachment C. A site location map and site layout map are presented as Figures 1 and 2, respectively.

1.0 MINE DESCRIPTION

The CEMEX Lapis Plant is located adjacent to the Pacific Ocean in the city of Marina, in Monterey County, California. State Highway 1 is located east of the site and access is via Lapis Road (Figure No. 2). The site is situated among agricultural, private, and public lands along the coastline of Monterey Bay.

According to the approved Reclamation Plan, the site incorporates about 104 acres. The operation is characterized by beach sands and eolian sand dunes of the Flandrian complex overlying Pre-Flandrian dune deposits. Operations in the eastern portion of the site include, upon entrance, a truck scale and administrative offices (Photograph Nos. 1 and 2), equipment maintenance and staging areas (Photograph Nos. 1 and 3) and former residential structures. A wet processing plant (Photograph No. 5), a dry processing plant (Photograph Nos. 2, 5 and 6), product stockpiles and bagged product storage areas (Photograph Nos. 1, 4, 6, 7, and 13) are also situated in the eastern portion of the site.

Sand extraction currently occurs at the western edge of the site on the beach backshore, which is defined as the upper zone of the beach, lying between the high-water line of mean spring tides and the upper limit of shore-zone processes. A suction dredge works within an extraction pond established in this location (Photograph Nos. 8 and 9). Northeastern and north central portions of the site are occupied by the east-west oriented feed-pipe connecting the dredge to the wet processing plant (Photograph Nos. 5, 10 and 11), a redwood canal (Photograph No. 11) which returns process water to sediment settling ponds (Photograph Nos. 11 and 12), and product stockpile areas (Photograph Nos. 6, 7 and 13). The product stockpiles are fed from both the wet and dry processing plants which sort sand by grain size through use of screens and/or a series of sieves. Two small boneyard areas are located in the central and eastern portions of the site (Photograph Nos. 14 and 15). Blowing sand constantly affects the mining operation, and presents particular challenges to ongoing revegetation efforts in the northern and northeastern portions of the site (Photograph Nos. 16, 17, and 18).

2.0 BACKGROUND

A chronology of pertinent events and actions is as follows:

August 1989	Revised Reclamation Plan incorporating response to certain comments set forth by the SMGB forwarded to City of Marina; cover letter dated June 10, 1991; received by Department of Conservation on June 13, 1991.
April 19, 1990	Lapis Revegetation Plan prepared; received by Department of Conservation on September 16, 1992.
April 10, 1991	Last documented revision to reclamation plan, noting added uses and area designations.
June 15, 1992	SMGB approved reclamation plan (Resolution #92-12) after appeal by operator claiming Lead Agency failed to act on reclamation plan application within a reasonable amount of time.
July 15, 2005	SMGB issued Notice of Violation (NOV) to operator for failing to possess a financial assurance cost estimate.

August 12, 2005	Operator submitted revised financial assurance cost estimate, which was subsequently evaluated and re-calculated by OMR.
January 12, 2006	SMGB approved revised financial assurance cost estimate in the amount of \$462,160.00.
July 9, 2009	SMGB approved revised financial assurance cost estimate in the amount of \$1,037,784.00.
January 12, 2012	SMGB approved revised financial assurance cost estimate in the amount of \$247,072.00.

3.0 RECLAMATION OBJECTIVE

As of 1995 the site was designated as being within the Marina Local Coastal Plan, Coastal Conservation and Development/Coastal Development Permit Combining District. It is stated in the approved Reclamation Plan (Item No. 23) that *"...the parcel will be available for other coastal dependent or visitor serving uses...Most of the site will have gentle slope to the ocean at elevations of +20' to +25'. Dune ridges will remain at lateral boundaries."*

It is also stated in the Reclamation Plan (Item No. 27) that *"At the conclusion of mining and in conjunction with the permitted secondary land use, a detailed grading plan will be developed to establish the final contour of the reclaimed lands. A revegetation plan has been prepared by LSA Associates dated April 1990, and is a part of this reclamation plan. Slopes will be stabilized to prevent erosion and blow-outs...Surface water run-off will be treated in a manner so as to prevent erosion."* It is also stated (Item No. 28) that *"Phase One Revegetation...includes reconstruction of the southerly slopes..."* It is further stated (Item No. 29) that *"Reclamation of the site will be consistent with potential second uses of the site. The selected second use will determine how future mining at this site may be affected. This reclamation plan is for the current mining area and does not address the sand deposits to the north. Future mining is not anticipated to the south and east; future mining to the north will not be affected by the implementation of this plan."*

4.0 OBSERVATIONS

Ongoing sand extraction, processing and shipping activities were occurring at time of inspection. The suction dredge was operating in the northwestern portion of the dredge pond during the inspection (Photograph Nos. 8 and 9), and no other (on-shore) extraction activities were noted.

Estimated Life of the Operation: It is stated in the approved Reclamation Plan (Item No. 14) that the estimated life of operation is "50 years or more." The duration of the first phase is undefined.

Depth of Excavation: No clear maximum depth of excavation is noted in the approved Reclamation Plan. Item 17 of the approved Reclamation Plan contains the phrase "Final Grade ~ 20 NGVD ft." on the same line as the phrase "Maximum anticipated depth".

Also, as discussed above, the approved Reclamation Plan indicates that upon completion of reclamation activities *"Most of the site will have gentle slope to the ocean at elevations of +20' to +25'."* The above elevations are considered final grades that will exist following backfilling of the dredge pond and recontouring of the western portion of the site. Maximum achievable depth of excavation with the current suction dredge operating during an extreme minus tide is approximately 40 feet below mean sea level (MSL). At time of inspection, current excavations within the dredge pond were estimated to be at depths of 5 to 8 feet below MSL.

Slope Stability: No slope stability issues were noted at time of inspection.

Topsoil Management: It is stated in the approved Reclamation Plan (Item No. 26) that the *"Parcel entirely overlies sand deposits, no topsoil exists."* The Division of Mines and Geology in their correspondence dated December 26, 1989, indicated that it was their view that *"a 'topsoil resource' does exist on these dunes."* No dedicated topsoil stockpile was observed at time of inspection, nor has a topsoil management program been implemented.

Soil Erosion Preventive Measures: No soil erosion concerns were noted on site at time of inspection. In November 2008, the Association of Monterey Bay Area Governments (AMBAG) released the Coastal Regional Sediment Management Plan (CRSMP) for Southern Monterey Bay. This report asserts, in part, that continued sand mining at the subject site is contributing to beach erosion along portions of southern Monterey Bay. SMGB staff continues to evaluate the implications of the CRSMP through ongoing discussions with the operator and other state regulatory agency staff.

Boneyard: A relatively small boneyard exists in the west-central portion of the site, to the southwest of the wet processing plant (Photograph No. 14). An additional equipment and scrap metal storage area is situated adjacent to the formerly used residential structures in the central eastern portion of the site (Photograph No. 15).

Revegetation Program: No specific time constraints are offered in the approved revegetation plan (LSA Associates, 1990), although a revegetation program has been implemented at the site. On December 27, 2012, the SMGB received an annual revegetation report for the site prepared by ICF International (ICF - dated 12/26/12). This report discusses invasive weed control and revegetation activities undertaken during 2012 on mined dune slopes in the southern portion of the site (Photograph Nos. 19 and 20) and ongoing activities in the northern and northwestern portions of the site.

At time of inspection observed revegetation efforts primarily included ongoing attempts to establish vegetative cover while minimizing invasion of ice plant and European dunegrass in the northern and northwestern portions of the site (Photograph Nos. 16 through 18), and ongoing weed control in the revegetated southern portion of the site. Revegetation efforts are reported by ICF, and previous revegetation consultants, to be complete in the southern portion of the site. Southern slopes were considered adequately vegetated at time of inspection. It is clear that revegetation efforts in the northern and northwestern portions of the site have met with varying degrees of success, and the operator reported at time of inspection that such efforts are continuing with the assistance of ICF. SMGB staff continues to work with the operator, their

revegetation consultant, and OMR staff in order to define a feasible plan for meeting revegetation success criteria on the northern portion of the Lapis Sand site.

5.0 DISTURBED AREA

The approved Reclamation Plan (Item 22) denotes the site incorporating approximately 104 acres. Mining operations have affected the entire 104 acre site, although significant portions of the dune slopes previously mined in the southern portion of the property are considered to have met reclamation requirements.

6.0 RECLAIMED AREA

No acreage has been reported as reclaimed by the operator. However, as noted above, slopes in the southern portion of the site are in their final configuration, and revegetation efforts on these slopes appear to be complete.

7.0 FINANCIAL ASSURANCE

The current financial assurance on file with the SMGB is in the form of an Irrevocable Standby Letter of Credit in the amount to \$1,037,784.00. On January 12, 2012, the SMGB approved a revised financial assurance cost estimate in the amount of \$247,072.00. At time of inspection the operator provided SMGB staff with a revised financial assurance cost estimate, dated December 2012, in the amount of \$255,550.97. The December 2012 financial assurance cost estimate is currently under review by SMGB staff. The existing financial assurance is deemed adequate.

8.0 VIOLATIONS / CORRECTIVE MEASURES

No violations or corrective measures were noted at time of inspection. It is recommended that the operator continue to monitor and control ice plant across the site, and to eradicate any occurrences of pampas grass and European beach grass.

9.0 REFERENCES

Greening Associates, Revegetation Report for Lapis Sand Plant: unpublished report prepared for the City of Marina, dated March 14, 2003.

Greening Associates, Revegetation Report, Lapis Sand Plant: unpublished report prepared for CEMEX, dated July 2006.

LSA Associates, Inc., Lapis Revegetation Plan: unpublished report prepared for RMC Lonestar, Inc., Pleasanton, California, dated April 19, 1990.

RMC Lonestar, Reclamation Plan, Lapis Plant, City of Marina, County of Monterey: dated August, 1989; revised October 22, 1988 (Items Nos. 22, 27 and 29) and April 10, 1991 (Items Nos. 20, 22, 27 and 28).

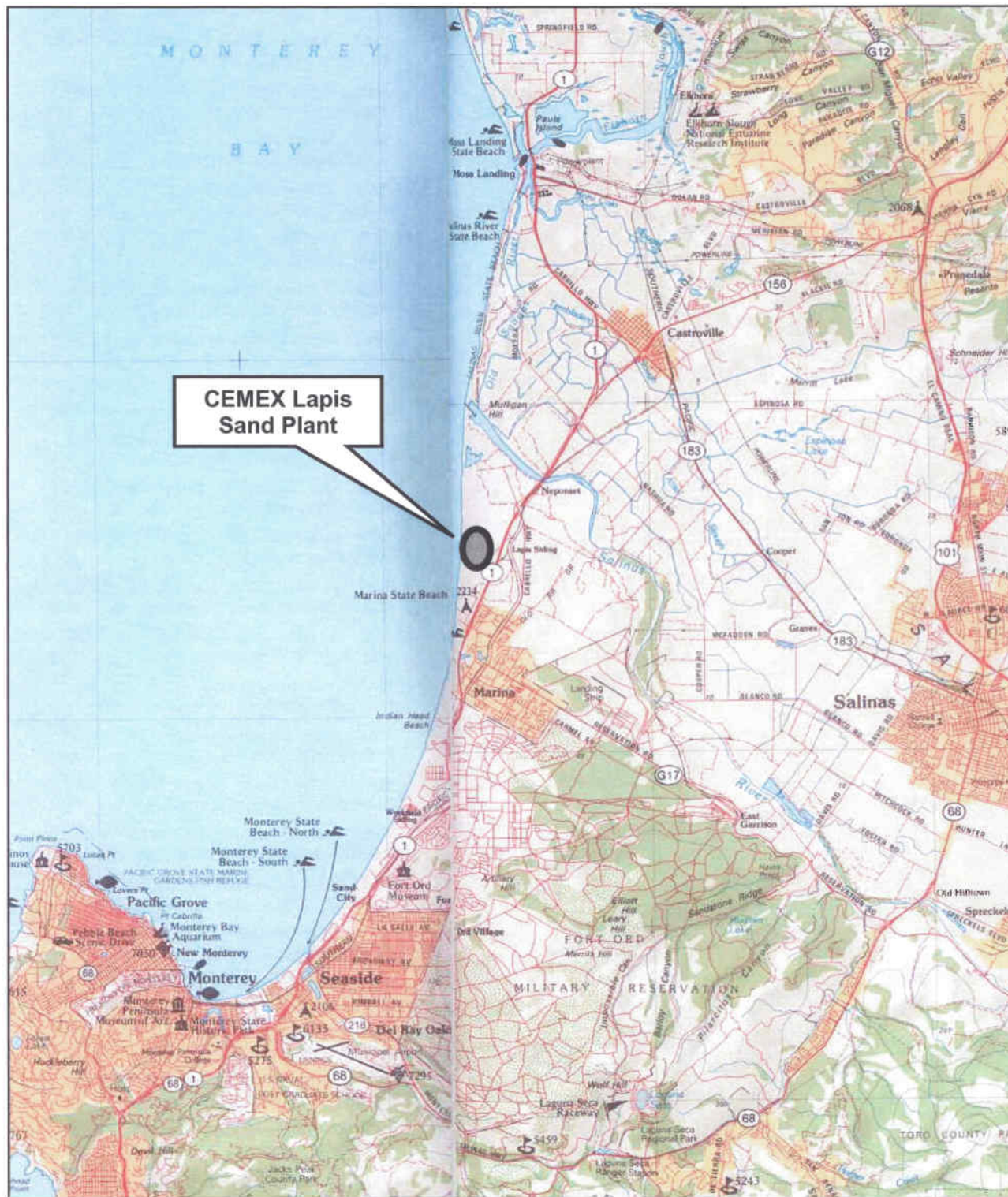
Coastal Regional Sediment Management Plan for Southern Monterey Bay, prepared for Association of Monterey Bay Area Governments, prepared by Philip Williams & Associates, Ltd. with Ed Thornton, Jenifer Dugan, and the Halcrow Group, dated November 3, 2008.

Greening Associates, Revegetation Report, Lapis Sand Plant: unpublished report prepared for CEMEX, dated June 2010.

LSA Associates, Inc., Review of Revegetation Efforts and Recommendations for Future Revegetation – Olympia and Lapis Quarries: letter report prepared for CEMEX, dated August 30, 2010.

LSA Associates, Inc., 2011 Annual Report – CEMEX Lapis Sand Plant, City of Marina, Monterey County, CA Mine ID No. 91-27-0006: letter report prepared for SMGB staff, dated December 28, 2011.

ICF International, 2012, 2012 Annual Report – CEMEX Lapis Sand Plant, City of Marina, Monterey County (CA Mine ID No. 91-27-0006): letter report prepared for CEMEX, dated December 26, 2012.



**FIGURE 1
SITE LOCATION MAP**

CEMEX LAPIS SAND PLANT
CA MINE ID No. 91-27-0006
CITY OF MARINA, CALIFORNIA

JANUARY, 2013

Note:

1. Map source = 1998 DeLorme Northern California Atlas and Gazetteer.
2. Not to scale.



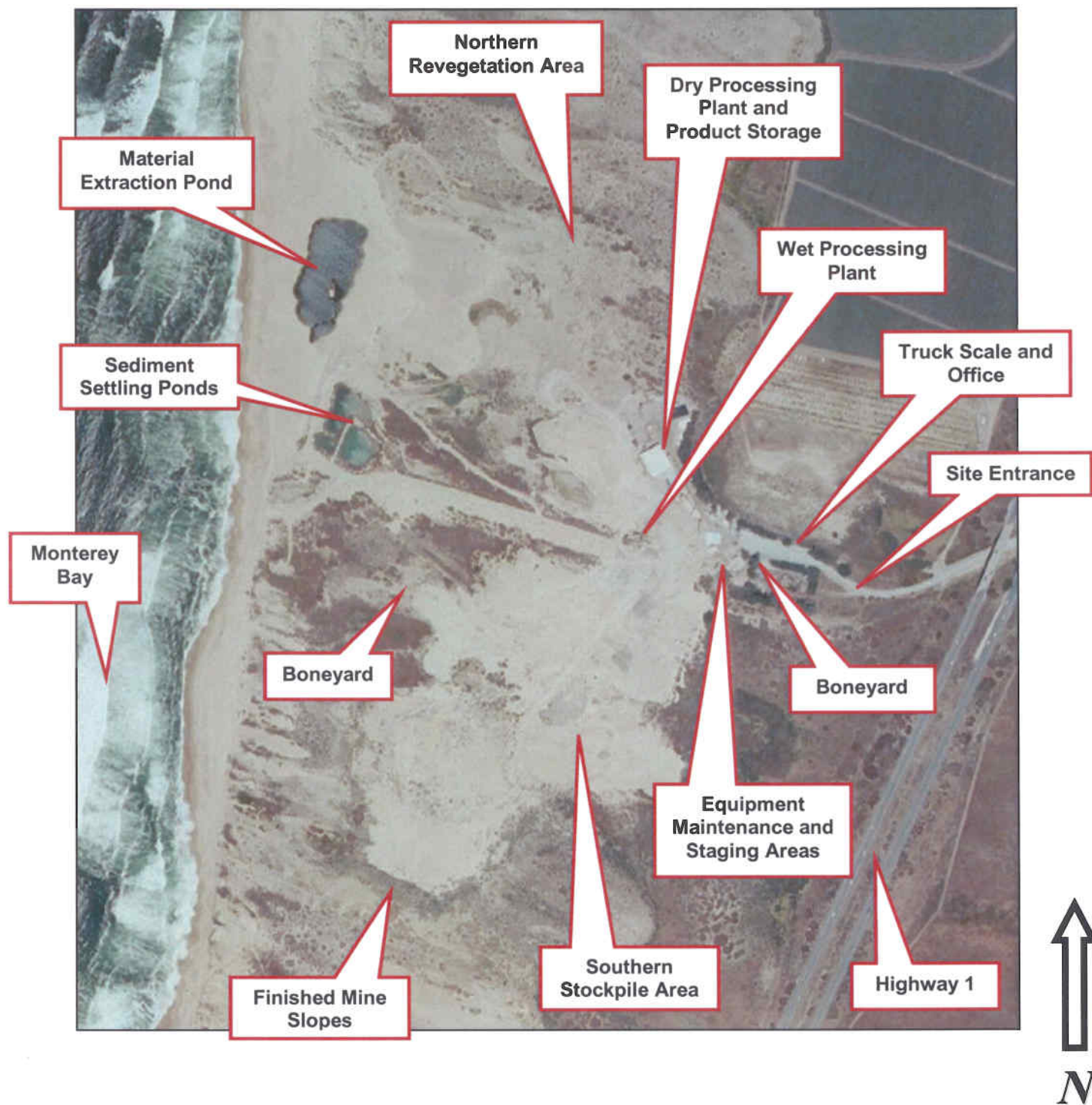


FIGURE 2 SITE LAYOUT MAP

CEMEX LAPIS SAND PLANT
CA MINE ID No. 91-27-0006
CITY OF MARINA, CALIFORNIA

JANUARY, 2013

Note:

1. Photo source = Esri, 2012.
(image date uncertain)
2. Not to scale.
3. Some features visible on air photo are not reflective of current site conditions.



Attachment A

2011 Mining Operation Annual Report

2011 Mining Operation Annual Report
Unavailable at time of Report production.

Attachment B

2012 Surface Mining Inspection Report

SURFACE MINING INSPECTION REPORT

Instructions for completing this form are on the reverse side. Attach notice(s) of violation(s) and order(s) to comply for all observed non-compliance.

I. Mine Name as reported by Operator on Mining Operation Annual Report Lapis	Inspection Date: January 17, 2013	CA MINE ID#: 91 -27-0006
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II. SMARA Lead Agency Name (City or County <u>only</u>) State Mining and Geology Board (SMGB)		
Inspector Will J. Arcand, CEG No. 2482		Telephone (916) 322-1082
Title Senior Engineering Geologist	Organization SMGB	
Mailing Address 801 K Street, Suite 2015		
City Sacramento	State CA	ZIP Code 95814
E-mail Address (Optional) will.arcand@conservation.ca.gov		

III. Mine Operator CEMEX		
Contact Person Ronald D. Wilson		Telephone (916) 941-2852
Mailing Address 5180 Golden Foothill Parkway, Suite 200		
City El Dorado Hills	State CA	ZIP Code 95762
E-mail Address (Optional) ronaldd.wilson@cemex.com		

IV. Does the operation have:	P	NR	No	Yes
A permit to mine?		X		Permit #
An approved Reclamation Plan?				RP # SMGB approved 6/15/1992, Resolution #92-12
Has the operator filed a Mining Operation Annual Report (form MRRC-2)? Check one: ☐ Yes ☐ No ☒ Unknown				
Is this operation on Federal Land? Check one: ☐ Yes ☒ No				
If "Yes", provide one or both of the Federal Mine Land Identification Numbers below:				
California Mining Claim Number (CAMC#): N/A				
U.S. Forest Service Identification Number (USFS ID#): N/A				

DISTRIBUTION: Original to Operator. Copies to: State (by Lead Agency), Lead Agency, State (by Operator), and BLM or USFS (if required).

DEPARTMENT OF CONSERVATION**OFFICE OF MINE RECLAMATION**

MRR-1 Page 2 of 3

SURFACE MINING INSPECTION REPORT

V. Does the Operator currently have a Lead Agency approved Financial Assurance? Check one: ☒ Yes ☐ No If "Yes", complete section below. If "No", refer to instructions on the reverse of this page and complete Section VI.		Inspection Date: January 17, 2013	CA MINE ID#: 91 -27-0006
Type of Financial Assurance Mechanism(s)	Financial Assurance Mechanism Number(s)	Current Amount on File	Date of Expiration
☐ Surety Bond		\$	
☐ Certificate of Deposit		\$	
☒ Letter of Credit	3060631	\$ 1,037,784.00	Automatic renewal
☐ Trust Fund		\$	
☐ Pledge of Revenue		\$	
☐ Budget Set Aside		\$	
☐		\$	
The Financial Assurance Amount must be adjusted annually. Attach a copy of the revised Financial Assurance Amount calculation with this report.		Date of Financial Assurance Amount Calculation: December 2012	
Does the current mechanism(s) on file cover the new annual calculation? ☒ Yes ☐ No		If "No", date operator was notified that a new mechanism is required:	

VI. Financial Assurance comments.

The current financial assurance on file with the SMGB is in the form of an Irrevocable Standby Letter of Credit in the amount to \$1,037,784.00. On January 12, 2012, the SMGB approved a revised financial assurance cost estimate in the amount of \$247,072.00. At time of inspection the operator provided SMGB staff with a revised financial assurance cost estimate, dated December 2012, in the amount of \$255,550.97. The December 2012 financial assurance cost estimate is currently under review by SMGB staff. The existing financial assurance is deemed adequate.

DEPARTMENT OF CONSERVATION
OFFICE OF MINE RECLAMATION

MRRC-1 Page 3 of 3

SURFACE MINING INSPECTION REPORT

VII. Is the operation in compliance with provisions of the approved Reclamation Plan with respect to:	OK	VN	NI	NA	CA MINE ID # 91 -27-0006
Wildlife Habitat	X				Inspection Date: January 17, 2013
Revegetation	X				
Agricultural Land				X	Weather Code(s): CR = Clear
Stream Protection				X	Duration of Inspection: 2 Hours
Tailings and Mine Waste Management	X				
Closure of Surface Openings	X				Approximate Disturbed Acreage: 104 of 104 acres
Building, Structure, and Equipment Removal	X				
Topsoil Salvage, Maintenance, and Redistribution	X				Status of Operation Code(s): A = Active during inspection
Backfilling, Regrading, Slope Stability, and Recontouring	X				
Drainage, Diversion Structures, Waterways, and Erosion	X				Status of Reclamation Code(s): R = Reclamation in progress
Other (list or explain below)					

VIII. Comments/Description of Violation(s) and Corrective Measure(s) Required

(NOTE: please indicate if you have attached notice(s) of violation(s) and correction order(s), in lieu of description on this form):

No violations or corrective measures were noted at time of inspection. It is recommended that the operator continue to monitor and control ice plant across the site, and to eradicate any occurrences of pampas grass and European beach grass.

IX. Number of Violations: None (0)	Inspector's Signature: 	Date Signed: 3/7/13
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DISTRIBUTION: Original to Operator. Copies to: State (by Lead Agency), Lead Agency, State (by Operator), and BLM or USFS (if required).

CEMEX LAPIS SAND PLANT

CALIFORNIA SURFACE MINING & RECLAMATION ACT **FINANCIAL ASSURANCE COST ESTIMATE**

CA Mine ID # 91-27-0006

DECEMBER | 2012

SMARA Lead Agency

State Mining and Geology Board
801 K Street, Suite 2015, Sacramento, CA 95814

Operator

Cemex Construction Materials, Inc.
5180 Golden Foothill Parkway, Suite 200, El Dorado Hills, CA 95762

Preparer

Benchmark Resources
2515 East Bidwell Street, Folsom, CA 95630

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- Appendix A General Prevailing Wage Determinations
- Appendix B Labor Surcharge and Equipment Rental Rates

INTRODUCTION

This Financial Assurance Estimate (FAE) is submitted to the State Mining and Geology Board as the Surface Mining and Reclamation Act (SMARA) Lead Agency in accordance with SMARA § 2773.1 for purposes of providing assurance for completion of reclamation for the Lapis Sand Plant owned and operated by Cemex Construction Materials, Inc., (Cemex) in accordance with the approved reclamation plan.

CURRENT STATUS

The Lapis Sand Plant is a sand extraction site operated by Cemex in the city of Marina, which is located in Monterey County. Sand continues to be extracted from an extraction pond in the western portion of the site. The sand is extracted using a suction dredge and then transported to the processing area in the eastern portion of the site. The processing area is where the sand is processed, stockpiled, and transported off-site. Process water used in processing activities is returned to sediments ponds via a redwood canal.

Revegetation and weed abatement activities continue to occur within previously mined areas in the southern, northern, and northwestern portions of the site. An annual report on revegetation, submitted under separated cover by ICF International, documents the success of ongoing weed abatement and revegetation activities and outlines future work necessary to meet reclamation objectives. The currently disturbed acreage totals approximately 75 acres. The disturbed acreage has not changed significantly from previous years. Disturbed areas requiring reclamation treatment include the:

- Administrative offices;
- Truck scale, equipment maintenance, and staging area;
- Equipment boneyard;
- Wet and dry processing plants and the associated piping/canal for transport of process water;
- Product stockpile areas;
- Previously mined areas undergoing ongoing revegetation treatment and weed abatement; and
- Location of the suction dredge and associated piping from the active mining area.

RECLAMATION GOALS AND SURFACE TREATMENT

The approved reclamation plan for the site comprises the document entitled *Reclamation Plan, Lapis Plant* (RMC Lonestar 1991) (Reclamation Plan); a map entitled Sheet 1, "Lapis Site Reclamation Plan (SMARA)" (Ashley 1991); and the *Lapis Revegetation Plan* (LSA Associates 1990) (Revegetation Plan). The reclaimed end use of the site, as outlined in Item 23 of the Reclamation Plan is for "other coastal dependent or visitor serving uses as allowed by the Marina Coastal Zone Land Use Plan." Item 27 of the Reclamation Plan further states, "At the conclusion of mining and in conjunction with the development of the permitted second land use, a detailed grading plan will be developed to establish final contour of the reclaimed lands." Last, Item 29 states, "Reclamation of the site will be consistent with potential second uses of the site. The selected second use will determine how future mining at this site may be affected." Therefore, the Reclamation Plan does not identify a specific second land use (e.g., open space, housing, wildlife habitat), except to the extent the reclaimed land use must be consistent with current land use designations.

In addition to the above statements, the following reclamation actions or treatments are specifically referenced in the Reclamation Plan:

- All residual items such as equipment, structures, and refuse will be removed from the site (Item 27).
- Surface-water runoff will be treated in a manner to prevent erosion (Item 27).

The Revegetation Plan, incorporated by reference in the Reclamation Plan, proposes using native species, with the exception of sea rocket, to revegetate disturbed areas of the site. The Revegetation Plan provides a list of potential species for revegetation and the associated mix of those species. Seeding would occur between October and March. Site preparation activities to begin before revegetation efforts would include:

- Grading slopes to have a convex shape at the top and a concave shape at the bottom,
- Ensuring slopes are not steeper than 2.5:1,
- Ensuring no topsoil is redistributed before seeding because none exists on-site, and
- Eradicating exotic plants on-site by applying Roundup or removing them by hand.

The Revegetation Plan provides three planting prescriptions, including hydroseeding with native seed and mulch, hand seeding, and hydroseeding a sterile seed.

Fertilization will be added to both hydroseed and hand-seeding mixtures. In addition, the following measures are outlined in the Revegetation Plan:

- Erosion control, where necessary, will include hydromulch, straw, or netting.
- Rilling greater than 9 inches will be repaired through snow fencing, straw bales, or jute netting.
- Monitoring efforts will occur for 3 years.

F AE SCOPE

This FAE is calculated for reclamation of current surface disturbances and necessary reclamation that must still occur to meet the obligations of the approved Reclamation Plan.

COST ESTIMATING

The following section of this report contains the FAE calculations. The format and calculations follow the *Surface Mining and Reclamation Act Financial Assurance Guidelines* (State Mining and Geology Board 2004). Labor rates are derived from current California prevailing wage rates (see Appendix A). Equipment rates used are based on the *Labor Surcharge and Equipment Rental Rates* (see Appendix B). Equipment usage and efficiency are based on the *Caterpillar Performance Handbook* (Caterpillar 1997). Acreages for grading and revegetation surface treatment reflect the most current available data.

RECLAMATION CALCULATIONS AND COST SUMMARY

1.0 PRIMARY RECLAMATION ACTIVITIES

TASK 1.1 - GENERAL AND/OR SLOPE GRADING (DISTURBED SURFACES AND INTERNAL ROADS)

Method:

There are approximately fifteen acres of disturbed surfaces requiring some for of surface grading. Approximately five acres of general surface grading and ten acres of slope grading. The majority of the slope onsite meet final reclamation grade of 2.5:1. Approximately 30,000 cubic yards of grading would be required to complete this task.

Miscellaneous Information:

D8R Dozer with a universal blade (2 ft overlap); Avg. Speed: 2.5 mph; 50 minute hour; Production Rate: 925 cubic yards per hour. Water truck to supress dust would operate 25% of the time.

A. Equipment

Equipment	Quantity	\$/Hour	# of Hours	Cost (\$)
Caterpillar D8R Dozer	1	\$184.54	32	\$5,905.28
Water Truck	1	\$59.31	8	\$474.48
Total Equipment Cost for this Task:				<u>\$6,379.76</u>

B. Labor

Labor Category	Quantity	\$/Hour	# of Hours	Cost (\$)
Operating Engineer	1	\$59.85	32	\$1,915.20
Truck Driver	1	\$50.30	8	\$402.40
Total Labor Cost for this Task:				<u>\$2,317.60</u>

C. Materials

Item	Quantity	\$/Unit	Cost (\$)
N/A	0	\$0.00	\$0.00
Total Material Cost for this Task:			<u>\$0.00</u>

D. Direct Cost for this Task

Equipment Cost + Labor Cost + Materials Cost: \$8,697.36

TASK 1.2 - MOVE AND SPREAD NON-SPEC MATERIAL

Method:

There are five open water areas on site requiring backfill to surrounding grade. The open water areas include the active sand extraction area, sediment basins, and fresh water containment. Approximately 120,000 cubic yards of onsite stockpiled material would be necessary to bring these open water areas to surrounding grade. The material necessary to backfill these areas would come from existing stockpiles and need to be transported approximately 1,000 feet. The task of loading and transporting backfill material would be accomplished by a Caterpillar 633D scraper or similar piece of equipment. A Caterpillar D8R Dozer or similar would be used to push the material into areas requiring backfill until the final is reached.

Miscellaneous Information:

D8R Dozer with a universal blade (2 ft overlap); Avg. Speed: 2.5 mph; 50 minute hour; Production Rate: 925 cubic yards per hour. Cat 633D Scraper: Production Rate: 850 cu. yds/hr (Avg. Dist:1000 ft; Operator: Avg. Material: loose; Efficiency: 50 min. hr.) A water truck to suppress dust would operate 25% of the time.

A. Equipment

Equipment	Quantity	\$/Hour	# of Hours	Cost (\$)
Caterpillar 633D Scraper	1	\$234.46	141	\$33,058.86
Caterpillar D8R Dozer	1	\$184.54	130	\$23,990.20
Water Truck	1	\$105.62	35	\$3,696.70

Total Equipment Cost for this Task: \$60,745.76

B. Labor

Labor Category	Quantity	\$/Hour	# of Hours	Cost (\$)
Truck Driver	1	\$50.30	35	\$1,760.50
Operating Engineer	1	\$59.85	271	\$16,219.35

Total Labor Cost for this Task: \$16,219.35

C. Direct Cost for this Task

Equipment Cost + Labor Cost: \$76,965.11

2.0 REVEGETATION

TASK 2.1 - REVEGETATION

Method:

As outlined in the ICF International Inc. Revegetation Annual Report (submitted under separate cover) revegetated slopes in the south pit meet the success criteria outlined in the approved Reclamation Plan. Native dune vegetation in the North Pit continues to mature, reproduce, and expand in cover. Areas where sand-trapping devices and other debris had been removed in 2011 remain stable and in 2012 did not exhibit any signs of substantial wind erosion. The primary goal for reclamation outside the actively mined areas of the North Pit is to accelerate sand build-up and revegetation success where needed in order to meet success criteria. Supplemental plantings will employ transplanting of native dunegrass (*Poa douglassii*) from adjacent dunes, planting existing nurserygrown stock from 2011, and direct application of seed collected in 2011.

Miscellaneous Information:

N/A

A. Revegetation

Equipment	Quantity	\$/Acre	# of Acres	Cost (\$)
Supplemental Plantings	1	\$6,500.00	5	\$32,500.00
Total Equipment Cost for this Task:				<u>\$32,500.00</u>

B. Labor

Labor Category	Quantity	\$/Hour	# of Hours	Cost (\$)
Landscape Labor (General)	1	\$44.33	80	\$3,546.40
Total Labor Cost for this Task:				<u>\$3,546.40</u>

C. Direct Cost for this Task

Equipment Cost + Labor Cost: \$36,046.40

3.0 PLANT STRUCTURES AND EQUIPMENT REMOVAL

TASK 3.1 - DISMANTLE AND TRANSPORT PLANT AND ANCILLARY EQUIPMENT OFF SITE

Method:

Removal of the following plant and ancillary equipment: office and scale house, dry plant and warehouse, wet plant, maintenance shed, concrete slabs and footings, underground fuel storage tank, boneyard clean-up and removal, mobile equipment, and floating sand dredge.

Miscellaneous Information:

A quote to removal all equipment listed above was provided with last years financial assurance cost estimate. It is assume this quote is still accurate but to be conservative has been increase by 5% to account for inflation, including changes in labor and equipment rates.

A. Direct Cost for this Task

Bankhead Equipment Quote: \$28,875.00

TASK 3.2 - GENERAL SITE CLEANUP**Method:**

Miscellaneous clean-up of areas surrounding the plant site and ancillary structures and other general clean-up within or surrounding current surface disturbance areas.

Miscellaneous Information:

N/A

A. Equipment

Equipment	Quantity	\$/Hr	# of Hours	Cost (\$)
Flatbed Truck	1	\$73.99	8	\$591.92
Total Equipment Cost for this Task:				<u>\$591.92</u>

B. Labor

Labor Category	Quantity	\$/Hour	# of Hours	Cost (\$)
Truck Driver	1	\$50.30	8	\$402.40
Laborer	1	\$44.33	16	\$709.28
Total Labor Cost for this Task:				<u>\$1,111.68</u>

C. Disposal**Miscellaneous Information:**

Disposal costs are per dumpster including hauling and tipping fees. Concrete (10 cy dumpster) Misc. Material (30 cy dumpster).

Structure/Equipment and Type	Volume Cu. Yds.	Unit Cost Basis	Disposal Cost (\$)	Cost (\$)
General Site Cleanup (Misc.)	30	1	\$1,500	\$1,500.00
Total Material Cost for this Task:				<u>\$1,500.00</u>

D. Direct Cost for this Task

Equipment Cost + Labor Cost + Materials Cost: \$3,203.60

4.0 MISCELLANEOUS COSTS

TASK 4.1 - INVASIVE SPECIES PREVENTION AND WEED CONTROL

Applicability:

As outlined in the ICF International Inc. Annual Revegetation Report a large scale weed management effort was conducted in Fall/Winter 2012. Iceplant was the primary target of this year's effort. The majority of iceplant was removed by hand to protect the native dune plants that occur in the areas. Weed abatement activities will continue to occur over the next several years in conjunction with revegetation activities and monitoring.

Method:

Laborers to control non-native weeds if they inhibit revegetation planting.

Miscellaneous Information:

Assume 5 days weed control annually.

A. Equipment

Item	Quantity	\$/Day	# of Hours	Cost (\$)
Flatbed Truck (4-Axle Truck)	1	\$73.99	8	\$591.92
Total Cost for this Task:				<u>\$591.92</u>

B. Labor

Labor Category	Quantity	\$/Hour	# of Hours	Cost (\$)
Landscape Labor	1	\$44.33	120	\$5,319.60
Truck Driver	1	\$50.30	8	\$402.40
Total Labor Cost for this Task:				<u>\$5,722.00</u>

C. Materials

Item	Quantity	\$/unit	Cost (\$)
N/A	0	\$1	\$0.00
Total Material Cost for this Task:			<u>\$0.00</u>

D. Direct Cost for this Task

Equipment Cost + Labor Cost + Materials Cost: \$6,313.92

5.0 MONITORING

Method:

Monitor for successful revegetation, slope stability, erosion control, final grading, and maintenance. Prepare closure report.

Miscellaneous Information:

Revegetation and weed abatement monitoring estimated at \$2,500.00 per visit, with three visits needed annually. Preparation of closure report estimated at \$2,500.00.

A. Monitoring

Monitoring Task	\$/Visit	Visits/ Year	Monitoring Years	Cost (\$)
Revegetation Monitoring	\$2,000.00	3	3	\$18,000.00
Closure Report	\$2,500.00	1	1	\$2,500.00
Total Monitoring Cost for this Task:				<u>\$20,500.00</u>

B. Direct Cost for this Task

Total Monitoring Costs: \$20,500.00

6.0 SUMMARY OF COSTS

Direct Costs:

1.0 Primary Reclamation Activities Costs	\$85,662.47
2.0 Revegetation Costs	\$36,046.40
3.0 Plant Structures and Equipment Removal Costs	\$32,078.60
4.0 Miscellaneous Costs	\$6,313.92
5.0 Monitoring Costs	\$20,500.00
<i>Total of Direct Costs</i>	<i>\$180,601.39</i>

Indirect Costs:

Supervision (5% of Direct Costs)	\$9,030.07
Profit/Overhead (11.5%)	\$20,769.16
Contingencies (10%)	\$18,060.14
Mobilization (5%)	\$9,030.07
<i>Total of Indirect Costs</i>	<i>\$56,889.44</i>
<i>Total of Direct and Indirect Costs</i>	<i>\$237,490.83</i>

Lead Agency Administrative Cost (10% of Costs)	\$18,060.14
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Total Estimated Cost of Reclamation: \$255,550.97

Attachment C

Annotated Site Photographs



Photograph No. 1. Product stockpiles, truck loading area, administrative offices, truck scale, and equipment maintenance area in central eastern portion of site (viewing east).



Photograph No. 2. Truck scale and administrative office located at site entrance. Dry processing plant visible in background (viewing northwest).



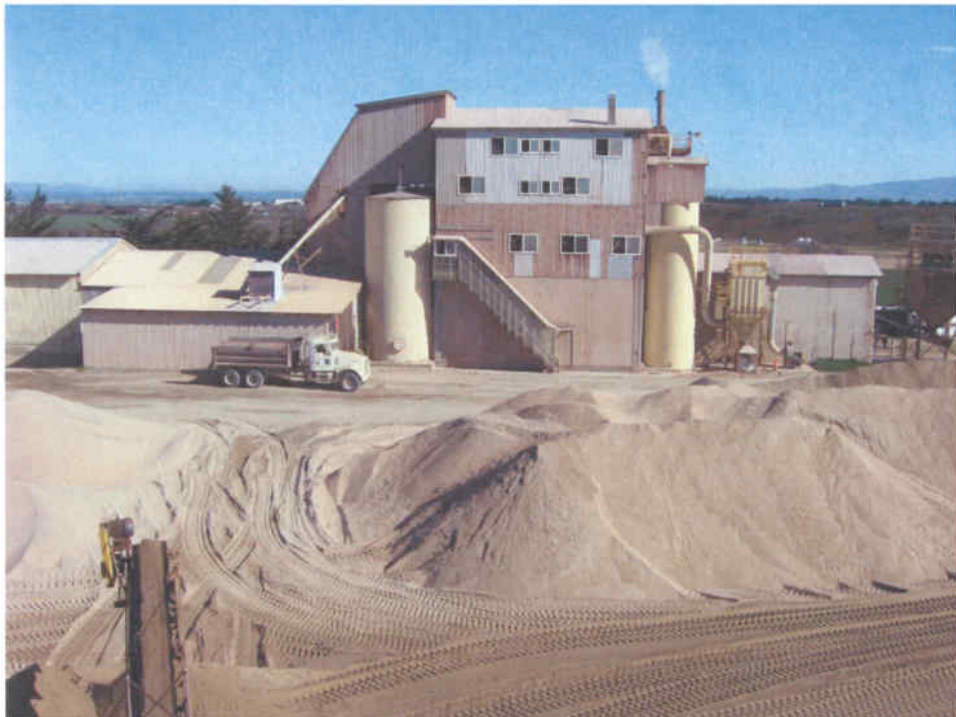
Photograph No. 3. Equipment staging and maintenance area in central eastern portion of site (viewing south).



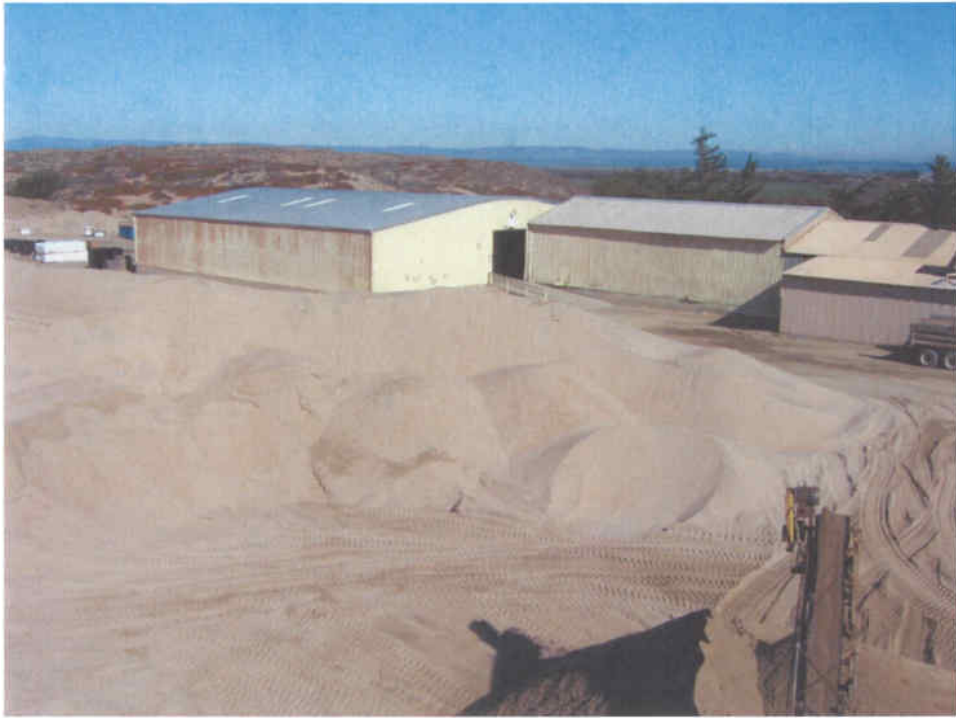
Photograph No. 4. Truck loading area and stockpile area in eastern portion of site (viewing west).



Photograph No. 5: Wet processing plant (middle distance), dry processing plant (upper left) and dredge feed pipe and pumping unit in west central portion of site (viewing east).



Photograph No. 6. Southwest side of dry processing plant, and material stockpiles, as viewed from the wet processing plant (viewing northeast).



Photograph No. 7. Bulk sand stockpiles and loading area, and northern portion of dry processing plant and bagged product storage area (viewing north).



Photograph No. 8. Current extraction area (dredge pond) on back beach at western edge of site (viewing north-northwest).



Photograph No. 9. Suction sand dredge situated in the southern end of the material extraction pond adjacent to Monterey Bay at the western edge of the site (viewing northwest).



Photograph No. 10. Western end of sand feed-pipe leading from the dredge pond to the wet processing plant (viewing north-northwest).



Photograph No. 11. Visible from left to right are the dredge pond access road, process water return canal, dredge sand feed-pipe, and primary settling ponds as viewed from the wet processing plant (viewing west).



Photograph No. 12. Process water settling ponds in western portion of site (viewing south).



Photograph No. 13. Overview of loading area and bulk sand product stockpile area in central southeastern portion of site (viewing east-southeast).



Photograph No. 14. Portion of main boneyard area situated in the central portion of the site (viewing west).



Photograph No. 15. Equipment storage and scrap metal boneyard area located adjacent to former residential structures in eastern portion of site (viewing southeast).



Photograph No. 16. Overview of portion of revegetation area along the northern perimeter of the site (viewing east-southeast).



Photograph No. 17. Revegetation plantings in the northwest portion of the site (viewing northeast).



Photograph No. 18. Northern revegetation area showing former location of various test structures for control of blowing sand (viewing west).



Photograph No. 19. Revegetated slopes (lower center and right) adjacent to sand stockpiles in the southeastern portion of the site (viewing east).



Photograph No. 20. Successfully revegetated slopes in the southern portion of the site (viewing southwest).

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A SEDIMENT BUDGET FOR THE SANTA CRUZ LITTORAL CELL, CALIFORNIA

TIM C. BEST AND GARY B. GRIGGS

SEPM (Society for Sedimentary Geology)

SPECIAL PUBLICATION NO. 46

A SEDIMENT BUDGET FOR THE SANTA CRUZ LITTORAL CELL, CALIFORNIA

TIM C. BEST

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AND

GARY B. GRIGGS

Department of Earth Sciences and Institute of Marine Sciences, University of California, Santa Cruz, CA, 95064

ABSTRACT: Beach compartments or littoral cells form the framework for our understanding of the sources, transport, sinks, and storage of sand in the nearshore zone. In general, along the California coast, beach sand is derived from rivers or bluff erosion, moves alongshore under the influence of prevailing wave conditions, and ultimately is lost either to a submarine canyon or dune field.

The Santa Cruz Littoral Cell appears to extend as far north as San Francisco Bay and terminates downcoast at Monterey Submarine Canyon. Northwestern waves drive littoral drift at a rate of about 200,000 to 250,000 m³/yr at the Santa Cruz Harbor.

The major sources of sand within the Santa Cruz cell are coastal streams draining the Santa Cruz Mountains and 130 km of coastal bluffs. On the basis of the grain-size distribution of beach and nearshore sediments, a littoral cutoff diameter (0.18 mm) was established in calculating a sediment budget. Fluvial sediment transport measurements combined with flow-duration curves and grain-size distributions were employed to calculate input from coastal streams to the cell. Cliff height and length, sand content, and average long-term (50 to 75 years of aerial-photograph coverage) erosion rates were utilized to determine the littoral contribution from seacliff and bluff retreat. Coastal streams supply about 75 percent of the total littoral-sand input to the cell, bluff erosion contributes about 20 percent and the remaining 5 percent is from gully erosion and sand-dune deflation.

Sediment input to the cell is highly episodic in response to large and infrequent erosional events. The processes that deliver sand to the cell (principally bluff erosion and high stream flow) may operate at different frequencies than those that move sand through the cell (longshore transport). An additional complexity arises from potential changes in sand storage, either on the beach or along the inner shelf, which are capable of producing significant volumes of sand due to the large areas involved.

INTRODUCTION

A sediment budget is a quantitative statement of the relations between the rate of sediment production, transport, storage and discharge. For a littoral cell, it is the conceptual simplification of the interaction of processes that deliver sand into the littoral zone and transport it along the shoreline. Discrete beach compartments or littoral cells form a framework for our understanding of sources, transport, and outputs of sand in the nearshore zone. In a typical beach compartment, littoral transport begins at a rocky headland or section of coast where the upcoast supply of sand or littoral drift is restricted or minimal. Sediments enter the littoral cell primarily from coastal streams and bluff erosion, and are transported alongshore under the influence of the prevailing wave conditions (Inman and Frautschy, 1966). Ultimately, the sand is lost from the system or cell through either a submarine canyon, a coastal-dune field, or in some cases, direct removal through sand mining. In theory, each cell exists as a distinct entity with little or no transport of sediment between cells.

The use of sediment budgets has become common practice among fluvial geomorphologists; however, its application to the littoral zone is still in its infancy. Bowen and Inman (1966), working on the central California coast, were the first to develop a sediment budget for a littoral cell. In subsequent years, other littoral-budget studies have been completed by Hales (1978), Weggel and Clark (1983), Inman and Jenkins (1983), Oradiwe (1986), Dolan and others (1987), Morelock (1987), and Osborne and others (1989). These reports often focus on longshore transport rates or sediment input volumes and only qualitatively address the issue of sediment routing. Due in part to a lack of data, contributions from individual sources have often been evaluated either in very general terms, or using unverified assumptions or extrapolations.

Our lack of a quantitative understanding of littoral cells and sand budgets has become all too obvious along the California coast (Griggs, 1987a). The problems and costs associated with harbor dredging, where jetties or breakwaters have been constructed in the middle or downcoast ends of littoral cells with high-drift rates, on one hand, and the reduction of sand delivery to beaches due to impoundment of sediment behind dams in the coastal watersheds (Norris, 1964; Brownlie and Taylor, 1981), on the other, stem directly from the failure to incorporate this type of information in the land-use decision-making process. The application of a sediment budget to the nearshore zone is a useful tool in coastal land-use management, and is an essential step in understanding the importance of sediment routing along the coast. On the central and northern California coastline, a large gap exists in our present state of knowledge regarding both littoral-cell boundaries and production, transport, storage and loss of littoral sediment within these cells. This investigation was directed toward quantitatively evaluating sediment routing of littoral sands within a portion of the Santa Cruz Littoral Cell. A secondary goal was to evaluate the methodology used in developing a littoral-sediment budget.

PHYSICAL SETTING

The study area extends along the central California coast from Tunitas Creek in San Mateo County in the north to Twin Lakes Beach in Santa Cruz County in the south, and inland to the crest of the Santa Cruz Mountains (Fig. 1). The northern boundary of the study area was initially assumed to correspond to the upcoast boundary of the Santa Cruz Littoral Cell. Although a regional study by Inman (1976) suggested that this cell extended as far north as the entrance to San Francisco Bay, more recent studies by Weber

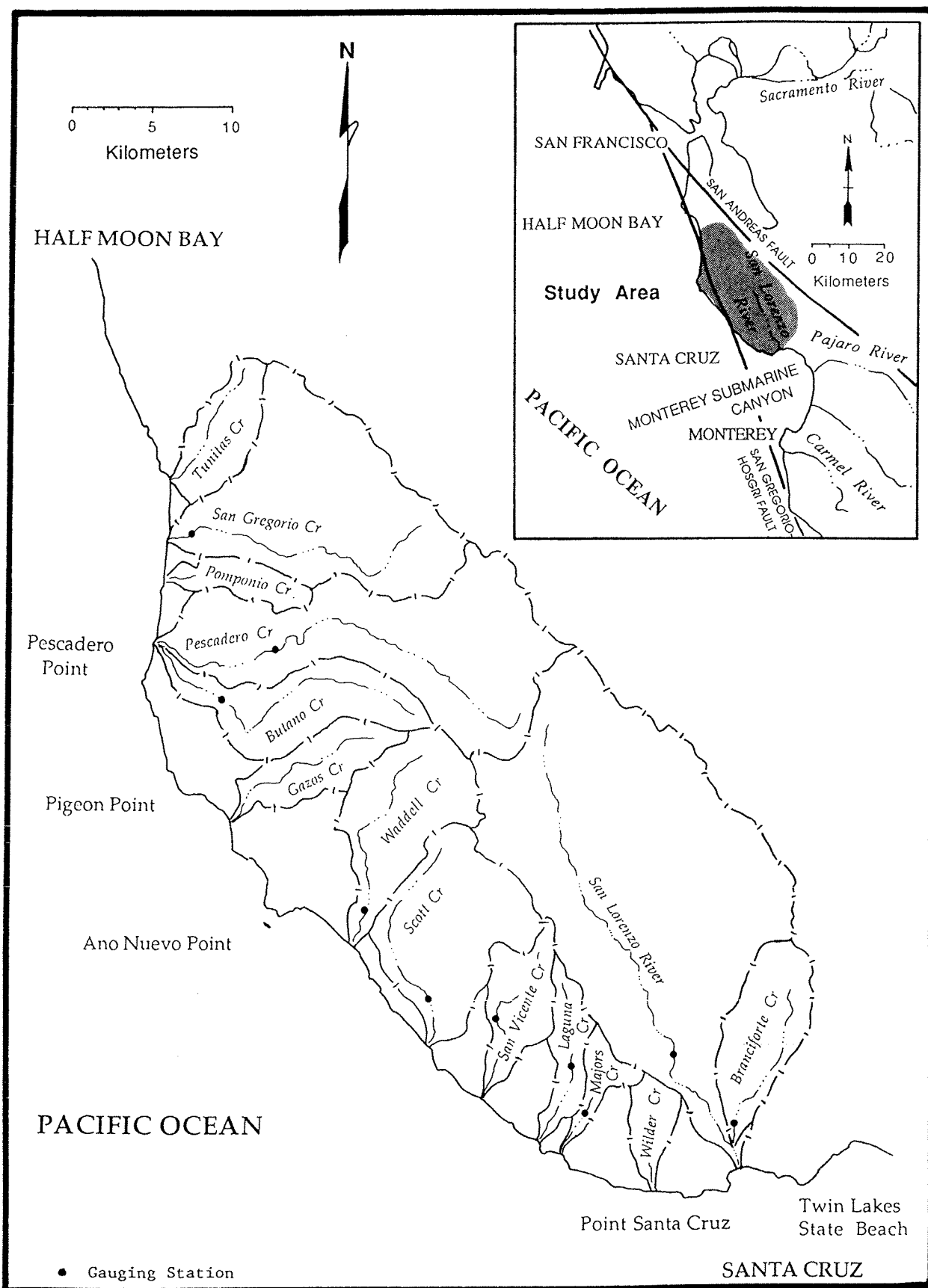


FIG. 1.—Study area and location of principal drainage basins.

(1979) and Griggs (1987a) based on heavy-mineral provinces identified by Yancey and Lee (1972) delineated the northern boundary of the cell at Tunitas Creek, which was the northern boundary used in this study. Habel and Armstrong (1978) in a state-wide overview, terminated the Santa Cruz cell at the northern edge of Monterey Bay. It became apparent at the end of this study that the Santa Cruz Littoral Cell extends at least as far north as the entrance to San Francisco Bay.

The Santa Cruz Littoral Cell terminates downcoast at Monterey Submarine Canyon (Fig. 1). The border of the study area, however, was chosen at Twin Lakes State Beach (the Santa Cruz Small Craft Harbor), a point within the cell where rates of littoral transport are reasonably well known. Net transport within the cell is from northwest to southeast.

The 80 km of littoral-cell coastline north of Monterey Bay are characterized by steep, 5- to 50-m-high coastal bluffs, occasional pocket beaches and coastal dunes. To the east, the Santa Cruz Mountains are drained by a number of small, steep coastal streams, the mouths of which have been drowned by the Holocene rise in sea level. Their lower reaches are typically marked by low-gradient flood plains, coastal lagoons and marshes.

The study area is located within the Salinian Block, an elongate, northwest-trending tectonic sliver bounded on the

northeast by the San Andreas fault and on the southwest by the San Gregorio-Hosgri fault system (Fig. 1). In general, Paleozoic metamorphic rocks (marbles and schists) and Cretaceous granitic rocks form the basement complex of this portion of the Santa Cruz Mountains. These rocks are overlain by a sequence of more than 10,000 m of Tertiary marine conglomerates, sandstones, siltstones and mudstones (Nielsen and Brabb, 1979; Clark, 1981).

A series of up to five prominent marine terraces indents the seaward slope of the Santa Cruz Mountains along the length of the littoral cell (Fig. 2). Overlying these terraces is a thin (usually 1.5 to 6 m), nearly continuous mantle of poorly consolidated marine and non-marine gravels, sands and silts. Quaternary sand dunes are found at the mouths of Pescadero, San Gregorio, Waddell and Scott Creeks, and locally overlie the marine-terrace deposits at Ano Nuevo Point, Franklin Point and Sand Hill Bluff.

The Santa Cruz Littoral Cell is characterized by a Mediterranean climate with 90 percent of the rainfall occurring between November and March. The relatively abrupt rise of the Santa Cruz Mountains produces pronounced orographic effects with mean annual rainfall ranging from 45 to 70 cm along the coast and increasing to 150 cm along the crest of the range (Rantz, 1971). Storms are typically of short duration but often of high intensity.

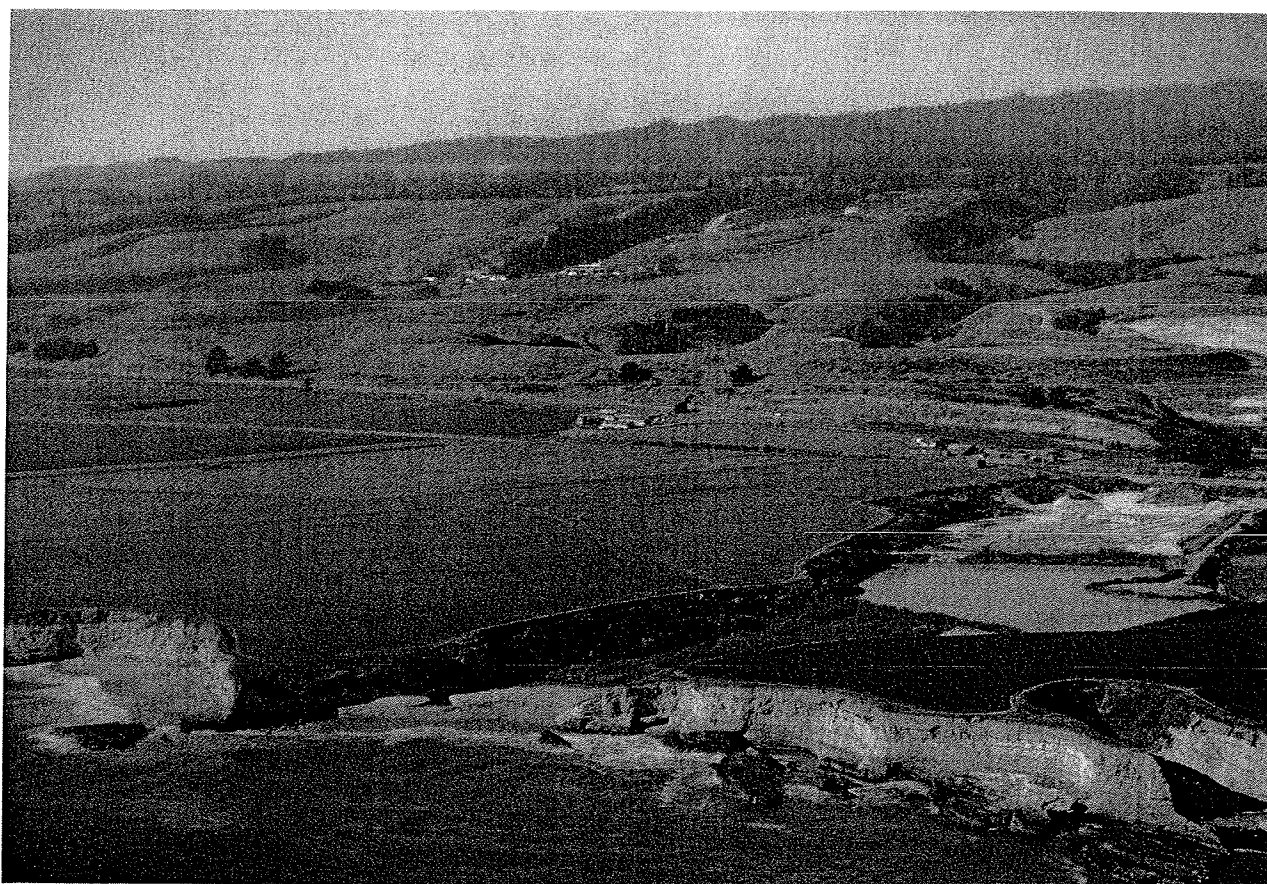


FIG. 2.—Coastal marine terraces and actively eroding sea cliffs 11 km north of Santa Cruz. Tertiary Santa Cruz Mudstone capped by unconsolidated marine and non-marine Quaternary terrace deposits form the eroding sea cliffs.

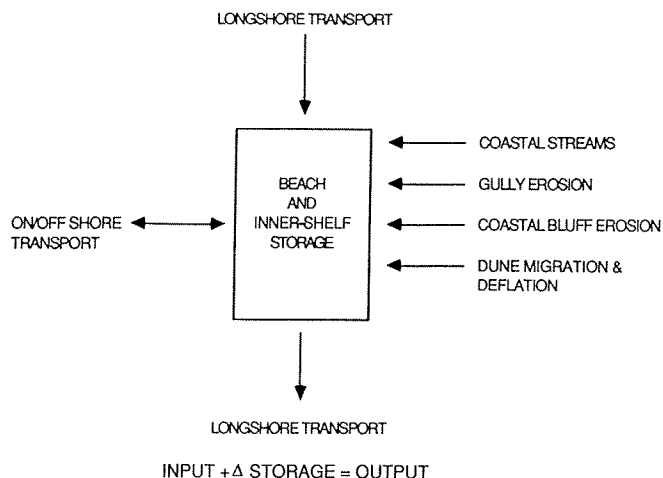


FIG. 3.—Conceptual diagram of sediment routing in the Santa Cruz littoral cell.

APPROACH

Construction of any sediment budget requires 1) identification of source, storage, and output elements, 2) recognition and quantification of erosional and transport processes, including an understanding of the relative importance of persistent versus episodic events, and 3) an understanding of grain size and composition of material in storage and transport (Dietrich and others, 1982; Lehre, 1981).

Sediment routing in the Santa Cruz Littoral Cell can be represented by a conceptual model (Fig. 3). To develop the budget, we will systematically evaluate the importance of each source and output element and attempt to evaluate a range of potential error. In this investigation we are concerned only with material coarse enough to remain on the beach face or in the nearshore zone in appreciable quantities. Fine-grained material (i.e., fine sands, silts and clays) that is lost permanently from the cell will not be included in any budget calculations.

GRAIN-SIZE DISTRIBUTION OF MATERIAL IN LONGSHORE TRANSPORT

The rate of longshore transport is greatest immediately shoreward of the breaker zone (Komar, 1971, 1976) and decreases offshore. It is reasonable to assume that the areal extent of longshore transport is limited in a shore-normal direction by available wave energy and nearshore bathymetry. Because of the direct relation between wave energy (near-bottom current velocity) and particle diameter entrained in transport (Silvester and Mogridge, 1971; Komar and Miller, 1973, 1975), a threshold velocity exists for sediment movement. Assuming a steady-state environment, some minimum grain size should exist below which particles will not remain within the active zone of littoral transport in any appreciable quantity. Material smaller than this size (designated the littoral cutoff diameter) will be lost permanently offshore.

The cutoff diameter for the Santa Cruz cell was determined by comparing the grain-size distribution of 42 com-

posite beach-face samples taken throughout the study area, offshore bottom sediments, and dredge spoil collected at the Santa Cruz Harbor.

Beach samples are all well sorted with an abrupt cut off to a fine-grained tail. The maximum curvature of the fine tail is interpreted to represent the local cutoff diameter of particles in transport. The D_{10} is the particle size for which 10 percent of the sample by weight is finer, and closely approximates the maximum curvature of the fine tail. The mean D_{10} or cutoff diameter within the study area is 0.22 mm but decreases downcoast from an average of 0.45 mm near Tunitas Creek to 0.18 mm at Twin Lakes Beach (Fig. 4). We interpret this alongshore reduction to be a product of both selective sorting as well as differences in available wave energy. Giving more weight to the finer-grained samples, and also to those obtained geographically closer to the downcoast end of the study area, we chose the littoral cutoff diameter of 0.18 mm for the cell, a value equal to the mean plus one standard deviation of all samples. Hicks (1985) calculated a cutoff diameter from Santa Cruz Harbor dredge spoils at 0.18 mm using D_{16} (the average particle size plus one standard deviation).

Grain-size distributions are known for offshore samples collected at depths from 25 to 200 m (Lee and others, 1970; Yancey and others, 1970). In general, mean size decreases offshore, and nearly all sediment is finer than 0.18 mm (of the 44 offshore samples, only four had D_{90} values greater than 0.18 mm), which offers additional support for the selection of 0.18 mm for the littoral cutoff diameter within the Santa Cruz Cell.

SEDIMENT INPUT

Sediment input to the Santa Cruz Littoral Cell is principally from coastal streams, gullies, seacliff erosion, sand dunes, and longshore transport. Onshore transport from the inner shelf appears to constitute only a minor contribution. Biogenous and hydrogenous inputs are unimportant to the budget as well.

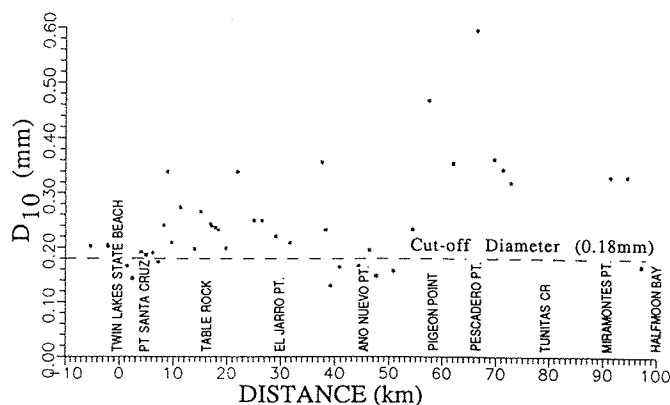


FIG. 4.— D_{10} and cutoff diameter of beach sand collected along the coastline from Santa Cruz to Half Moon Bay. Stars represent D_{10} values for individual beach-sand samples; dashed line represents cutoff diameter for material in littoral transport.

Coastal Streams

Coarse-grained sediment delivery by coastal streams is usually the dominant source of sand to littoral cells along the coastline of California (Komar, 1976; Griggs, 1987a; Stow and Chang, 1987). The coastal watersheds draining the west side of the Santa Cruz Mountains are limited in areal extent but have relatively large sediment yield. To evaluate the littoral-sediment yield requires: 1) estimating total sediment yields, 2) adjusting for the coarse-grained fraction (greater than 0.18 mm), and 3) adjusting the total yield for any changes in floodplain storage.

Thirteen streams with basin areas greater than 12 km² drain 85 percent of the 1140-km² study area (Fig. 1). In general these basins are narrow; streams are deeply incised and drain steep terrain. The mouths of these streams have been drowned by the Holocene rise in sea level, and thus have low-gradient flood plains or coastal lagoons that serve as temporary sediment storage sites. Although the streams are perennial, sand bars commonly block their mouths during dry summer months. The mouths of all of the coastal streams between Wilder and San Vicente Creeks have been blocked by highway and railroad fill, leading to sediment impoundment during the past century.

The study area is underlain predominantly by Tertiary clastic marine sediments with local exposures of granitic basement. Overlying the bedrock is a thin veneer of colluvium and soil. The shallow depth of colluvium on hillslopes, combined with lack of large sediment bars and overbank deposits along the stream channels, suggests that storage of sediment in the upper portions of the watersheds is minor.

A large portion of the sediment produced within these basins is believed to be due to mass movements (primarily shallow-debris flows), which occur during winters of intense rainfall (Griggs, 1982; Smith and others, 1982; Ellen and Wiczorek, 1988). Lehre (1981) determined that over 80 percent of all sediment mobilized and 55 to 65 percent of all sediment reaching the main channel in a small 1.4-km² drainage basin northwest of San Francisco was due to shallow landsliding. Thus, sediment input to stream channels should be very episodic in response to very large storms.

Vegetation in these basins consists of redwoods, oak and madrone on side slopes and valley bottoms, and chaparral and grasslands on ridge crests. Whereas the San Lorenzo

River basin has been considerably altered by human activity (principally logging, quarrying and grading associated with construction activities), which has increased erosion rates and sediment yields, most of the smaller coastal basins have remained relatively undisturbed since the redwood logging of the past century.

Several previous studies have addressed sediment yield of these stream basins. Brown (1973), Macy (1976), Griggs and Paris (1982), Hicks (1985), and Nolan and Marron (1988) have estimated sediment yield for portions of the San Lorenzo River, whereas Curry and others (1986) and Williams (pers. commun. 1990) have addressed the sediment yield from Butano Creek. The majority of these studies, however, are based on limited data and do not necessarily reflect the long-term sediment yield of the basin.

Daily stream flow has been monitored on 10 coastal streams, which drain 68 percent of the total study area (Table 1). Sediment transport has been monitored at five of these stations (U.S. Geological Survey, 1931–1960, 1963–1988). Only the San Lorenzo River and Pescadero Creek have over one year of sediment-transport data, however (Table 1). Stream flow and sediment transport at Waddell Creek were monitored during the winter of 1986 as part of this study. The focus of this portion of the investigation was to evaluate the sediment yield at ungauged basins or at basins where sediment data are limited.

Sediment yield can be computed by developing a number of relations that integrate measurements of stream discharge and sediment transport. By normalizing characteristic variables between watersheds (i.e., basin area, precipitation, geology, etc.) and developing relations between stream discharge and sediment load, sediment yields from gauged basins can be used to predict the yield at ungauged basins.

A flow-duration curve relates discharge and percent of time that this discharge is exceeded. At ungauged basins or basins where flow record is short, an average flow-duration curve can be generated from nearby gauged basins having similar terrain by normalizing to mean annual discharge (Fig. 5). Mean annual discharge at an ungauged stream, in turn, can be estimated from rainfall-runoff relations (Fig. 6).

Sediment-transport curves, relating water discharge to sediment discharge, can be developed from measurements of suspended sediment, bedload, or any size fraction for which data are available (Colby, 1956). Where sediment data are unavailable, an average sediment-rating curve based

TABLE 1.—SUMMARY OF GAUGING RECORDS FOR STREAMS IN NORTH SANTA CRUZ COUNTY AND SOUTH SAN MATEO COUNTY

Stream	Drainage Area at Gauging Sta. (km ²)	Stream-Flow Measurements	Suspended-Sediment Measurement	Bedload Measurement
San Gregorio Creek near San Gregorio	131.2	1969–present	1986	1986
Pescadero Creek near Pescadero	118.9	1951–present	1971, 73, 75, 86	1986
Butano Creek near Pescadero	47.4	1962–1974	—	—
Waddell Creek near ranger station ^a	59.8	1986	1986	1986
Scott Creek near Big Creek	65.0	1958–1973	—	—
San Vicente Creek near Davenport	15.8	1970–1988	—	—
Laguna Creek near Davenport	8.0	1970–1976	—	—
Majors Creek near Santa Cruz	9.8	1970–1976	—	—
San Lorenzo River at Big Trees	274.5	1937–present	1972–82, 86 ^b	1972–82 ^b
Branciforte Creek at Santa Cruz	44.8	1940–43, 1951–68	—	—

^aGauged for the purpose of this study. All other gauging stations established by USGS.

^bMean daily sediment discharge values available from 1972–1982.



FIG. 5.—San Lorenzo River at Santa Cruz during the flood of January 4, 1982.

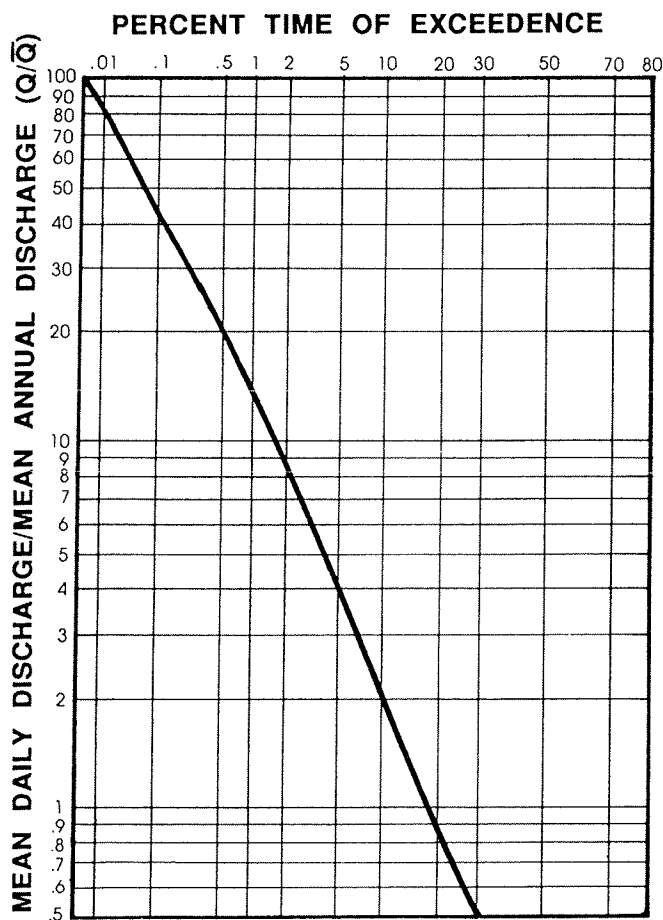


FIG. 6.—Unit flow-duration curve for the coastal streams in north Santa Cruz County and south San Mateo County for the period of record 1937–1988. Discharges have been normalized by mean annual discharge. Flow-duration curve is based on U.S. Geological Survey gauged streams, summarized in Table 1.

on measurements obtained from similar basins in an area can be used to approximate the rates of sediment transport at the ungauged stream (Figs. 7 and 8). Combining the flow-duration curve with the sediment-transport relation allows us to compute sediment yield from a basin. Sediment-transport values for the San Lorenzo River, the largest basin within the study area, have been reported for the period 1972–1982 (U.S. Geological Survey, 1963–1988) and provide the most accurate measure of actual sediment yield.

The sediment yields for the major streams draining the study area are summarized in Table 2. For the period of available data, the littoral-size fraction comprised 16 percent of the total load, of which 40 percent was transported as bedload. The relation between stream flow and the percentage of littoral sediment in transport indicates that at high flows a larger fraction of the total load is coarse-grained sediment. As flow increases, a larger portion of the total load is contributed to the cell.

The sediment delivery from coastal watersheds is very episodic. Forty-six percent of the total load of the San Lorenzo River for the period of sediment discharge record (1972–1982) was transported during five individual storm events, with 32 percent of the total suspended load carried during the January 4–5, 1982 flood, a 30-year event (Griggs, 1987b; Fig. 9). Suspended load for 1982 accounts for 52 percent of the total load for the entire 11 years of sediment record. Hicks (1985) suggests that 70 percent of the littoral-size load of the San Lorenzo River for the period of record 1972–1983 was delivered by the high flows during the major storms of 1982 and 1983. The infrequent but high-intensity rainfall events and subsequent stream discharge from these steep short basins can clearly dominate sediment input to the littoral cell.

The average annual total sediment yield calculated for the entire study area amounts to 365 tons/km², with the San Lorenzo River (at the Big Trees gauging station) having a slightly higher yield of 553 tons/km². This value for the San Lorenzo River is about half of that presented in the U.S. Geological Survey reports for the period of record using mean daily flow values (931 tons/km²). Sediment yield determined from the mean daily method is normally more accurate than that generated from flow-duration curves. Unfortunately, mean daily sediment-discharge values are only available for the San Lorenzo River. Because this study relies on sediment-data collection at lower flows and over a shorter time frame than those of the U.S. Geological Survey, the values reported here likely underestimate actual “long-term” conditions. Based on this comparison, we believe that this underestimate is no more than 50 percent.

The average annual littoral-sediment yield (material larger than the cutoff diameter) for the study area is therefore in the range of 61 to 122 tons/km². Applying this value to the remaining basins (those larger than 12 km²) in the 1140-km² study area and assuming a bulk density of 1600 kg/m³ produces an average of 43,000 to 87,000 m³ of littoral material annually from all stream sources.

Aggradation or an increase in sediment storage in coastal lagoons and flood plains due to sea-level rise could reduce these littoral-sediment yield values. Few studies address recent stream-channel aggradation in the study area, although

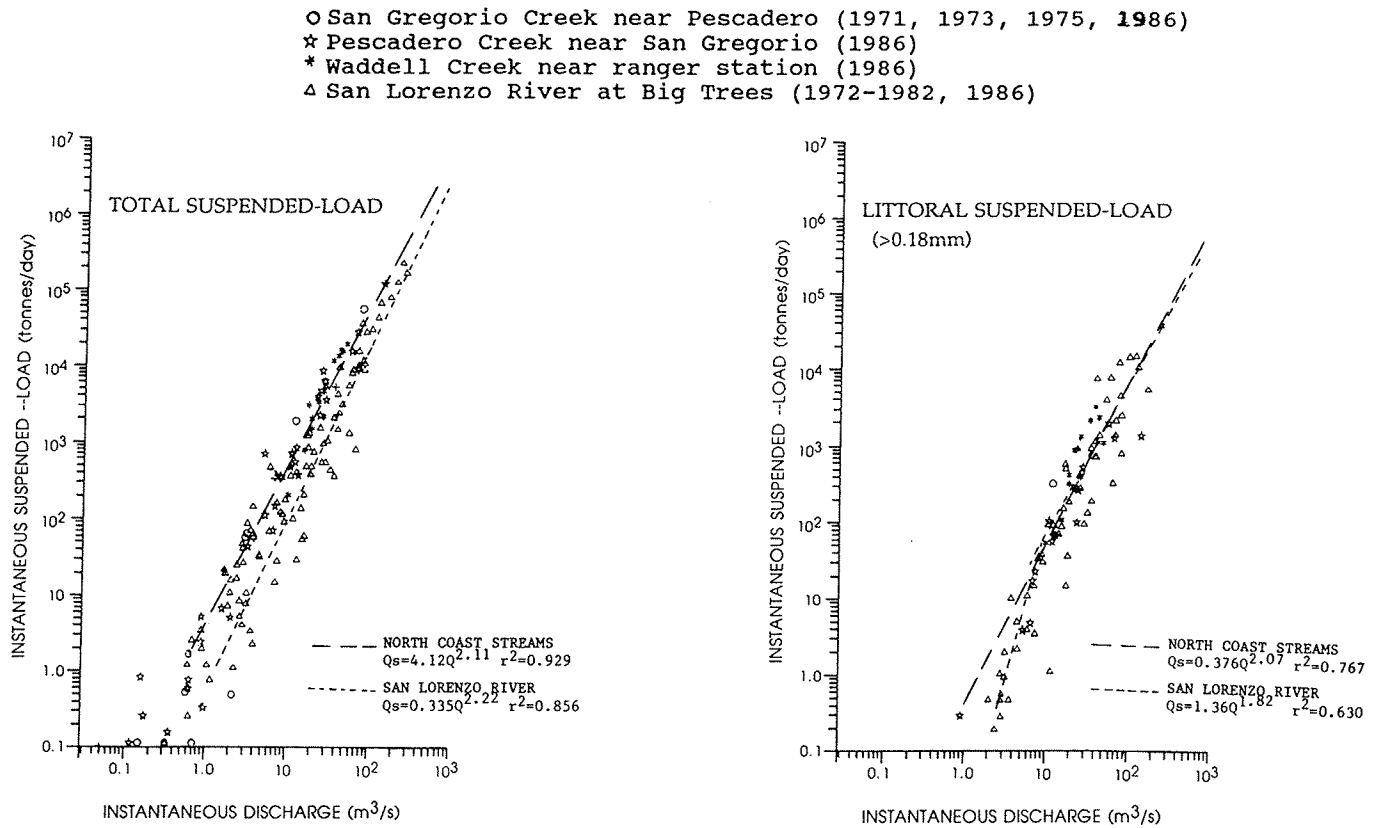


FIG. 7.—Total and littoral suspended-load rating curve for the coastal watersheds between Santa Cruz and Half Moon Bay.

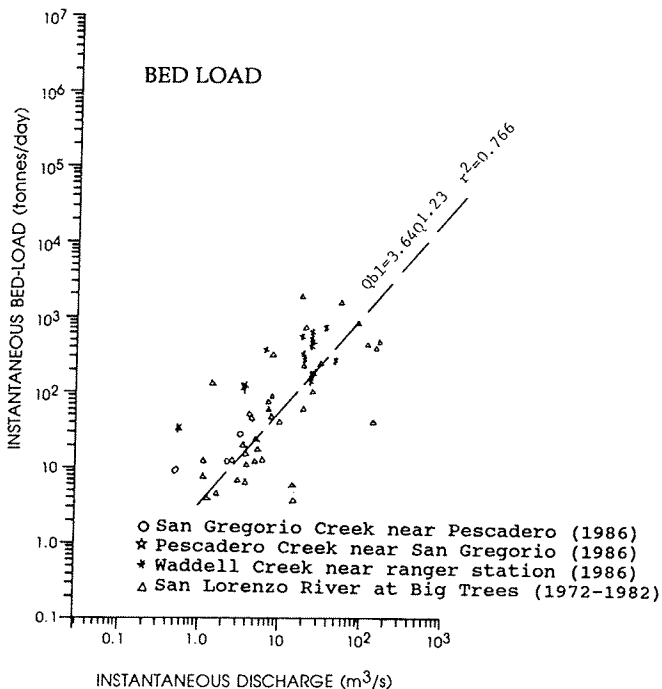


FIG. 8.—Bedload-rating curve for the coastal watersheds between Santa Cruz and Half Moon Bay.

Griggs and Paris (1982) do report on the aggradation of the lower reaches of the San Lorenzo River in response to dredging below natural grade during construction of a flood-control project in 1957–1959. Aggradation expectedly followed dredging until an equilibrium gradient was attained. Scour continues to occur during high flows followed by aggradation during low-flow periods. Aggradation of the Butano Creek flood plain, which has been partially modified by levees, has been addressed by both Curry and others (1986) and Williams (pers. commun., 1990). Both workers examined floodplain morphology through a comparison of topographic maps and aerial photographs dating back over 100 years. Williams concluded that net current yield is relatively small; Curry suggested that localized aggradation followed the 1986 storms. Based on all available information, we believe that the amount of net aggradation in the lower reaches of the coastal streams over the past 50 to 100 years is relatively small with respect to the overall sediment yield of the individual basins. However, we recognize that additional work is required in this area.

Gully Erosion

Extensive gullying characterizes the coastal hills along the northern portion of the study area (Fig. 10). The majority of gully erosion occurs along a 4-km-wide coastal

TABLE 2.—SEDIMENT LOAD FOR COASTAL STREAM BASINS IN NORTH SANTA CRUZ AND SOUTH SAN MATEO COUNTY (in tons/yr)

Stream	Drainage Area (km ²)	Suspended Load		Bedload		Total Load	
		Total Load	Littoral Load	Total Load	Littoral Load	Total Load	Littoral Load
Tunitas Creek at beach	30.1	1,290	105	299	227	1,590	332
San Gregorio Creek near San Gregorio	131.2	47,800	3,620	2,450	2,030	5,025	5,650
Pomponio Creek at beach	18.6	679	55	206	163	885	219
Pescadero Creek near Pescadero	118.9	49,700	3,760	2,510	1,930	52,210	5,690
Butano Creek near Pescadero	47.4	11,000	857	1,040	807	12,040	1,670
Gazos Creek at beach	29.8	2,700	218	462	299	3,160	517
Waddell Creek near Ranger Station	59.8	19,600	1,506	1,460	953	21,060	2,460
Scott Creek at beach	76.6	36,100	2,750	2,090	1,900	38,190	4,740
San Vicente Creek at beach	29.1	3,090	247	234	209	3,324	455
Laguna Creek at beach	20.8	1,290	105	299	236	1,580	341
Major Creek at beach	12.1	372	29	140	109	512	138
Wilder Creek at beach	14.6	366	30	143	109	509	139
San Lorenzo River at Big Trees	274.5	142,000	21,900	9,890	9,250	140,100	31,100
Branciforte Creek at Santa Cruz ^a	44.8	1,500	606	877	816	2,377	1,422
Total metric tons/yr		318,000	35,600	22,300	19,200	294,000	54,900

^aTributary of the San Lorenzo River.

strip between Pigeon Point and Half Moon Bay, with the basins between San Gregorio and Pescadero Creeks being the most extensively affected. Over the past 50 years there has been a dramatic increase in both the size and number of gullies (Swanson, 1983). Gully networks are preferentially confined to the marine-terrace deposits and alluvial

and colluvial materials overlying the Purisima Formation. Gullying results from subsurface soil piping through more permeable horizons, and channelized overland flow (Swanson, 1983).

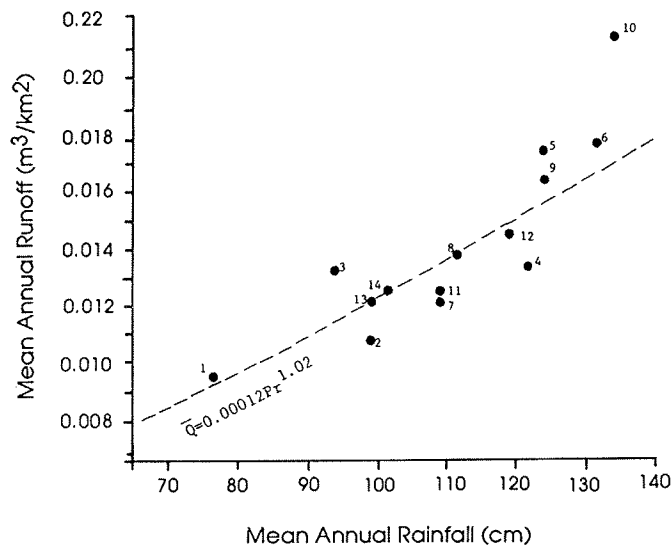
Sediment yield was estimated at the 1.2-km² Long Gulch sub-basin located 1 km south of Pomponio Creek (Figs. 1 and 10) that represents approximately 17 percent of the 7.4-km² area currently undergoing active gullying. We determined the sediment yield from Long Gulch by integrating measurements of individual gully lengths and widths (determined from aerial photographs) with the field relations between top width and cross-sectional area. The littoral fraction of the total load was determined from sieve analysis of materials exposed in the gully walls. We then applied the sediment yield from Long Gulch to the other gullied areas to determine the total and littoral input from coastal gullying to the cell.

Average sediment yield from the coastal gullies is increasing as new gullies form and existing gullies enlarge. Between 1928 and 1982 the average sediment yield from the gullies of this coastal area was about 1,660 m³/km². For the period of stream sediment record, however (1972 to 1982), average annual yield was roughly twice this value, about 3,900 m³/km². This represents a total sediment load of 29,000 m³/yr for the gullied area.

Based on grain-size analysis of the materials exposed in the gully walls, only about 10 to 20 percent of the total load has a particle diameter greater than the littoral cutoff size. The majority of littoral-size sediment originates from the overlying marine-terrace and alluvial deposits. Although gullying is evident in the Purisima Formation, the sediments are too fine grained to be a significant source of littoral sediment. The littoral input to the cell from gullying is currently about 2,900 to 5,800 m³/yr but is expected to increase slightly.

Seacliff Erosion

The shoreline throughout the study area consists predominantly of an uplifted sequence of marine terraces fronted by actively eroding, near-vertical sea cliffs. The cliffs are



NORTH COAST BASINS

- 1 San Gregorio Creek near San Gregorio
- 2 Pescadero Creek near Pescadero
- 3 Butano Creek near Pescadero
- 4 Scott Creek near Big Creek
- 5 San Vicente Creek near Davenport
- 6 Laguna Creek near Davenport
- 7 Majors Creek near Santa Cruz

SAN LORENZO RIVER BASINS

- 8 San Lorenzo River near Boulder Creek^b
- 9 Boulder Creek near Boulder Creek^b
- 10 Bear Creek at Boulder Creek^b
- 11 Zayante Creek at Zayante^b
- 12 San Lorenzo River at Big Trees
- 13 Branciforte Creek at Santa Cruz

SOQUEL CREEK BASINS

- 14 Soquel Creek at Soquel^{a,b}

- a: Outside of study area
b: Not used in regression analysis

FIG. 9.—Mean annual rainfall-runoff relation for the coastal Santa Cruz mountains region. Mean annual rainfall from Rantz (1971); mean annual runoff from U.S. Geological Survey (1931–1960, 1963–1988).

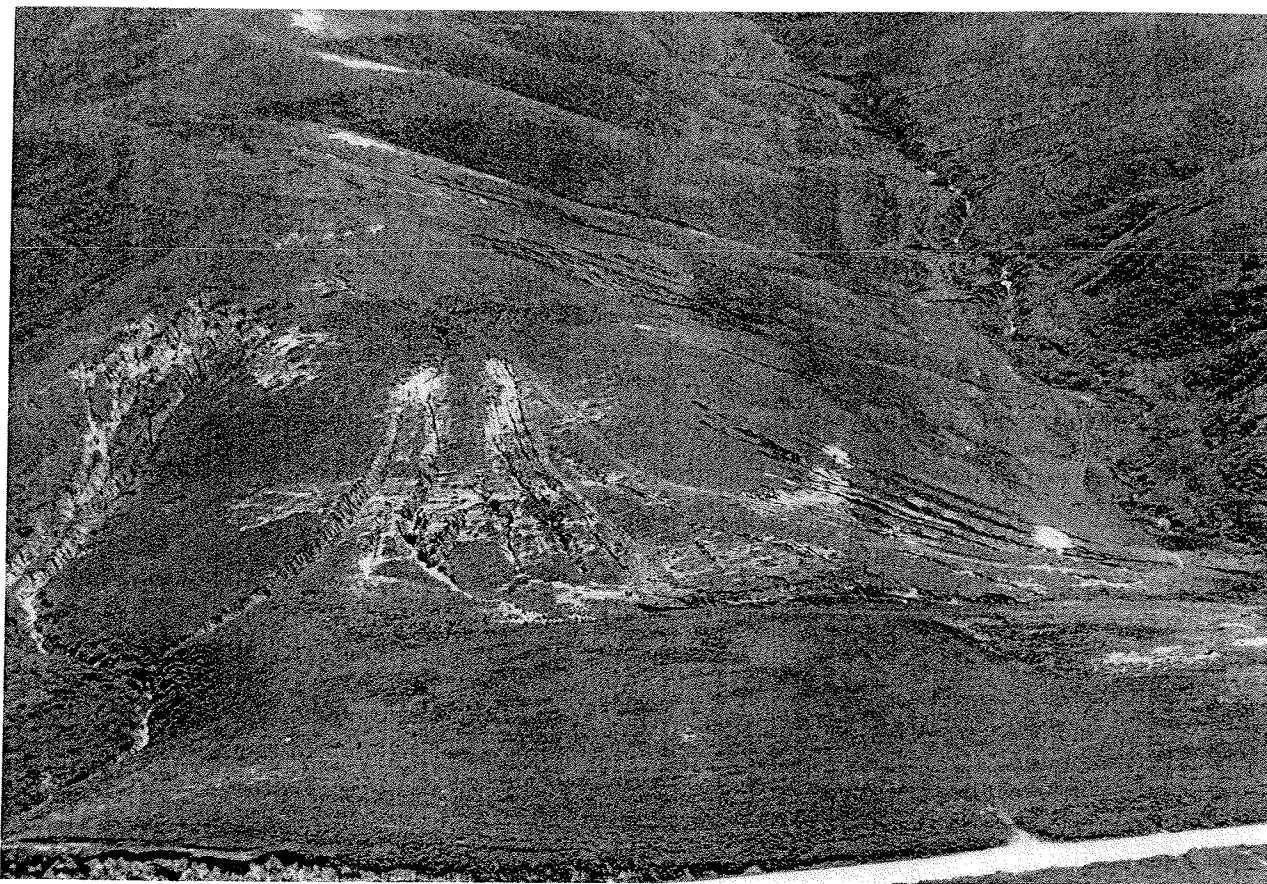


FIG. 10.—Actively eroding gullies in Long Gulch, between Pomponio Creek and Pescadero Creek, San Mateo County coast. Note road in foreground for scale.

interrupted by relatively small pocket beaches that have formed at the mouths of the coastal streams (Fig. 2). Terraces are well developed due primarily to the nearly flat-lying or gentle seaward dip of the underlying well-bedded sedimentary rocks. Sea cliffs range in height from 5 to 50 m, have an abrupt cliff edge, and typically erode to form an irregular coastline. Lithology and structure are the dominant factors influencing seaciff morphology.

The Santa Cruz Mudstone dominates the sea cliffs throughout the southern portion of the study area and is exposed between Pt. Santa Cruz and Ano Nuevo Creek. The Pigeon Point Formation (well indurated silts, sands and gravels) crops out from White House Creek to Pescadero Creek. The Purisima Formation (mudstone, siltstone and very fine-grained sandstone) is exposed both north of Pescadero Creek and along the cliffs within the city of Santa Cruz. Quaternary dunes, terrace deposits and alluvium comprise the low bluffs in the Ano Nuevo area.

The production of littoral sand from a segment of shoreline through seaciff erosion (Q_s) is the product of the cross-sectional area of sea cliff (A , equal to cliff length $\times$ height), the average annual rate of cliff retreat (dx/dt), and the percentage of that material which is greater than the cutoff diameter (percent CD), or:

$$Q_s = A(\text{percent CD})dx/dt.$$

Rates of seaciff retreat are governed by the ability of large storm waves to attack the base of the cliff and the relative ease with which cliff material can be dislodged, either directly by wave attack, or through subaerial processes such as rock falls (Fig. 11). Episodic and locally variable rates of cliff retreat result from a combination of 1) alongshore differences in the strength of cliff materials (Griggs and Johnson, 1979; Sunamura, 1983), 2) the infrequent occurrence of high tides and extreme storm waves capable of producing significant erosion and removing debris from the base of the cliff, 3) concentration of wave energy due to local bathymetry, and 4) the presence or absence of a protective beach.

Rates of bluff retreat also may be influenced by large earthquakes, such as the 7.1-magnitude October 17, 1989 Loma Prieta earthquake. This was the largest earthquake to affect the central coast since the 1906 San Francisco earthquake, and it produced isolated cliff failure throughout the entire study area (Plant and Griggs, 1990). For the most part, these failures consisted of isolated rock falls or soil slips resulting in up to 1 m of bluff retreat. Similar cliff failures were noted during the 1906 event (Lawson, 1908). In addition to the instantaneous bluff failure during the 1989 earthquake, tension cracks formed as much as several meters landward of the cliff edge in many locations along the shoreline of the study area. These are expected to lead to

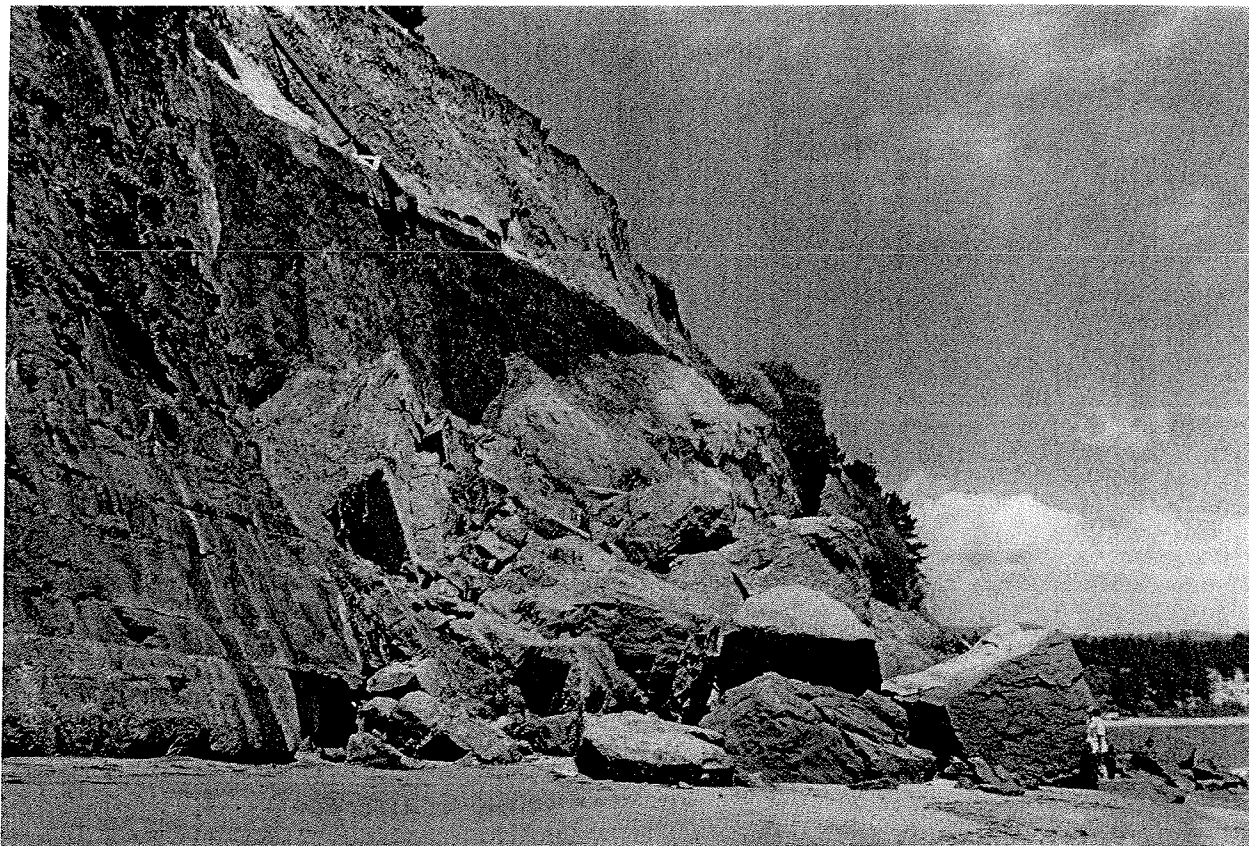


FIG. 11.—Block fall landsliding along the coastal seacliffs south of Santa Cruz. Failure occurred along joint sets due to undercutting by surf action. Note person on side of photo for scale.

additional failure in subsequent wet winter months. It is clear that a large-magnitude earthquake may play an important but infrequent role in cliff recession.

Rates of seacliff retreat over the past 50 to 100 years were computed from a comparison of time-sequential aerial photographs, ground photographs and historic coastal surveys and maps. Methods used involved measurements of the position of the seacliff edge at individual locations during the time covered by available maps or photographs.

Lithology and structure of the cliff-forming materials exert the dominant control on rates of seacliff retreat. Within the 50- to 100-year data base used, the well-cemented sandstones and conglomerates of the Pigeon Point Formation show negligible erosion (Figs. 12 and 13). In contrast, cliffs containing the Purisima Formation and Santa Cruz Mudstone erode at average rates of 0 to 20 cm/yr, with the Purisima eroding more rapidly by virtue of its general lack of cementation and induration. The mudstone is extensively jointed, which allows for hydraulic quarrying or block removal as well as rock falls from the cliff. The common presence of an intertidal shore platform in the mudstone throughout much of the study area (Fig. 2) buffers the base of the cliff from direct wave attack, thus allowing for only moderate rates of erosion.

The most rapid rates of cliff retreat occur in the Ano Nuevo Point area and typically exceed 30 cm/year. These high-erosion rates are due to a combination of 1) the relatively low height (less than 10 m) of the marine terrace and sea cliff at this location, 2) the material exposed in the bluff being dominantly unconsolidated and therefore, very erodible terrace deposits and dune sands, and 3) the direct exposure of the point to severe storm waves. This small section of the cell is a potentially significant source of sand for the budget due to a combination of the rapid-erosion rates and availability of sand-size material.

The area of sea cliff that provides potential sediment to the littoral budget was determined from measurements of cliff length and height. Height was measured from the bluff top to a depth of about 4 m below sea level, the approximate zone within which active erosion of the bedrock is concentrated. The thicknesses of the different stratigraphic units exposed in the sea cliff were determined from a combination of direct field measurements, near-horizontal aerial photographs taken at cliff-top altitude from offshore, topographic maps, and vertical aerial photographs using a parallax bar.

Based on both a visual evaluation of the seacliff materials and a number of grain-size analyses, it is evident that the

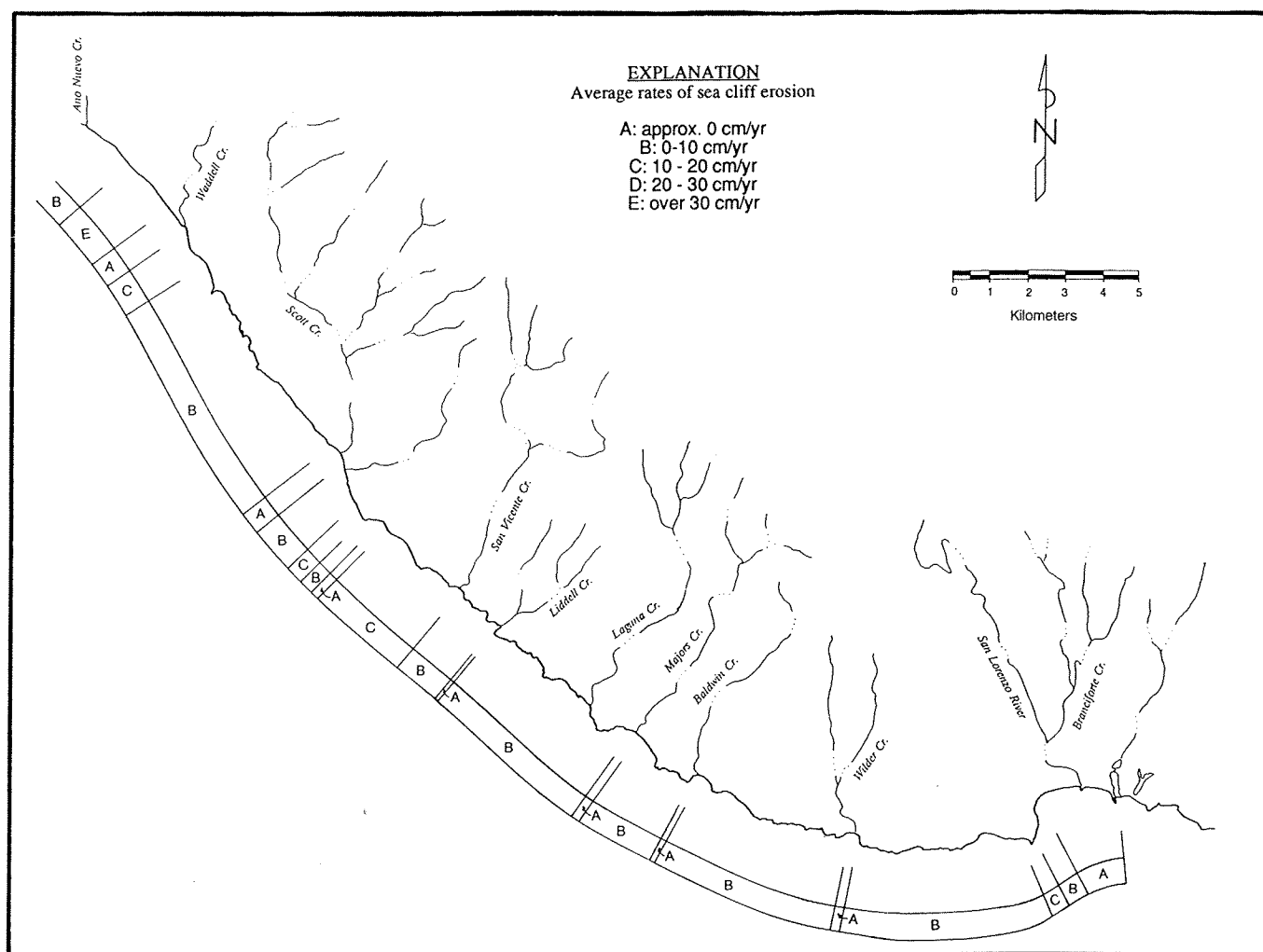


FIG. 12.—Average rates of seacliff retreat—Santa Cruz Small Craft Harbor to Ano Nuevo Creek.

exposed bedrock materials do not contain or provide a significant amount of littoral sand. The Santa Cruz Mudstone and Purisima Formation are too fine grained. The Pigeon Point Formation is sufficiently coarse grained, but is eroding very slowly. Terrace deposits, on the other hand, are relatively coarse grained. Between Santa Cruz and Ano Nuevo Creek, the amount of littoral sand (greater than 0.18 mm) contained in the terrace deposits ranges from 16 to 78 percent, with an average of 52 percent. From Ano Nuevo Creek to Tunitas Creek the range is from 1 to 28 percent, with an average of 19 percent. In the Ano Nuevo area, 77 percent of the dune sand is larger than the cutoff diameter.

For the portion of the littoral cell updrift of the Santa Cruz Small Craft Harbor, the contributions of the individual geologic units to the littoral budget from seacliff retreat are summarized in Table 3. The unconsolidated, relatively coarse-grained Quaternary deposits, which cap the bedrock terrace along the entire length of the cell, supply 52 percent of the littoral sand produced from seacliff retreat. Although the Purisima Formation and Santa Cruz Mudstone form the

sea cliffs for most of the study area, they are too fine grained to contribute significant amounts of littoral-size material. The short stretch of recent dunes at Ano Nuevo is the source for most of the remainder of the sand provided by seacliff retreat to the cell.

Sand Dunes

Modern sand dunes overlie the marine-terrace deposits at Ano Nuevo Point, Franklin Point, and Sand Hill Bluff, and also occur locally at the mouths of Pescadero, San Gregorio, Waddell and Scott Creeks. Evidence has been put forth that in the recent past (.2-.25 ka) the coastline at Ano Nuevo Point extended seaward to include Ano Nuevo Island (Weber, 1979). The existence of a receptive windward-facing beach and a low-relief peninsula allowed for a broad beach and dune field to develop. Sand slowly moved across the point in a series of barchan dunes and eventually cascaded off the cliff along the south shore. The opening of the channel between the point and the island in the mid-1700s re-

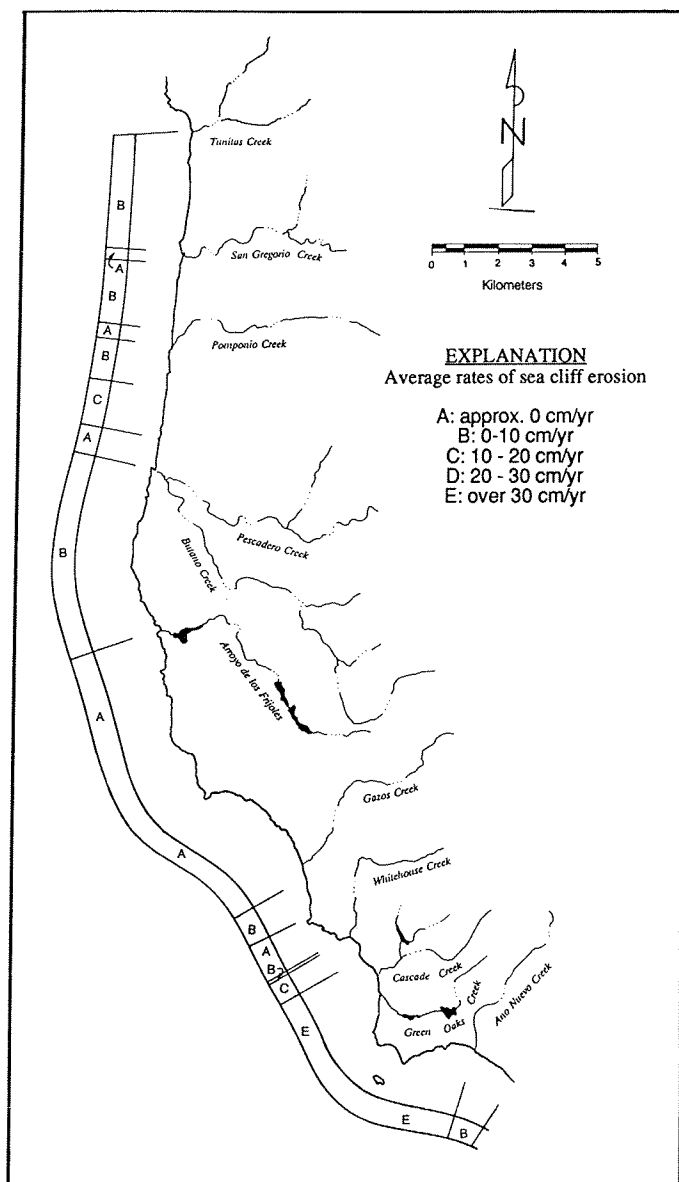


FIG. 13.—Average rates of seacliff retreat—Ano Nuevo Creek to Tunitas Creek.

duced the sediment supply to the dune field and the dunes have subsequently stabilized and deflated. Currently, only a minor amount of sand is blown onto the point along the north shore between Table Rock and North Point.

An evaluation of the significance of this source involving time-sequential aerial photographs combined with field measurements of dune frontage and height, as well as grain-size distribution, indicates present contribution of littoral-size sand from the dunes is about 1,700 m³/yr, and is expected to decline as the dune field stabilizes further.

Because of the relatively small size of the dune fields at Franklin Point, Sand Hill Bluff, and locally at the stream mouths, the amount of sand transferred between these storage sites and the littoral cell is minor.

TABLE 3.—SUMMARY OF AVERAGE ANNUAL SEDIMENT INPUT OF BEACH-SIZE SAND TO THE SANTA CRUZ LITTORAL CELL BY SEACLIFF EROSION BETWEEN SANTA CRUZ AND TUNITAS CREEK

Geologic Unit	Average Sediment Input (m ³ /yr)	Percent of Cliff Budget
Purisima Formation	250–360	2
Quaternary marine terrace	6,880–12,100	58
Quaternary dunes	5,040–7,500	40
TOTAL	12,170–19,960	100%

Onshore Transport

A number of processes have been discussed in recent years as potentially significant in transporting littoral sediments across the shelf, either onshore or offshore (Wright, 1987). Whether or not this type of transport takes place is of considerable importance to this study. To date there have been no specific investigations within the study area addressing the on/offshore transport of coarse-grained material.

Significant storage of littoral sediment on the inner shelf is a difficult component in any budget to evaluate (Bowen and Inman, 1966). Due to the large area involved, a small increase in thickness of sediment cover can produce a very large volume. Typical offshore-survey methods utilized do not allow for the resolution in sediment depth or thickness required to make precise estimates of this component.

Extensive offshore sampling across the shelf of the study area (Lee and others, 1970; Yancey and others, 1970) indicates that at depths greater than 25 m nearly all of the sediment is finer than 0.18 mm (the littoral cutoff diameter), suggesting that neither significant onshore nor offshore transport of littoral sand takes place in the cell. This storage component is potentially significant, however, and needs better resolution.

Longshore Transport

If the boundaries of a littoral cell are selected correctly, and there is no leakage or transfer of sediment between cells, then littoral transport is not a budget input to consider. As this study progressed, however, it became evident that the heavy mineral-province boundary identified by Yancey and Lee (1972) did not constitute a littoral-cell boundary. Although Habel and Armstrong (1978) delineated three littoral cells between Monterey Bay and San Francisco, there are no major sinks along this entire coastline capable of forming the termination of a cell. It is now evident that the Santa Cruz cell extends upcoast at least to the entrance of San Francisco Bay.

Because the sediment sources north of Tunitas Creek were not systematically evaluated, and because there have been no studies on longshore-transport rates in that area, sediment input to the littoral cell from upcoast longshore transport is a largely unknown quantity at present.

The majority of coarse-grained sediment entering the San Francisco Bay from either the Sacramento or San Joaquin Rivers is trapped within the bay (Griggs and Hein, 1980). The D_{50} of bottom sediments collected off the mouth of the San Francisco Bay range between 0.10 and 0.33 mm, fin-

ing offshore (Thompson, 1981), suggesting that there may be some very fine-grained sand that does leave the bay entrance.

Some information regarding sediment transport does exist for the area immediately offshore of the mouth of San Francisco Bay (Doug Pirie, Corps of Engineers, South Pacific Division, pers. commun., 1990). About 380,000 m³ of material is dredged each year on average from the shipping channel at the entrance to San Francisco Bay and placed on the outer end of the bar, which lies immediately to the south of the shipping channel (average annual dredging volumes range from about 225,000 to 750,000 m³). The north side of the channel experiences the greatest shoaling each year following dredging, whereas the south bar does not exhibit any net accretion despite the dumping of dredged material, suggesting that sediment transport is dominantly from north to south, or downcoast. The dredged material has a D_{50} of about 0.2 mm, or is very fine grained. Some of the material appears to move onshore and accumulates in the sand dunes along the northern San Francisco peninsula.

The ultimate depositional site for the remaining material is not completely understood at present. There is no evidence of large accumulations of this material on the immediate downcoast beaches nor is there evidence of large littoral-drift rates or volumes progressing southward through the littoral cell in the Half Moon Bay area. Some of this large volume of relatively fine-grained dredged material undoubtedly is transported alongshore to the south, and may in fact support the submerged fine-grained portion of the beach as well as contribute to the exposed beach face. The volumes or importance of these materials are unknown at present, however.

SEDIMENT OUTPUT

The principal output of coarse-grained material from the littoral cell is by longshore transport. Due to channel filling and the annual dredging associated with the maintenance of the Santa Cruz Small Craft Harbor, a number of studies have been directed toward understanding the littoral-drift processes and rates at this location within the cell (Table 4).

Potential littoral-transport rates have been calculated in the vicinity of the harbor from both wave hindcast data (Anderson, 1971; Walker and others, 1978) and from wave data measured directly offshore from a slope array (Seymour and others, 1980). The calculation of the potential rate of littoral transport is a relatively common approach in

coastal-engineering investigations and involves the conversion of incident wave energy into a downcoast littoral component. This quantity depends on the longshore component of wave power, which is a function of wave energy and the angular approach of the wave to the shoreline. There are some difficulties and limitations with this approach, which include the transformation of deep-water wave spectra to the shoreline in areas of significant refraction, as well as the very close dependence on nearshore bathymetry.

It is worth comparing the potential littoral transport values determined at the harbor area using this approach (Table 4), specifically those of Seymour and others (1980) and Walker and others (1978), which vary by a factor of six. One partial explanation for this difference is that Seymour only used one year of wave data, and this was a year of only moderate wave conditions. Another more significant variable in this approach, however, is the extreme sensitivity to the amount of wave refraction. The lack of very good bathymetric control, for example, can significantly affect the calculations of potential transport. Oradiwe (1986), for example, in calculating potential littoral transport around the shoreline of Monterey Bay, noted that an angular difference of 1° between the angle of wave approach and the bottom contours at the break point produced annual drift rates varying from 152,000 m³ upcoast to 160,000 m³ downcoast. A 2° angular difference produced a difference in potential transport rate of nearly 600,000 m³ annually.

Moore (1972) and Walker and others (1978) estimated net annual longshore transport rates of 191,000 and 230,000 m³, respectively, based on accretion rates against the upcoast jetty of the Santa Cruz harbor following its construction in 1963–1965. Walker and Williams (1980) suggest that 134,000 to 288,000 m³ of sand annually bypass the harbor mouth. Seymour and others (1980) conclude that the amount of bypassing is minimal. An analysis of aerial photographs from the harbor mouth and the beach shape on opposite sides of the harbor suggests some bypassing is taking place, although its volume is unknown.

Griggs and Johnson (1976), Walker and Williams (1980) and Griggs (1987a) used dredging data from the Santa Cruz Harbor to obtain minimum values for rates of littoral transport. The more recent dredging volumes (120,000 to 145,000 m³ annually) are more representative than the earlier data due to the continuing impoundment of drift against the upcoast jetty in the first 15 years following construction. Dredge figures are minima for two reasons. First, they do not account for any sand bypassing the harbor entrance and secondly, the figures are for "pay yardage," which is the volume contractors actually bid to remove based on required channel depths. Periodic comparison of pay yardage with actual dredged yardage indicates that the latter volumes may be significantly larger, in part due to continued infilling of the channel during the weeks of dredging.

Based on this evaluation of all previous calculations of rates of littoral transport and potential littoral transport at the harbor, we feel that a reasonable value at this point in the cell is from 200,000 to 250,000 m³ annually.

The principal sink for sand within the Santa Cruz Littoral Cell at the present time is Monterey Submarine Canyon (Fig.

TABLE 4.—SUMMARY OF LONGSHORE-TRANSPORT RATES IN THE VICINITY OF THE SANTA CRUZ SMALL CRAFT HARBOR

Reference	Transport Rate (m ³ /yr)
Moore (1972)	191,000
Anderson (1971)	270,000 (max)
Walker and Dunham (1978)	230,000–380,000
Seymour and others (1980)	47,000
Walker and Williams (1980)	114,000–380,000
Griggs (1987a)	120,000–145,000 (min)

1). The canyon heads into the shoreline in the center of Monterey Bay at Moss Landing. Three branches of the canyon extend to within about 100 m of the shoreline, where they appear to be effective in removing most of the sand moving downcoast within the cell.

DISCUSSION OF SEDIMENT BUDGET

Input and output volumes for the portion of the Santa Cruz Littoral Cell within the study area are summarized in Table 5. Principal sources of littoral sand are the coastal streams, bluff erosion, and probable longshore transport from upcoast. Annual input volumes from the streams and bluffs range from about 60,000 to 114,000 m³, of which about 72 to 76 percent is from coastal streams and 18 to 20 percent is from bluff erosion. Output from the cell through longshore transport at the Santa Cruz Small Craft Harbor averages about 200,000 to 250,000 m³ annually.

Excluding longshore transport from upcoast into the study area, the computed average annual input volumes total only 24 to 57 percent of the longshore transport near the downcoast end of the cell; 86,000 to 190,000 m³ of material transported out of the cell annually are unaccounted for by our measured inputs. There are three possible explanations for this discrepancy: 1) the cell boundary initially selected is incorrect and there is significant input from sources upcoast of the cell boundary; 2) a reduction of storage either along the beaches or on the inner shelf; and 3) temporal variations in sediment delivery (e.g., stream input during major floods) that have not been adequately accounted for due to the relatively short data base.

In retrospect, the northern limit of the cell as delineated on the basis of heavy-mineralogy provinces (Yancey and Lee, 1972; Weber, 1979; Griggs, 1987a) is incorrect. Although there is a mineralogical change that takes place at Tunitas Creek, it does not appear that this is a result of a littoral-cell boundary, rather a change in the bedrock in the coastal drainage basins. Based on coastal geomorphology, the presence of beaches and known bathymetry, we now believe that the northern boundary of the Santa Cruz Littoral Cell extends at least to the mouth of San Francisco Bay, about 50 km upcoast (Fig. 1).

There are no major streams that drain this additional portion of coastline, but the entire area consists of near-vertical, high, eroding cliffs of the Purisima Formation to the south, granite at Montara Point, and young erodible Pleistocene sediments of the Merced Formation, as well as unconsolidated recent dunes in the San Francisco peninsula area. Smaller drainage basins, more subdued topography, and lower annual rainfall suggest that sediment yield from the streams north of the study area is less than those within the study area. Although some areas of this coastline are relatively stable, many sections are undergoing rapid retreat (Tinsley, 1972; Griggs and Savoy, 1985); this high-erosion rate combined with some large deep-seated coastal landslides suggests that coastal-bluff erosion plays a more important role in sediment input to the cell than the bluffs within the original study area. In addition, the gullies, which are prominent in southern San Mateo County south of Tunitas Creek, also extend northward to Half Moon Bay.

Preliminary estimates of additional littoral sediment input from coastal streams, gullies, and bluff erosion from Tunitas Creek to the mouth of San Francisco Bay amount to 20,000 to 45,000 m³/yr (Table 5). This excludes sediment entering the cell either through or across the mouth of San Francisco Bay from the north. These are both unknown quantities at present.

As discussed earlier, on the basis of information from the Corps of Engineers dredging history (Doug Pirie, pers. commun., 1990), there is considerable fine-grained material (380,000 m³ with a D_{50} of 0.2 mm) dredged from the shipping channel each year that appears to be moving into the northern end of the cell in the San Francisco peninsula area. Some of this material ends up in the dunes of the peninsula and some significant quantity may move southward alongshore under the prevailing longshore currents. This relatively fine-grained material may add significant volume to either the subaerial or offshore portion of the beach prism of the San Mateo and Santa Cruz County coastlines. There are locations along this coastline where large inputs of littoral-size sand should be apparent, however, and are not, which still leaves considerable uncertainty regarding the ultimate depositional site of this large volume of material. Detailed mineralogical and grain-size studies would be required in order to resolve this component of the budget.

Changes in storage may account for some of the remaining deficit. Excess sand in littoral transport may be stored temporarily along the inner shelf and also subaerially on the beach. A thinning of the beach and/or nearshore bottom-sediment accumulation can generate significant quantities of sediment. Quantifying these changes in storage is difficult without precise long-term surveys. A comparison of pocket beach elevations northwest of Santa Cruz indicates that the resolution of the time-sequential aerial photographs is inadequate to address fully the subtle changes in beach volume. Long-term changes in storage may also be masked by the seasonal on/offshore sediment exchange between the beach and nearshore bottom. This potential discrepancy, or deficit, can potentially be significant due to the large volume of material that can be generated by a relatively small change in either beach height or nearshore-sediment thickness over a large area. For example, the re-

TABLE 5.—SUMMARY OF THE AVERAGE ANNUAL SEDIMENT INPUT AND OUTPUT OVER THE PAST 50 YEARS TO THE SANTA CRUZ LITTORAL CELL BETWEEN THE SAN LORENZO RIVER AND TUNITAS CREEK

	Sediment Input (m ³ /yr)
Coastal streams	43,000–87,000
Gully erosion	2,900–5,800
Bluff erosion	12,000–20,000
Dune deflation	1,700
On/offshore	0
Longshore transport from upcoast	
Streams, bluffs, gullies	20,000–45,000
San Francisco bar and bay	?
TOTAL	79,600–159,500
	Sediment Output (m ³ /yr)
Longshore transport	200,000–250,000
TOTAL	200,000–250,000

removal of 1 cm from a stretch of shoreline 100 m wide and 130 km long (the total distance from the entrance of San Francisco Bay to the Santa Cruz Harbor) could generate 130,000 m³ of sediment.

In addition, thinning of the beaches and a reduction in the amount of littoral sand in storage, in part, may have taken place in response to major changes in the Ano Nuevo Point area over the past 100 to 200 years. Weber (1979) suggests that prior to the 18th century, Ano Nuevo Island was attached to the mainland as a peninsula. This peninsula provided a large upcoast trap for sediment and is believed to have accumulated a 6- to 9-million-m³ reservoir of beach and dune sand. The opening of the channel between the island and the present point some time in the mid-1700s allowed the trapped sand to move downcoast, creating temporarily wider beaches south of Ano Nuevo. There is some evidence in beach-width and shoreline-erosion trends (Weber, 1979) to suggest that this hypothesized pulse of sand now may be nearly gone, with subsequent thinning of the beaches. Thus, potential contribution from this large volume of sand in storage may have amounted to as much as 30,000 to 45,000 m³/yr for this 200-year period.

CONCLUSIONS

1) Based on an analysis of coastal and nearshore geomorphology as well as the sediment budget, it is now apparent that the Santa Cruz Cell extends upcoast at least as far as the entrance to San Francisco Bay. Mineralogical differences in beach sand are not adequate in themselves to define the cell boundary. In the Santa Cruz Cell, sediment enters the littoral zone principally by coastal streams and seacliff erosion. Material is reworked in the surf zone; finer grained sediment is transported offshore and the coarser grained material (greater than the littoral cutoff diameter) remains in littoral transport. Sand is temporarily stored on beaches and along the inner shelf before being ultimately lost to Monterey Submarine Canyon.

2) A careful look at the grain size of both beach and offshore sand in the littoral cell reinforces the significance of a littoral cutoff diameter, a grain size below which the sediment cannot remain on the beach, but moves offshore. The littoral cutoff diameter within the Santa Cruz cell is about 0.18 mm.

3) Sediment input to the cell is highly episodic in response to large and infrequent erosional events. Considerable caution must be exercised in calculating littoral sand inputs from individual sources due to both temporal variations (e.g., the extremely episodic nature of stream sediment delivery) and spatial variations (e.g., the alongshore variations in cliff height, stratigraphy, grain-size distribution, and erosion rates).

4) Current littoral drift rates at the downcoast end of the study area are relatively well documented and range from 200,000 to 250,000 m³/yr.

5) Calculated input volumes from all sources that supply the Santa Cruz Littoral Cell range from 80,000 to 160,000 m³/yr. Additional material may enter the cell from the area off the entrance to San Francisco Bay.

6) Coastal streams supply about 75 percent of the total

littoral sand to the cell, whereas bluff erosion contributes about 20 percent.

7) Those processes that deliver sand to a cell (bluff erosion and high-stream flow, for example) may operate at different frequencies than those that move sand through a cell (longshore transport).

8) Changes in sand storage, either on the beach or along the inner shelf, can potentially produce significant volumes of sand due to the large areas involved. The lack of precision in the methods of investigation makes these quantities elusive to determine, however. In the Santa Cruz Cell it appears that a significant portion of the current littoral drift may have been due to a reduction of sediment storage. Historically, this is apparent at Ano Nuevo Point, although a general thinning of all beaches may also be occurring.

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Coastal Regional Sediment Management Planning In Southern Monterey Bay, California

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Abstract

The coastal dunes and beaches of southern Monterey Bay (the Bay) are eroding at approximately four feet per year, placing oceanfront property, infrastructure, and natural habitat at risk of loss. Erosion is exacerbated by mining operations that extract sand from the beach near the City of Marina. Recognising that much of California's coastal erosion, sediment supply and demand issues can be attributed to human modification of natural processes at regional scales, Regional Sediment Management (RSM) is being pursued by the responsible agencies. This paper presents the findings of the Coastal RSM Plan developed to address erosion in the Bay. The Plan first evaluates the sedimentary processes, erosion rates and sensitive species and habitat along the coast. Those data sets are then combined with economic, ecological, and societal considerations, to identify critical areas of erosion and to propose RSM-based solutions. The Plan recommends three main RSM strategies for the Bay. (1) reduce or eliminate mining of sand from the beach at Marina. Sand mining creates a sediment sink which increases erosion potential and, if stopped, erosion rates would slow. (2) allow dune erosion to continue without human intervention along the undeveloped sections of the Bay. This erosion would continue to supply large volumes of sand to the beaches, providing benefits for sensitive species and habitats, recreation and tourism. (3) investigate beach nourishment to ameliorate erosion along the southern developed part of the Bay, where the majority of high risk facilities are located.

Keywords: *Sedimentary processes, coastal erosion, coastal habitats, regional sediment management, beach nourishment, sand mining*

1 Introduction

For recreational, economic, and ecological reasons, the sandy beaches and coastal dunes of southern Monterey Bay are among the coastal region's most prized natural resources. Due to a persistent rise in sea level, reductions in sand availability, and public and private development practices, the southern Monterey Bay shoreline south of the Salinas River is eroding, on average, at the fastest rate in California (Hapke *et al.*, 2006). This erosion compromises the

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ability of the beaches and dunes to buffer oceanfront development and infrastructure from storms and flooding, provide vital natural habitat, and successfully accommodate recreation and tourism.

Along the California coast, state, federal, and local agencies have adopted a new paradigm to address coastal erosion problems caused by human modification. Recognizing that much of California's coastal sediment supply and demand issues can be attributed to changes affecting natural processes at regional scales, the Coastal Sediment Management Workgroup (CSMW), a collaborative workgroup of state, federal and local agencies and other stakeholders involved in sediment management, is pursuing Regional Sediment Management (RSM) throughout coastal California. RSM involves the beneficial reuse of non-contaminated sediment whenever feasible and appropriate, to restore or augment natural processes, and utilizes the littoral cell as the basic planning unit (CSMW, 2006). This paper describes findings from the Coastal RSM Plan developed by CSMW and its partners to address erosion within the southern Monterey Bay littoral cell, between the Salinas River mouth to the north and Point Piños at the southern boundary (Figure 1).

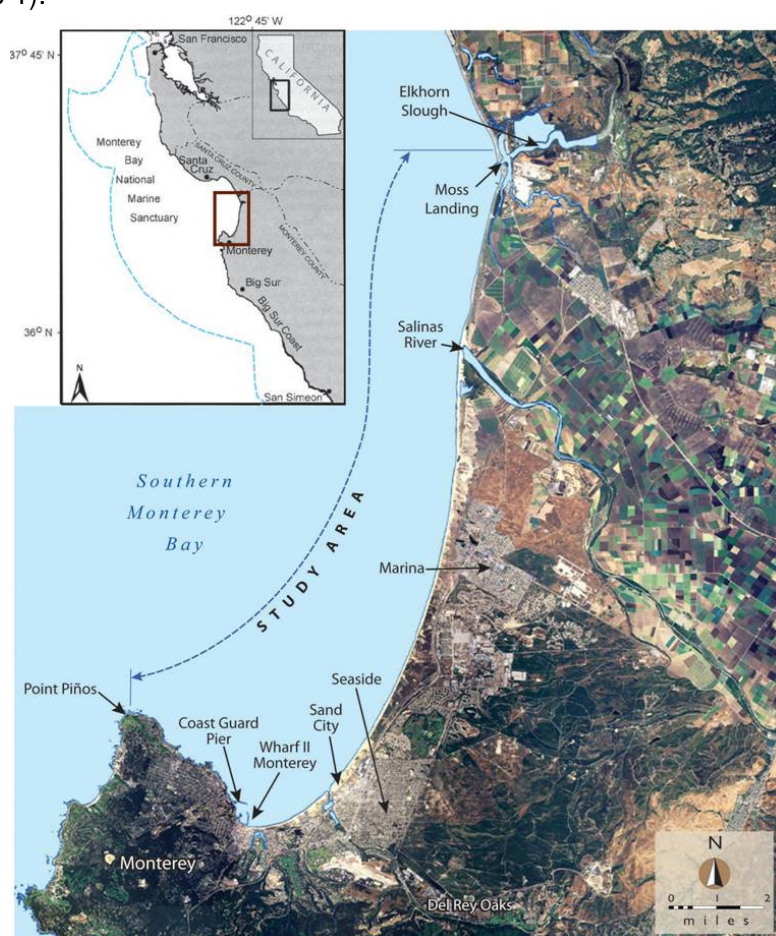


Fig. 1. Location map of southern Monterey Bay showing main developed areas

2 Environmental Setting

The shoreline between the Salinas River mouth and the Wharf II breakwater of Monterey Harbor is composed of sandy beaches backed by relict sand dunes up to several miles wide and 150 feet high (Griggs and Patsch, 2005). Areas landward of the relict dunes are dominated by reclaimed lowlands, and seaward the beaches are bounded by a continental shelf which descends into Monterey Submarine Canyon. Apart from short lengths of riprap and seawall at Sand City and Monterey, the majority (over 96% by length) of the southern Monterey Bay shoreline is unarmoured (Stamski, 2005). The shoreline north of the Salinas River to Moss Landing is occupied by low relief active dunes backing sandy beaches, which are stable or accreting (Hapke *et al.*, 2006).

2.1 Wave Climate and Beach Particle Size

The nearshore wave climate of southern Monterey Bay is dominated by waves from the northwest (Storlazzi and Wingfield, 2005). Refraction occurs as the waves pass over Monterey Submarine Canyon focusing wave energy at Marina and Fort Ord and defocusing energy at Moss Landing. In addition, the shoreline between Monterey and Sand City is sheltered by Point Piños headland from waves from the south and west, resulting in reduced wave energy. The net effect is a large alongshore energy gradient with relatively small wave heights at Monterey increasing to relatively large wave heights at Fort Ord and Marina (Thornton *et al.*, 2007).

The particle size of the beaches between Marina and Wharf II is positively correlated with wave height (Thornton *et al.*, 2007). The smallest mean particle size of approximately 0.2 mm (fine sand) occurs near Monterey Harbor. The mean particle size then increases northwards to a maximum of approximately 0.7 mm (coarse sand) at Fort Ord and Marina, followed by a small decrease to 0.6 mm (coarse sand) further north towards the Salinas River mouth.

2.2 Sand Transport and the Littoral Cell

The southern Monterey Bay littoral cell can be divided into three main sub-cells (Figure 2) (Patsch and Griggs, 2007). The boundaries of the sub-cells are defined based on a change in direction of the mean alongshore transport. Wave refraction in Monterey Bay results in a net alongshore sediment divide at the Salinas River, with sand transported north towards Monterey Submarine Canyon and south towards Sand City. A third sub-cell is defined between Point Piños and Monterey Harbor where the alongshore sand transport is to the southeast (Patsch and Griggs, 2007).

It may be possible to further subdivide the central sub-cell at Sand City. Orzech *et al.* (2010) showed that net sand transport between Sand City and Wharf II (defined as the southern bight) is weakly to the north, owing to a more easterly orientation of the shoreline, resulting in a poorly-defined convergence with the net southerly transport from Fort Ord (Figure 2). At the convergence, which is likely to be seasonally variable in location, sand may migrate offshore. Reid *et al.* (2006) mapped a lobe of medium-grained sand extending offshore in the vicinity of the convergence zone.

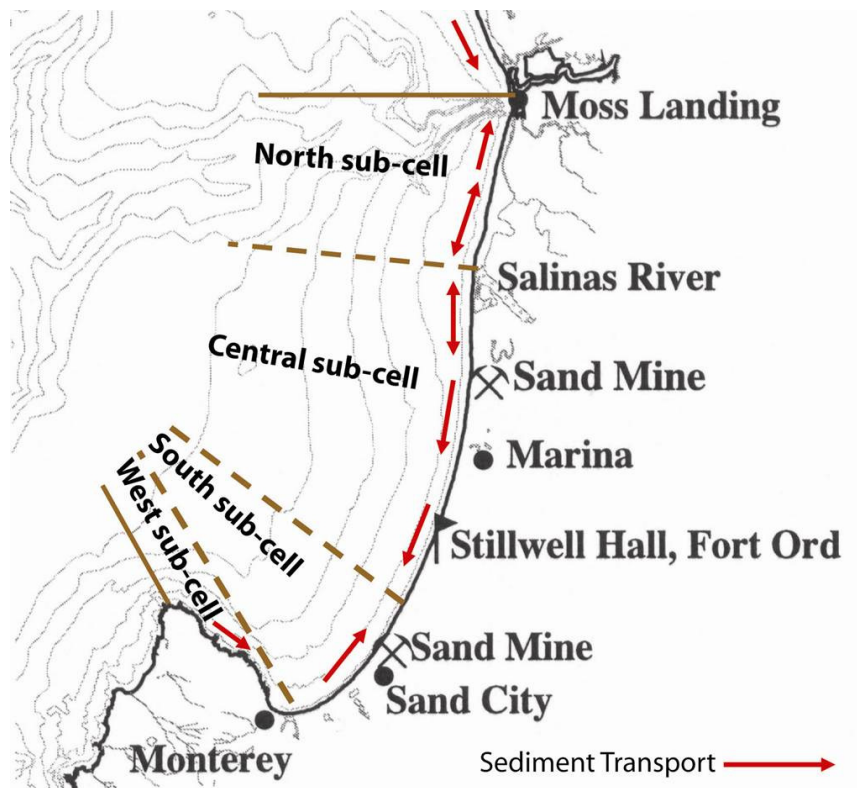


Fig. 2. Southern Monterey Bay littoral sub cells and net sediment transport

2.3 Sediment Supply to the Littoral Cell

The largest input of sand to the southern Monterey Bay littoral cell is from erosion of the relict coastal dunes south of the Salinas River. Dune erosion rates between 1985 and 2005 of 0.4 and 4.7 ft/year were measured by Thornton *et al.* (2006), equating to an average sand yield of approximately 200,000 yd³/year to the littoral cell. Sand supplied to Monterey Bay from the Salinas River is approximately 65,000 yd³/year (McGrath, 1987). CSMW and AMBAG (2008) estimated that only around 10,000 yd³/year (average annual net) of this sand is transported south into the littoral cell, leaving approximately 55,000 yd³/year of sand transported north towards Monterey Submarine Canyon.

2.4 Mining of Sand from the Beach

Southern Monterey Bay has been the most intensively mined shoreline in the United States. Sand mining near the mouth of the Salinas River started in 1906, and expanded to six commercial sites; three at Marina and three at Sand City (Figure 3). Five of these operations used drag lines to mine coarse sand from the surf/swash zone. The sixth mine is located at Marina approximately two miles south of the Salinas River mouth, where the sand is hydraulically extracted just landward of the beach berm by a dredge floating on a self-made pond. Although all drag line sand mines were closed by 1990, the hydraulic Marina operation,

which began in 1965, is ongoing today. The beach-sand mining operation at Marina efficiently takes advantage of the cross-shore sorting of sediment, where coarse sand is washed over the berm to fill the pond during times of high winter waves and high tide. The pond is repeatedly filled with sand over time and this sand is continuously dredged and removed from the system. CSMW and AMBAG (2008) estimated that approximately 200,000 yd³/year of sand has been mined from the beach at Marina over the most recent decades.

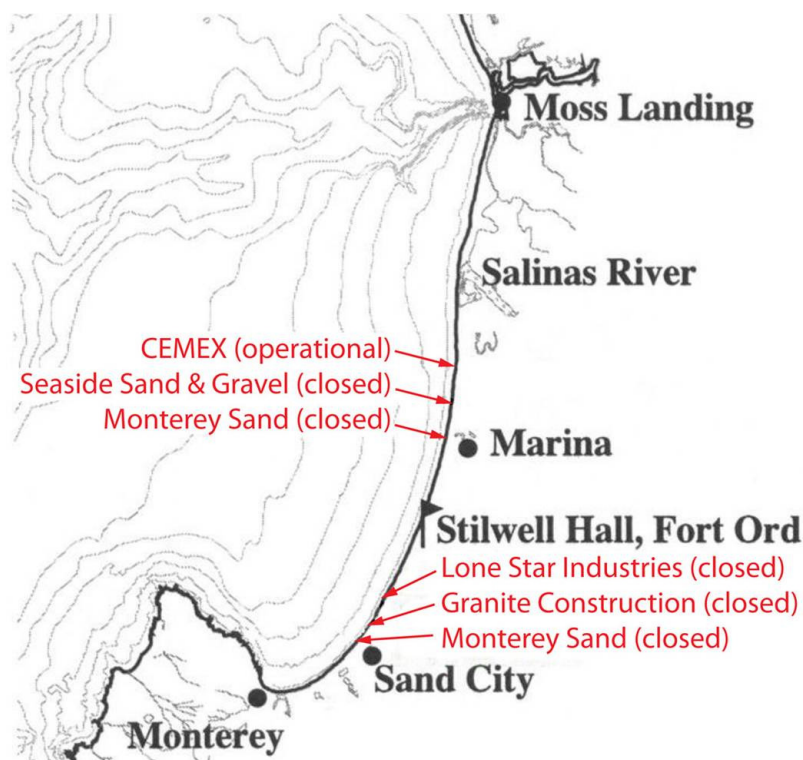


Fig. 3. Location of former and operating beach-sand mines in southern Monterey Bay

2.5 Shoreline Habitats

One of the most important functions of the southern Monterey Bay beach, shoreface, and dune system is its role as habitat for a unique flora and fauna. The dunes represent one of the most important coastal dune ecosystems in California. Numerous native dune plants are either already listed or are on the candidate list for the federal register of endangered and threatened species. The beaches of southern Monterey Bay are home to numerous invertebrate species, which reach high abundance and biomass providing crucial food/prey sources for shorebirds and seabirds. Sensitive nearshore subtidal habitats include rocky reefs, kelp forests, and eelgrass beds (Figure 4), which provide important habitat for fish, invertebrates, and marine mammals. A rocky reef of shale is situated offshore of Del Monte Beach, approximately 600 feet from the beach in up to 230 feet of water. A kelp forest grows on the nearshore portion of the

reef. To the west of the Del Monte kelp forest is an eelgrass meadow, which once covered 0.1 square miles of the sea bed in water depths of 20-30 feet.

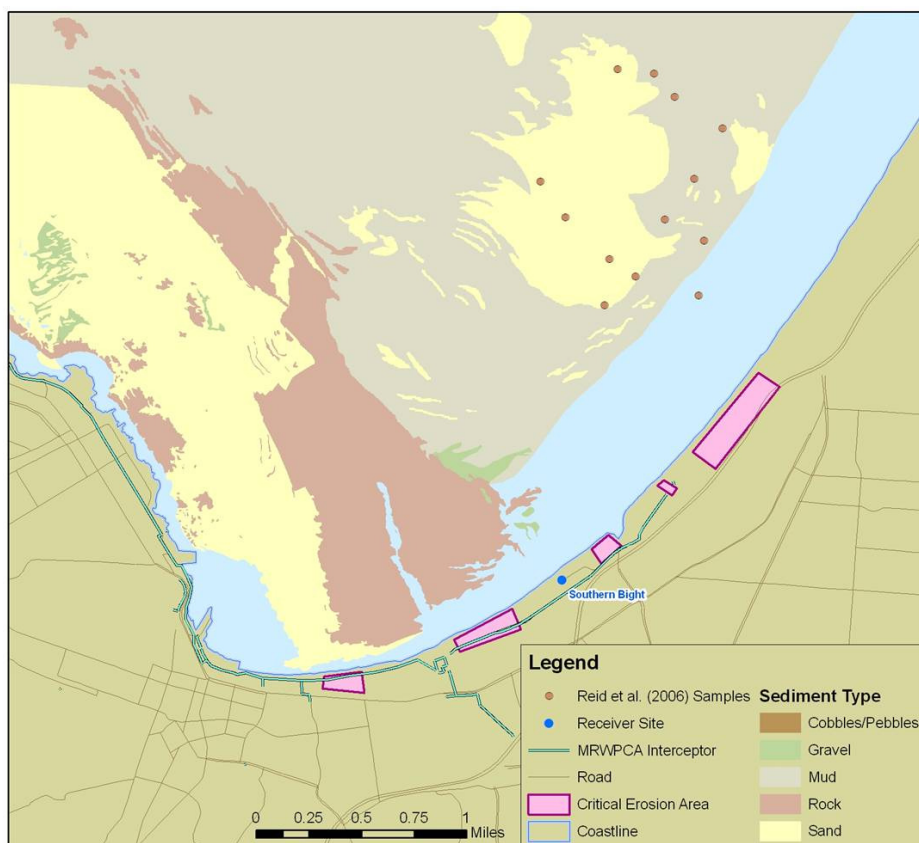


Fig. 4. Locations of sensitive subtidal habitat, critical areas of erosion, and a potential offshore source of sand for beach nourishment

3 Critical Areas of Erosion

In order to delineate critical areas of erosion within the southern Monterey Bay littoral cell, two criteria were adopted in the Coastal RSM Plan to prioritize erosion responses over a planning horizon of 50 years; risk of erosion and consequences of erosion. The risk of erosion over a 50-year period is based on the risk analysis developed by PWA and Griggs (2004). Three risk categories were defined in the Coastal RSM Plan (CSMW and AMBAG, 2008):

1. Low risk areas are those with a low probability of being impacted by erosion over the next 50 years.

2. Moderate risk areas are not likely to be affected by chronic erosion over the next 50 years, but are potentially susceptible to short-term storm event erosion within the planning horizon.
3. High risk areas are those that will be located seaward of the shoreline position anticipated in 50 years or presently vulnerable to short-term event-based erosion.

PWA and Griggs (2004) defined the level of risk by assuming that long-term historic erosion rates would continue over the next 50 years. For the definition of critical areas of erosion in the Coastal RSM Plan, the historic erosion rates of Thornton *et al.* (2006) were used with an increment of approximately 20% added to the erosion rate for potential increases due to future sea-level rise (CSMW and AMBAG, 2008).

All the areas identified at high or moderate risk of erosion were assessed as to the consequences of their loss. Three consequence categories were defined; high consequence, moderate consequence, and low consequence, based on an evaluation of their economic (potential loss of infrastructure), ecological (potential loss of habitat), and human health and safety (potential loss of life) value. The majority of sites at high to moderate risk of erosion with high consequences of loss are associated with infrastructure located close to the shoreline (Figure 4).

3.1 Monterey Interceptor and Pump Stations

The Monterey Interceptor pipeline which carries raw (untreated) wastewater between Seaside and Wharf II is buried beneath the beach or in the dunes, passing through pump stations at Monterey and Seaside. The pipeline and its pump stations are vital facilities that need to remain fully operational indefinitely, and the consequences of their erosion would be significant economic, environmental, and human health impacts. Between Wharf II and the Monterey Pump Station the pipeline lies beneath the beach, and over the next 50 years is under threat from exposure due to beach lowering as the shoreline profile migrates landward. The Monterey Interceptor between Monterey Beach Resort and Seaside Pump Station is buried in the dunes, approximately 100 to 175 feet from the dune bluff. Based on approximate future erosion rates of between 1.5 and 3.0 ft/year, the shoreline would be expected to erode 75-150 feet over the next 50 years, and parts of the pipeline may be compromised over the next 40 years. Seaside Pump Station is located approximately 100 feet from the edge of the low-lying dunes that front the facility. The future rate of erosion is estimated at approximately 3.0 ft/year, and the facility could be compromised by erosion in about 30 years.

3.2 Marina

The Sanctuary Beach Resort is located on the dune top at Marina (Figure 1) and under threat over the next 50 years through continued erosion of the dune bluff: The seaward-facing wall and buildings of the complex are set back approximately 120 feet from the top of the bluff. The bluff is estimated to erode at approximately 5.5 ft/year over the next 50 years, meaning that the resort would be compromised in approximately 20 years time. The loss of this facility would have high economic consequences to the region as it is a popular tourist destination.

3.3 Southern Bight

In addition to the Monterey Interceptor and Seaside Pump Station, the southern bight contains several other critical areas of erosion. These include oceanfront properties, which are currently protected from erosion by coastal armoring. Ocean Harbor House condominiums are located on the dunes behind Del Monte Beach in Monterey. Since the condominiums were completed in 1969, a history of erosion problems resulted in a series of emergency revetments that have recently been replaced by a massive seawall. The seawall fixes the shoreline while the dunes to either side continue to erode. The condominiums are privately owned and the consequences of their loss would be economically damaging and hazardous to safety.

The Monterey Beach Resort hotel is located on north Del Monte Beach, surrounded by a seawall. Since it was built in 1968, shoreline erosion has occurred up and down coast, and the protected hotel has become a headland. The presence of the seawall has led to beach erosion to the extent that during high tides there is now no public access in front of the hotel. The future erosion rate at north Del Monte Beach is estimated to be approximately 1.5 ft/year. The hotel continues to be a popular tourist destination and loss of this facility would have high economic consequences.

4 Regional Sediment Management Approaches

Three regional sediment management approaches are recommended in the Coastal RSM Plan as potential solutions to the coastal erosion problems in southern Monterey Bay (CSMW and AMBAG (2008) (Figure 5). These are 1) reduce or eliminate large-scale removal of sand from the beach through mining at Marina; 2) allow the natural processes of dune erosion to continue without intervention north of Sand City; and 3) beach nourishment in the southern bight to slow erosion rates.

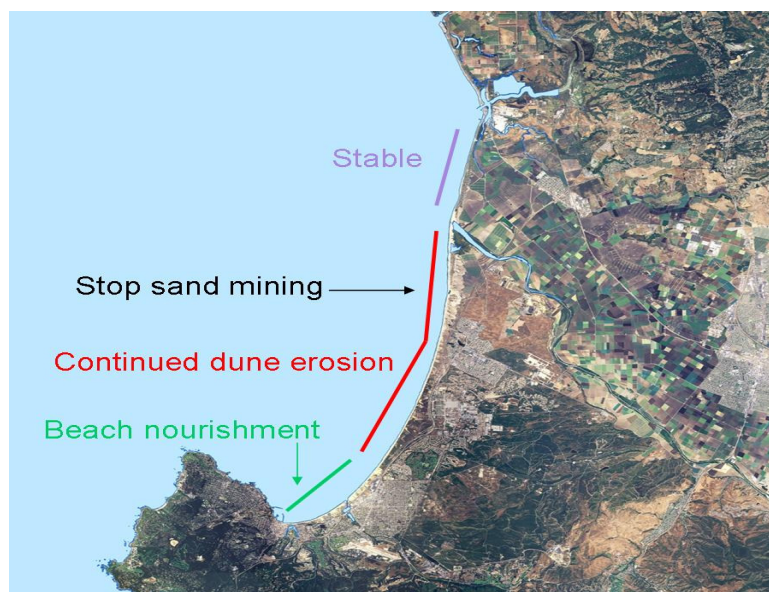


Fig. 5. Potential regional sediment management approaches in southern Monterey Bay

4.1 Reduce or Eliminate Removal of Sand from the Beach at Marina

The main human factor that affects the sediment budget of the southern Monterey Bay littoral cell is sand mining from the beach at Marina. Historically, the mining of sand from the beach has disrupted alongshore sand transport, and ultimately resulted in enhanced beach erosion. Cessation of mining sand from the beach at Marina would allow approximately 200,000 yd³/year of sand to remain in the littoral system. Gross alongshore sand transport is sufficiently high in southern Monterey Bay to distribute the sediment demand caused by mining throughout the littoral cell, and especially to the south. Cessation of mining would reduce erosion rates by about half, and would provide more sand to buffer future erosion, increase beach widths, reduce threat of damages to property and infrastructure, and enhance beach habitat.

Erosion is particularly acute at the Sanctuary Beach Resort critical area of erosion (Figure 1). This resort is located approximately one mile south of the sand mine and the erosion rates of the dunes on which it is located are directly affected by the extraction of sand from the beach. Replenishment of the beach in front of the Sanctuary Beach Resort with sand that would otherwise be removed from the system would provide a larger and more effective buffer to waves, reducing the dune erosion rates. The Coastal RSM Plan recommends cessation of mining of sand from the beach because of its impact on regional rates of shoreline erosion. Details of potential strategies to implement this recommendation, including both regulatory and non-regulatory possibilities, are described in the Plan (CSMW and AMBAG, 2008).

4.2 Allow Dune Erosion to Continue

As the coastal dunes are the primary source of sand to the beaches, the 'no action' approach would allow the natural processes of dune erosion to continue without human intervention. In the portion of the littoral cell from the City of Sand City to the Salinas River (approximately 13 miles), erosion of the dunes is providing large quantities of sand to the littoral system, helping to maintain the beaches and affording benefits for sensitive species and habitats. The dunes are sufficiently wide and high so there is no threat of flooding to the low-lying areas behind them. This region is not a good candidate for beach nourishment owing to the high wave energy, highly erosive nature of the beach with large particle size, and a relatively high rate of sediment transport. The Coastal RSM Plan recommendation is to allow the dunes between the Salinas River and the northern boundary of the City of Sand City to continue to erode (CSMW and AMBAG, 2008).

4.3 Beach Nourishment

At locations where it is not desirable to allow natural erosion processes to continue, due to the beach resource being lost and/or important facilities are at high risk and consequences of erosion, the Coastal RSM Plan recommends beach nourishment to modify the shoreline. The Southern Monterey Bay Coastal Erosion Workgroup, a taskforce of local, state and federal agencies, NGOs and other interested stakeholders, proposed analysis of the feasibility of beach nourishment to ameliorate erosion along the southern bight, and the Coastal RSM Plan generally supports that proposition (CSMW and AMBAG, 2008), assuming that environmental

concerns can be addressed. Numerous critical areas of erosion are located along the southern bight (Figure 3) and healthy beaches are especially important for recreation and tourism.

Beach nourishment appears to be geomorphologically feasible in the southern bight for a number of reasons. Relatively lower wave energy and sand transport, and occupation of a potential sub-cell (the southern bight could be self-contained in terms of net sand transport, Figure 1) means that any placed sand would remain in this coastal segment for a longer period of time. Beach nourishment would also reduce the need for 'hard' shore protection, and would provide positive ecological benefits associated with wider beaches over the longer term. Sand would need to be placed at a location away from the rocky reef, kelp forest and eelgrass meadow to avoid disturbance due to suspension and turbidity, and be allowed to spread along the shoreline.

The Coastal RSM Plan targets two substantive sources of sand for beach nourishment where the sediment is a similar particle size (or larger) to the beaches of the southern bight (CSMW and AMBAG, 2008); sand offshore from Sand City, and Monterey Submarine Canyon. A large body of medium-grained sand is located offshore from Sand City (Reid *et al.*, 2006). The mean particle size of this offshore sand (0.25-0.5 mm) is compatible with the beach sands of the southern bight and it is a potential large source of sand for beach nourishment. In addition, the head of Monterey Submarine Canyon, marking the northern boundary of the southern Monterey Bay littoral cell (Figure 1), is effective at capturing littoral sediments that are diverted offshore by Moss Landing harbor jetties (Smith *et al.*, 2007). This sand could be recovered before being lost down the canyon and used for nourishment. However, the canyon is some distance away and therefore may not be as economically attractive as the sand deposit offshore of Sand City.

Conclusions

Over the next 50 years, the coastal dunes of southern Monterey Bay are predicted to erode at rates between approximately 1.0 and 6.0 ft/year. Over this planning time frame, numerous oceanfront facilities are at high risk due to this erosion, and will require implementation of mitigation measures to prevent loss. The beaches and dunes of southern Monterey Bay also provide important habitat for native animals and numerous shorebirds. Sensitive subtidal habitats, including rocky reef, kelp forest, and eelgrass meadow are located adjacent to the Monterey shoreline.

The dominant supply of sand to the littoral cell is produced from erosion of the coastal dunes south of the Salinas River. Current dune erosion rates range from approximately 0.5 to 5.0 ft/year, equating to a sand volume of approximately 200,000 yd³/year supplied to the littoral system. The most significant sink for sand is the ongoing beach-sand mining operation at Marina, which currently permanently extracts 200,000 yd³/year from the beach, similar to the annual sand volume yielded by the dunes.

The Coastal RSM Plan for southern Monterey Bay (CSMW and AMBAG, 2008) examined regional sediment management options that restore coastal habitat by removing or lessening disturbances to natural sedimentary processes that exacerbate coastal erosion. The Coastal

RSM Plan recommends implementing three regional sediment management strategies for the southern Monterey Bay shoreline:

1. Reduce or eliminate mining of sand from the beach at Marina. If this sand is available and subsequently transported alongshore, it could provide a significant additional buffer to dune erosion by waves. The effect would be more immediate close-by, but would eventually benefit the shoreline further afield.
2. Allow dune erosion to continue without human intervention from the City of Sand City to the Salinas River. This erosion will continue to supply large quantities of sand to the beaches, helping to maintain their healthy condition and provide benefits for sensitive species and habitats, recreation and tourism.
3. Investigate beach nourishment to ameliorate erosion in the southern bight, which includes the cities of Monterey, Seaside, and Sand City. The majority of high risk facilities are located within this stretch of shoreline, and healthy beaches therein are particularly important for recreation and tourism.

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EVALUATION OF EROSION MITIGATION ALTERNATIVES

for Southern Monterey Bay

Prepared for
Monterey Bay Sanctuary Foundation
and
The Southern Monterey Bay Coastal
Erosion Working Group

May 30, 2012



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**EVALUATION OF EROSION MITIGATION ALTERNATIVES
for
SOUTHERN MONTEREY BAY**

Prepared for

Monterey Bay Sanctuary Foundation
and the
Southern Monterey Bay Coastal Erosion Working Group

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FINAL
May 30, 2012

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ACRONYMS

AMBAG	Association of Monterey Bay Area Governments
B/C	Benefit Cost Ratio
BEACON	Beach Erosion Authority for Clean Oceans and Nourishment
BT	Benefits Transfer
CCC	California Coastal Commission
CDP	Coastal Development Permit
CRSMP	Coastal Regional Sediment Management Plan
CSBAT	Coastal Sediment Benefit Analysis Tool
CSMW	Coastal Sediment Management Working Group
DEFRA	Department of Environment, Food and Rural Affairs
ENR	Engineering News Record
FS	Factor of Safety
LCP	Local Coastal Program
MBNMS	Monterey Bay National Marine Sanctuary
MBSF	Monterey Bay Sanctuary Foundation
MCWD	Marina Coast Water District
MHW	Mean High Water
MLLW	Mean Lower Low Water
MRWPCA	Monterey Regional Water Pollution Control Agency
NAVD	North American Vertical Datum of 1988
NIBS	National Institute of Building Sciences
NPS	Naval Postgraduate School
ReCAP	Regional Cumulative Assessment Project
ROI	Return on Investment
RUM	Random Utility Model
SCOUP	Sand Compatibility and Opportunistic Use Program
SLR	Sea Level Rise
SMB	Southern Monterey Bay
SMBCEW	Southern Monterey Bay Coastal Erosion Workgroup
TDC	Transfer of Development Credits
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
WTP	Willingness to Pay

1. INTRODUCTION

1.1 PURPOSE AND OBJECTIVES

The goal of this *Evaluation of Erosion Mitigation Alternatives for Southern Monterey Bay* (Alternatives Study) is to provide an assessment of various erosion mitigation measures to support development of a regional strategy to address coastal hazards in southern Monterey Bay.

The purpose of the project is to provide a technical evaluation of various erosion mitigation measures, conduct a cost benefit analysis of some of the more promising measures and to make recommendations on Subregional approaches for effectively addressing coastal erosion in Southern Monterey Bay (SMB). Each of these measures was identified by the Southern Monterey Bay Coastal Erosion Workgroup (SMBCEW; See 1.2.1). In this study, each of the erosion mitigation measures were evaluated using a variety of criteria and compared with more traditional types of shore protection via a cost benefit analysis. A series of project alternatives were then developed. Each *Alternative* was comprised of one or more *mitigation measures* for each critical erosion Subregion that will avoid erosion hazards, protect upland development, and maintain beach health. This analysis therefore supports development of one or more shore management strategies for southern Monterey Bay, potentially as part of a Regional Shoreline Management Plan. The terminology is summarized in Section 1.1.3 Definitions.

While focused on southern Monterey Bay, this report is expected to clarify the benefits, costs, and effectiveness of a range of erosion mitigation management measures for California's shores over multiple time horizons. Specifically, this report assesses the effectiveness of each measure at protecting upland property and beach widths, and compares the costs and benefits of each measure with coastal armoring, the status quo strategy for mitigating erosion impacts. This report is also expected to begin to inform adaptation to increased coastal hazards and vulnerability resulting from accelerated sea level rise.

1.1.1 Objectives

The objectives of this Alternatives Study are to make recommendations on shore erosion mitigation measures to be pursued in the SMB that will:

- maintain ecological and recreational functions
- mitigate impacts to the physical, ecological and recreational functions
- be compatible across multiple jurisdictions and Subregions
- adaptable to future climate changes
- support the overall goal of producing a Shoreline Management Plan for SMB

1.1.2 Evaluation of Erosion Mitigation Measures

Through the work of SMBCEW, an initial laundry list of erosion mitigation measures was brainstormed in 2006 (Appendix 8.1). For a variety of feasibility reasons, ranging from cost, to ineffectiveness to inappropriateness of the technique in the geomorphic setting, this initial list of 55 was reduced to a list of 22 measures.

These 22 measures form the focus for this report:

1. Managed Retreat (Relocation / Removal)
2. Transfer of development credit
3. Fee Simple Acquisition
4. Rolling easements
5. Conservation Easements
6. Present use tax incentive
7. Structural Adaptation
8. Habitat Adaptation
9. Setbacks for Bluff top Development
10. Setbacks + Elevation for Beach Level Development
11. Cessation of Sand Mining from the Beach
12. SCoup/ Opportunistic Sand
13. Beach Dewatering – Active
14. Beach Dewatering - Passive – PEMs
15. Beach Dewatering – Active – Desalinization wells
16. Nourishment (evaluated in CRSMP)
17. Seawalls
18. Revetments
19. Groins
20. Emergent Breakwaters
21. Artificial Reefs/ Submergent Breakwaters/Low crested structures
22. Perched Beaches

1.1.3 Definitions

Measures are individual mitigation measures; a combination of them will form Subregional **alternatives**, a combination of alternatives across the SMB region form the coastal hazard mitigation / adaptation **strategy**, which will feed into the development of a Shoreline Management **Plan for SMB**. Erosion mitigation measures are also called “tools” for convenience in this report. The terminologies for these and for other key parameters used in this report are defined as follows:

- Measure: A method of mitigating erosion damages to the man-made and/or natural environment;
- Alternative: One or more measures selected for a Subregion;
- Strategy: A regional plan comprised of alternatives selected for each Subregion;
- Region: Also known as the littoral cell, from the Monterey peninsula to Moss Landing
- Subregion: A section of shore used in this and related reports based on physical conditions; and,
- Reaches: A length of shoreline with similar development characteristics and erosion rates used in the Cost Benefit Analysis
- Critical Erosion Areas: Locations identified in the Coastal Regional Sediment Management Plan where erosion is expected to have adverse erosion effects within the planning time frame; and,

- Planning Time Frame and Horizons: The overall time frame is 100 years , divided into the following intervals, or “Horizons”:
 - o 0-5 years
 - o 6-25 years
 - o 26-50 years
 - o 51-100 years

1.2 BACKGROUND

The need for this alternatives study was recognized and pursued by the SMBCEW and supported by the Monterey Bay National Marine Sanctuary (MBNMS). This technical evaluation of mitigation measures and alternatives for addressing coastal erosion in the Southern Monterey Bay region is the second of two individual, yet complementary, components of a larger integrated approach for sediment management and addressing coastal erosion in the SMB region. The other component is the *Coastal Regional Sediment Management Plan for the Southern Monterey Bay* (CRSMP), which was completed in 2008 (PWA et al., 2008). Support for these studies was provided by the California Coastal Sediment Management Workgroup (CSMW), and by the MBNMS. Both components have been carried out under the direction of MBNMS and the Association of Monterey Bay Area Governments (AMBAG), a California joint powers agency representing the counties of Monterey, San Benito, and Santa Cruz, and the cities within, in close collaboration with the SMBCEW, local municipalities, and other local stakeholders.

To ensure consistency throughout this SMB collaborative regional shoreline management process, information and scientific findings from the CRMSP were utilized for this analysis of erosion mitigation alternatives. The CRSMP provided the scientific basis for information on erosion rates, coastal processes, and geomorphology. In particular, historic erosion rates were used, and the rates were not increased to account for accelerated sea level rise.

Results of armoring or attempting to hold the shore in place through engineering structures create a host of problems, many of which are incompatible with maintaining a natural beach system that supports the local tourism economy and coastal ecosystem. Generally, on a natural shore, as the shore erodes, beach width is maintained. However, when structures are built on an eroding shore, passive erosion occurs in which the beach in front of the structure becomes drowned over time as the adjacent shore continues to erode. This results in the structure projecting like a peninsula out into the ocean, which blocks lateral (alongshore) access.

The southern Monterey Bay shore is on average the most erosive sandy shore in California (Hapke et al., 2006). Despite the high erosion rates, beach widths have not narrowed over time along most of the littoral cell (Reid, 2004). Although only a very small proportion of the shore is armored at this time, there are several examples of passive erosion occurring: the rip-rap seawall fronting Stillwell Hall in Fort Ord (since removed) and the rip-rap at the end of Tioga Avenue in Sand City. In addition, the shore access is presently blocked at high tide at the Monterey Beach Resort and the Ocean Harbor House condominiums seawalls (both are located in Monterey) during the winter when the beach is seasonally reduced. This situation is expected to become worse due to continued erosion, and increased erosion as sea levels rise,

and the seawalls will project into the ocean, blocking access along the beach. This anticipated loss of the beach in southern Monterey Bay is a key driver of this study to find better alternatives than traditional engineering structures.

Threats to coastal development have increased the pressure to protect coastal upland with various types of coastal armoring such as seawalls and revetments to reduce erosion. The MBNMS has been addressing the issues of coastal erosion and armoring in the context of updating the Sanctuary's Management Plan, as well as in reviewing and authorizing permit applications that involve disturbance of the seabed. As part of its revised management plan, the MBNMS developed *Coastal Armoring Action Plan* addressing coastal erosion and armoring issues. The goal of this action plan is to reduce expansion of hard coastal armoring in the coastal areas near the MBNMS through proactive regional planning, project tracking, and comprehensive permit analysis and compliance. The Coastal Armoring Action Plan recommends developing a more proactive and comprehensive regional approach that minimizes the negative impacts of coastal armoring on a sanctuary-wide basis (MBNMS, 2008).

1.2.1 Southern Monterey Bay Coastal Erosion Workgroup

Consistent with the *Coastal Armoring Action Plan*, the SMBCEW was initiated in 2005 by the MBNMS, in collaboration with the City of Monterey and other state and local partners, and with the support of Congressman Sam Farr. The workgroup was formed to facilitate the development of a regional approach to address coastal erosion within the Southern Monterey Bay region between Moss Landing and Wharf II in Monterey. The 20-member workgroup is made up of scientists, federal and state agencies, local governmental representatives, conservation interests and other local experts. The goals of the SMBCEW are to: compile and analyze existing information on erosion rates and geomorphology in the region, as well as identify corresponding critical erosion areas, including threats to private and public structures within the Southern Monterey Bay (SMB) region; identify and assess the complete range of options available for responding to erosion in the region; and, based upon the above analyses, to develop a proactive and comprehensive regional shore preservation, restoration, and management plan with selected site-specific and broader area-wide recommendations for responding to coastal erosion that minimize environmental and socioeconomic impacts to the maximum extent feasible—this current Alternatives Study will be used in the development of this comprehensive plan.

1.2.2 Coastal Regional Sediment Management Plan

The Coastal Regional Sediment Management Plan (CRSMP) for the Southern Monterey Bay region is a related study that was completed and adopted by the AMBAG Board of Directors in 2008 (PWA et al., 2008). The CRSMP and this Alternatives Study are intended to be complementary decision support and planning tools, each assessing a distinct set of options for mitigation of coastal erosion and sea level rise impacts in the SMB. The CRSMP compiled the best existing information on coastal processes, erosion rates, and geomorphology, identified sources of sediment that could potentially be used in beach nourishment projects to reduce erosion hazards, and evaluated some of the regulatory and permitting framework involved in managing sediment within Southern Monterey Bay (SMB). The CRSMP also made recommendations on sediment management approaches to be pursued for the SMB region including cessation of sand mining from the beach, continuation of natural dune erosion in the less developed

reaches, and a sand nourishment project in the southern portion of the littoral cell to provide additional storm protection. The key recommendations from the CRSMP are shown in Figure 1. The recommendations also identified the need for a study which used the CRSMP as a baseline to build a regionally comprehensive erosion abatement approach, a portion of which forms the basis for this report. The CRSMP for the SMB was the first Coastal Regional Sediment Management Plan completed in California.

The plan covers the *Southern Monterey Bay Littoral Cell*, which extends from Moss Landing to Point Pinos in Monterey. The CRSMP was completed by Philip Williams and Associates in November 2008 in collaboration with AMBAG. Technical input was provided by a stakeholder group, which included the SMBCEW, consisting of local agencies and municipalities and other stakeholders and led by the Monterey Bay National Marine Sanctuary. Input and review for the CRSMP was provided during numerous meetings including meetings of the AMBAG Board of Directors, the SMBCEW, and dedicated public outreach meetings throughout the course of the study. The CRSMP was formally accepted by the AMBAG Board of Directors in November 2008.

The information on geomorphology and coastal processes in the CRSMP provides the baseline inventory for the evaluation conducted for this study assessing the feasibility and suitability of the potential erosion mitigation measures identified by the SMBCEW. For more detail on the physical setting and processes in SMB, please refer to the CRSMP

(http://www.dbw.ca.gov/csmw/pdf/SMontereyBay_CRSMP_3Nov2008.pdf).

The CRSMP also identified sources of sediment that could be used in nourishment projects to reduce erosion hazards, and evaluated the traditional cost benefits of various scales of nourishment projects and included the potential recreational benefits. The CRSMP has a sediment management focus and analyzes and includes recommendations for beach nourishment projects for parts of the SMB shore—therefore the scope of this Alternatives Study does not include further analysis of beach nourishment and other sediment management approaches other than as a comparison to the other erosion mitigation measures.

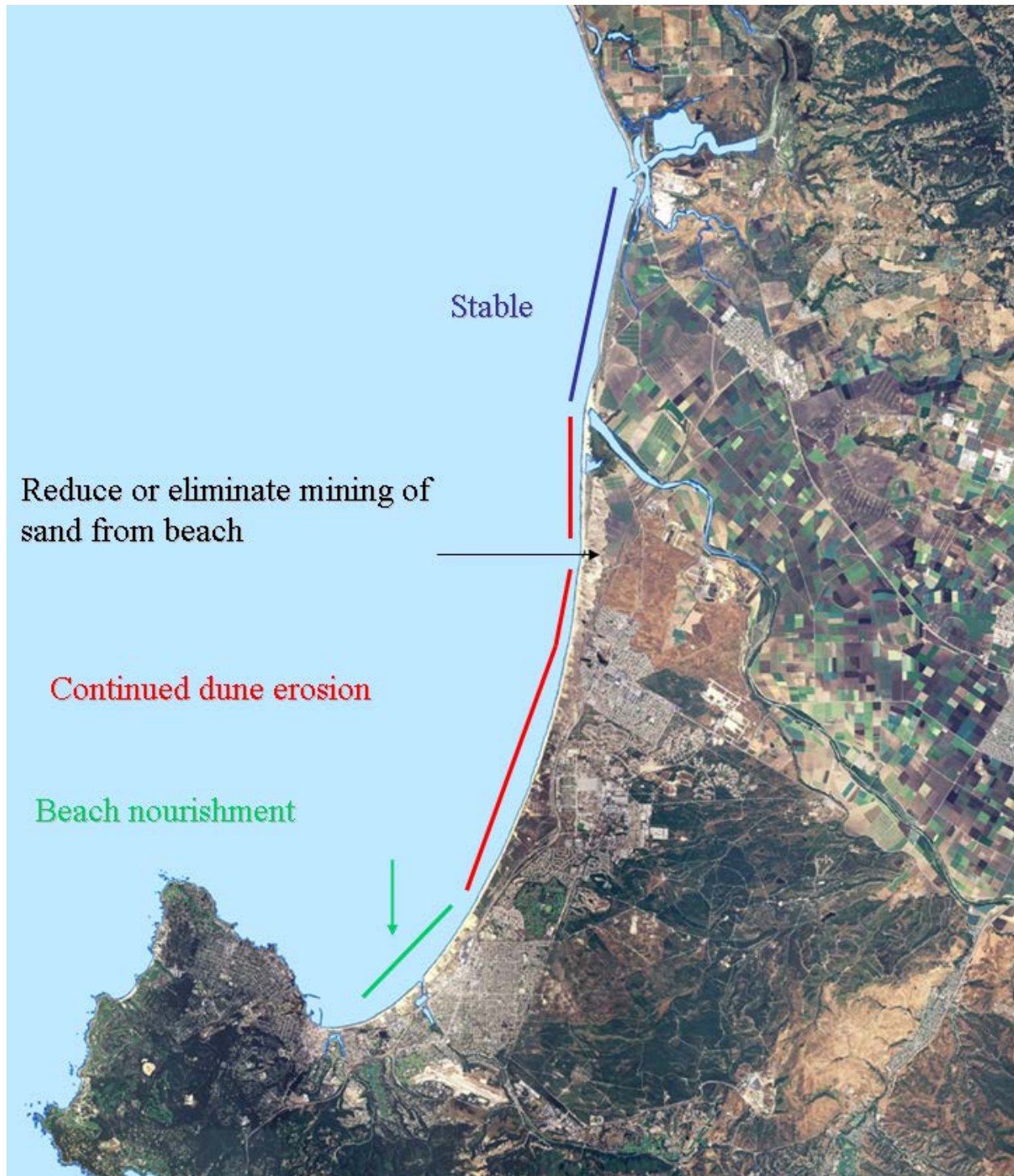


Figure 1 Summary of Recommendations from Coastal Regional Sediment Management Plan

The CRSMP subdivided the SMB shoreline into eight (8) Subregions of varying lengths and identified eight (8) Critical Erosion Areas within these Subregions. These Subregions were established based on similarities in coastal erosion rates, development patterns, and land use/ownership.

The eight (8) Subregions are as follows:

1. Subregion 1 – Wharf II to Del Monte Townhomes¹;
2. Subregion 2 – Del Monte Townhomes to Monterey Seaside Boundary
3. Subregion 3 – Monterey Seaside Boundary to Tioga Ave
4. Subregion 4 – Tioga Ave to Fort Ord
5. Subregion 5 – Ford Ord to Reservation Road
6. Subregion 6 – Reservation Road to Marine Dunes Resort
7. Subregion 7 – Marina Dunes Resort to Salinas River Mouth
8. Subregion 8 – Salinas River Mouth to Moss Landing

Critical Erosion Areas are defined in the CRSMP as development under threat from continued erosion using historic erosion rates over the next 50 years with a high-risk factor and potentially severe consequences. There are eight (8) Critical Erosion Areas in five (5) Subregions from South to North:

1. Del Monte Townhouses (Subregion 1)
2. Ocean Harbor House (Subregion 2)
3. Monterey Beach Resort (Subregion 2)
4. Monterey Interceptor (Subregions 1, 2 and 3)
5. Seaside Pump Station (Subregion 3)
6. Tioga Ave – Sand City (Subregions 3 and 4)
7. Marina Coast Water District Facilities (Subregion 6)
8. Sanctuary Beach Resort (Subregion 6)

The Subregions and Critical Erosion Areas are depicted in Figure 2.

¹ The Del Monte Townhomes are also known by their former name of La Playa Townhomes.

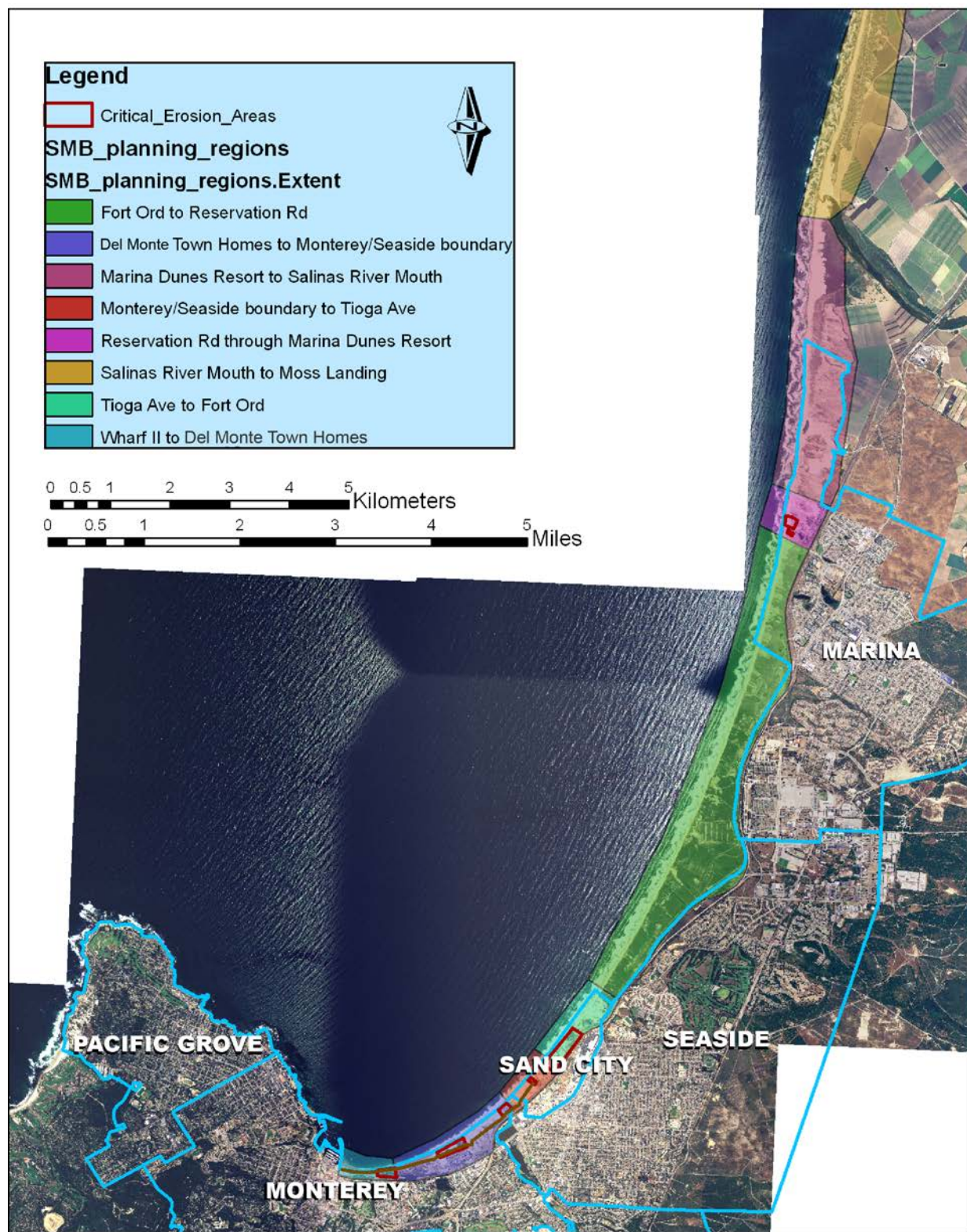


Figure 2 Southern Monterey Bay Subregions and Critical Erosion Areas

2. RECOMMENDATIONS – REGION, SUBREGION, AND CRITICAL EROSION AREAS

This section presents recommendations made by ESA PWA based on the interpretation of the results of the technical analyses conducted for this study. A separate assessment was completed for each measure using criteria including effectiveness, environmental impacts and a benefit cost analysis.

The recommendations from this Alternatives Study are organized into three sections:

- *Section 2.1 - Regional Recommendation*
This section revisits the CRSMP recommendations and identifies alternative strategies to be considered within a regional shoreline management plan for the entire SMB region;
- *Section 2.2 - Subregion Management Recommendations*
This section identifies the measures that are appropriate for each Subregion
- *Section 2.3 - Additional Recommended Studies*
This section identifies research and development topics to improve upon the analyses accomplished in this report and to support future work toward a regional shoreline management plan.

Most of these erosion mitigation measures will require additional feasibility studies, regulatory and permitting coordination, and collaborative planning, prior to being implemented. For example, planning for large scale nourishment or Rolling Easements may take a decade or more to implement so the recommendation may be identified in a future time horizon, but efforts to implement them should begin immediately. The recommendations therefore are listed over their effective time horizon. These combinations of recommendations for each Subregion support one another, for example ceasing sand mining and implementing opportunistic sand nourishment while planning for a larger one.

2.1 REGIONAL RECOMMENDATIONS

2.1.1 Evaluation of Recommendations from the CRSMP:

Cessation of sand mining from the beach - this recommendation initially identified in the CRSMP remains the most significant erosion mitigation measure that should be the highest priority for all jurisdictions in the southern Monterey Bay region. Further analysis done for this report shows that implementing this measure would reduce erosion rates by at least 60% across the entire region (see *Section 4.2.1 Cessation of Sand Mining from the Beach*). *The overall savings to the communities in the region by ceasing sand mining from the beach is estimated to have a present value equal to \$124.5 million in 2010 dollars.* The cost of cessation is unknown and could vary greatly based on whether the mine was purchased at fair market value, or operations are modified, or beach mining stops due to other potential processes such as regulatory or legal action.

Continuation of dune erosion to supply beach sediments– this recommendation identified in the CRSMP remains an important component to maintaining the natural sediment supply to these beaches. Analyses completed in this study show that Rolling Easements, are likely to be the least costly options for

continuing sediment supply sediment supply from erosion for the SMB Littoral Cell. Other implementation mechanisms for this strategy could occur on a parcel-by-parcel basis using a “no future armoring” condition, or through *Local Coastal Program* (LCP) updates, or regulatory or ordinance language by a local municipality or government agency with regulatory and permitting authority (e.g. Coastal Commission, local cities, or potentially a new Joint Powers Authority (JPA) focused on addressing coastal erosion). Specific implementation mechanisms for this recommendation would depend on levels of existing and potential coastal development and jurisdictional considerations. Action would likely not be required for undeveloped coastal areas.

Beach Nourishment – The CRSMP included a recommendation to consider developing a large beach nourishment project for the Southern Bight of the SMB (approximately 3 to 4 miles of coastline in Monterey, Seaside and Sand City) within Subregions 1 to 4 where development is most concentrated and the majority of the critical erosion areas are located. The CRSMP recommendations identified two distinct nourishment projects—large scale placements (two million cubic yards) and small scale placements of opportunistic sediments (e.g. 75,000 cubic yards from Monterey Harbor)—and found favorable benefit cost values for both projects, using the Coastal Sediment Benefits Analysis Tool (CSBAT).

Develop an opportunistic sand placement program

Consistent with the initial recommendation in the CRSMP, this program should be developed and applied as opportunistic sediment becomes available. This should not be considered an effective long-term erosion mitigation strategy due to the limited volumes of sediment. We assume that the volumes of available opportunistic sand are small, but there may be future opportunities to obtain larger volumes of sand, which would be incorporated into a larger nourishment alternative.

While analyses conducted herein show that small nourishments only have an incremental benefit to long term erosion mitigation, the low cost and applicability to specific sites show that it still provides some erosion mitigation benefits in the Southern Bight (Subregions 1-4) where erosion rates are less than -1.5 ft/year (45 cm/yr).

A more exhaustive analysis of the two CRSMP identified nourishment projects completed for this Alternatives Study expanded upon the CSBAT methodology by including potential structural damages, ecological and recreational benefits (see Section 3.5). The revised results generally indicate lower but still positive Benefit Cost (BC) ratios. The largest BC ratios were seen in the Southern Bight (Subregions 1-4) with lower BC ratios outside (Subregions 5-7). Higher costs are the result of the need to re-nourish more frequently outside the southern bight (Subregions 5-7) where erosion rates are higher. The benefit-to-cost ratios resulting from our analysis are considered high estimates due to two factors that require further investigation:

- The benefit to the beach ecosystem may be initially negative due to adverse effects to existing organisms, and frequent re-nourishment may not have a net benefit.
- Accelerated sea level rise may increase the required frequency of renourishment, thereby increasing costs and increasing the potential for adverse ecological effects.

In addition, the regulatory feasibility of nourishment projects in the Monterey Bay National Marine Sanctuary remains uncertain and it is likely that implementation of any large nourishment project would present challenges. Also, as pointed out in the CRSMP, the feasibility of attaining funding for beach nourishment while sand mining is occurring is dubious.

2.1.2 Additional Regional Recommendations

The benefit/cost analysis indicates that the land use planning measures not previously considered in the CRSMP are substantially more beneficial than any of the structural erosion mitigation measures. Therefore, regional coastal management should consider the land use planning measures in addition to the sediment management measures identified initially in the CRSMP. This finding largely depends on a regional approach that includes consideration of public trust resources associated with recreation and ecosystem services as opposed to the current practice of parcel level decision making which is largely responsible for the proliferation of shoreline armoring in SMB.

In SMB, the CRSMP and this Alternatives Study indicate the most promising approaches would be cessation of sand mining, Rolling Easements, and beach nourishment (for a full explanation and analysis of the various alternatives analyzed refer to *Section 4* of this report). However all of these measures have uncertain feasibility. A mechanism for cessation of the Marina commercial sand mining operation has not been identified. It is not known whether property owners will participate in a program of Rolling Easements or state agencies would require such a program. Large scale nourishment appears to be most effective in the southern bight where erosion rates are less and development exists; however ecological impacts would likely be highest in this reach as well, potentially affecting the benefits and costs of nourishment. Frequent re-nourishment due to accelerated erosion resulting from sea level rise or sand mining would further reduce viability of nourishment. Development of a regional shoreline management plan would therefore require further public process, planning and coordination.

We recommend that the following actions be included within the regional shoreline management process:

Monterey Regional Water Pollution Control Facilities

Continue planning and implementation to relocate the regional sewage infrastructure.

Monitoring of Coastal Changes

Establish a series of coastal transects that are monitored periodically over time. Appendix 2 is a recommended Monitoring Plan to track coastal changes. This monitoring plan should be implemented to assess long term changes and can be augmented for specific projects. This monitoring should focus on key issues such as effects of erosion management measures and research that will support a more accurate benefit cost analysis and adaptive management strategy

Institutional Funding Framework – As described in the CRSMP (PWA et al., 2008), regional management requires further development of an institutional framework and implementation mechanism including in particular a governance structure and funding. During the course of this study, several interesting concepts were identified in discussions with leading experts, for example, the concept of a

“sand bank” that would fund plan implementation via a coordinated “revolving fund” created from a range of sources such as permit fees (e.g. Coastal Commission permit sand mitigation fees), federal grants, or other sources (personal communications with Jim Titus, Meg Caldwell, and David Wilmot).

Regional Review of Setback Policies – Currently, local setback policies are the most commonly applied erosion mitigation measure but they differ in their application throughout the region. It should be noted that analyses show that this strategy is not effective in the long term and has the highest risk of regulatory takings lawsuits. It may make more sense to have a regional systematic setback policy however local issues may require additional considerations. Additionally, if revetments or armoring is eventually permitted, then setbacks only serve to delay the impacts.

It is recommended, at a minimum, that a “standard” setback for the region is established to facilitate coordinated regional planning. The Del Monte LCP standard, a 100 year average annual erosion rate calculation is the recommended minimum setback. A more appropriate setback would entail a minimum forecast period of 100 years and include consideration of accelerated sea level rise and other hazards such as tsunami run-up. Variations to this standard could be tiered based on the type and size of proposed development. The fact that communities have adopted less restrictive setbacks indicates that this recommendation may be difficult to implement and may include consideration of other factors such as local tax revenue, property values, and consensus about coastal hazards and environmental effects. Some variances may be warranted on some parcels since strict application of setbacks may preclude redevelopment in some cases and trigger takings claims (see Section 5).

Implement Pilot Projects – Several of the mitigation measures assessed in this study (e.g. passive dewatering) have less scientific certainty, and others such as the use of geotextiles and opportunistic beach nourishment, have unknown ecological impacts. It is recommended that current scientific literature is reviewed to reassess its applicability. It is also recommended that small-scale “pilot” experiments be conducted using some of the alternatives having less potential for environmental impacts and are more affordable. These pilot projects would be conducted using close monitoring of physical, ecological and recreational affects.

Public Education and Real Estate Disclosures – Given the high costs estimated to manage the hazards resulting from coastal erosion, we recommend public outreach and real estate disclosure to educate property owners on risks of coastal hazards. Public participation in development of the regional shore management plan would accomplish this to some degree. However, more systematic actions may be needed to reach a broader section of the public. For example, mapping of the coastal hazard zone (to include erosion, flooding, tsunamis) and required disclosure as part of real estate transactions would help ensure that the public was informed. The geographic scope of the zone could be expanded to include inland parcels based on a future sea level rise hazard assessment.

2.2 SUBREGION MANAGEMENT RECOMMENDATIONS

The recommendations for each Subregion are summarized in Table 1. This table only highlights the recommendations by Time Horizon and Subregion found in Section 2. It does not discuss rationales for

recommendations, or further delineate measures that are not likely to work, or may work but seem to be cost prohibitive. The detailed analyses used to identify these recommendations are found in the Erosion Mitigation Measures described in Section 4.2.

Table 1 Summary of Subregion Management Recommendations

Erosion Mitigation Measures	Time Horizon	Subregion							
		1	2	3	4	5	6	7	8
Rolling Easements	Immediate 0-5								
	Short - 6-25								
	Medium - 26-50								
	Long - 51-100								
Managed Retreat	Immediate 0-5								
	Short - 6-25								
	Medium - 26-50								
	Long - 51-100								
Transfer Development Credit	Immediate 0-5								
	Short - 6-25								
	Medium - 26-50								
	Long - 51-100								
Conservation Easements	Immediate 0-5								
	Short - 6-25								
	Medium - 26-50								
	Long - 51-100								
Fee Simple Acquisition	Immediate 0-5								
	Short - 6-25								
	Medium - 26-50								
	Long - 51-100								
Structural Adaptation	Immediate 0-5								
	Short - 6-25								
	Medium - 26-50								
	Long - 51-100								
Setbacks	Immediate 0-5								
	Short - 6-25								
	Medium - 26-50								
	Long - 51-100								
Sand Mining Cessation	Immediate 0-5								
	Short - 6-25								
	Medium - 26-50								
	Long - 51-100								
SCOUP	Immediate 0-5								
	Short - 6-25								
	Medium - 26-50								
	Long - 51-100								
Beach Dewatering	Immediate 0-5								
	Short - 6-25								
	Medium - 26-50								
	Long - 51-100								
Beach Nourishment	Immediate 0-5								
	Short - 6-25								
	Medium - 26-50								
	Long - 51-100								
Revetments	Immediate 0-5								
	Short - 6-25								
	Medium - 26-50								
	Long - 51-100								
Seawalls	Immediate 0-5								
	Short - 6-25								
	Medium - 26-50								
	Long - 51-100								
Perched Beaches	Immediate 0-5								
	Short - 6-25								
	Medium - 26-50								
	Long - 51-100								
Groins	Immediate 0-5								
	Short - 6-25								
	Medium - 26-50								
	Long - 51-100								
Breakwaters	Immediate 0-5								
	Short - 6-25								
	Medium - 26-50								
	Long - 51-100								
Artificial Reefs	Immediate 0-5								
	Short - 6-25								
	Medium - 26-50								
	Long - 51-100								

Subregions and Summary Statistics

Assessor's parcel-level data provided by AMBAG were reviewed for the entire study region. The following statistics were derived within the area between Moss Landing and Wharf II, and within 300 feet of the shore:

- 380 oceanfront parcels are on record within a total area of about 150 km² (1100 acres)
- 80 parcels (21%) are publicly owned making up 66% of the land area
- 300 parcels (79%) are privately owned making up 34% of the land area
- 288 of 380 parcels have 0 or NO assessed value (improved or land value)

2.2.1 Subregion 1 – Wharf II to Del Monte Townhouses

This entirety of Subregion 1 is located in the City of Monterey, and includes the area located between Wharf II and the Del Monte Townhomes² (Figure 3)³.

Erosion rates in this Subregion are less than those in the other Subregions, ranging from near 0 ft/yr (0 cm/yr) to 0.5 ft/yr (11cm/yr), with the lower rates near Wharf II increasing moving up-coast towards the Del Monte Townhouses. A wall was placed along Wharf II to arrest sand from filling in the Harbor; this has resulted in Wharf II acting as a breakwater accreting sand adjacent to the Wharf and building up a wide beach.

Wide beaches, low, active, migrating dunes, and minimal wave energy in comparison with the other Subregions, characterize this portion of the shore. Correspondingly, threats to existing structures are not as imminent as those found in other Subregions. Another unique aspect of Subregion 1 is the existence of fine-grained sand probably due to the addition of fine sediments in the runoff from the hills that collects near the drainage culvert at the wharf. The sand composition however becomes coarser moving to the north of the wharf.

Because of its proximity to popular Monterey tourist attractions, and availability of parking, this stretch is one of the most heavily used for beach oriented recreational activities, including walking on the beach, sunbathing, kayaking, fishing, beachcombing, SCUBA diving, and swimming. Monterey Abalone Company operates an abalone farm under Wharf II, which could potentially be impacted by turbidity changes.

² The name of this property has changed and has been called La Playa Townhomes and Parklands Monterey

³ Detail not shown: The section of beach from Wharf II to Camino El Estero is part of Monterey with the remainder being part of Monterey State Beach. Although it is owned by State Parks, the Monterey State Beach portion is under the jurisdiction of the City of Monterey through a Memorandum of Understanding.



Figure 3 Subregions 1 – 4

Existing Coastal Protection Structures and Practices:

The only existing armoring in this Subregion is a small amount of riprap at the fence line of the Del Monte Townhouses. The City of Monterey practices beach scraping in this location to build up a berm in front of the Catellus property in order to prevent wave run-up from reaching Del Monte Boulevard. The entire stretch of coast from Wharf II to the Ocean Harbor House condos is raked by the City to remove debris such as driftwood and seaweed.

Critical Erosion Sites Included:

Portions of the Monterey Interceptor; Catellus East Property; Del Monte Townhomes; Lake El Estero Storm Drain Outfall

Assessors Summary:

This area is about 3080 feet long, with 98 parcels. The total value of near oceanfront property (from the Assessors data) is \$29,568,253, with average values of \$301,716 per parcel and \$9,608 per foot of shore. This translates to \$31,522,310/km

2.2.1.1 Subregion 1 - Recommended Actions

Immediate term

- Implement land use planning measures (1. Rolling Easements; 2. Conservation Easements; 3. Fee Simple Acquisition of threatened structures with a hybrid lease back option for structures that are still suitable for habitation until they cease to be safe; 4. Fee Simple Acquisition)
- Cessation of Sand Mining from the beach
- Implementation of an opportunistic sand placement program (including potential use of sand from dredging of Monterey Harbor) to address critical erosion areas
- Other recommendations from observations not analyzed in the report:
 - Use of temporary structures (e.g. geotextile sand bags⁴, K-rails⁵) as an interim storm protection measure
 - Controlling storm water run-off at the Del Monte Townhouses to reduce sand saturation and reduce hotspot erosion
 - Reduce or eliminate beach grooming and the removal of beach wrack which in addition to supporting and comprising part of the sandy beach ecosystem also improves natural sand accumulation and retention processes

Short term

- Structural adaptation (underpinning and elevation) of threatened structures
- Relocation of portions of the Monterey Interceptor
- Beach nourishment (large). It should also be noted that there are significant regulatory hurdles to implementing this in the Monterey Bay National Marine Sanctuary. Also, note that for this Subregion, ecological impacts are likely to be the highest given the eel grass beds, offshore rocky reefs, and sandy beach ecosystem. It is NOT recommended that this option be considered without first ceasing sand mining from the beach.

⁴ Geotextile Sand Bags (also known as scour pillows) refer to plastic or other fabric bags filled with sand or gravel and used to form a barrier to erosion appropriate for minor erosion, low environmental loads and short durations. Other measures may also be useful but all should be subject to careful consideration before installation.

Medium term

- Groins as a sand retention structure show positive net benefits over 100 years in this Subregion and is worth further investigation in a feasibility study.

Long term

- Structural Adaptation or Relocation of transportation infrastructure
- Managed Retreat

2.2.2 Subregion 2 – Del Monte Townhomes to Monterey Seaside Boundary

This Subregion begins just beyond the Del Monte Townhomes property and continues to the Monterey-Seaside Boundary, slightly past the Monterey Beach Resort. The section of beach from the Ocean Harbor House condos to the Monterey Beach Resort is part of Monterey State Beach under the jurisdiction of State Parks and the land between the Del Monte Townhomes and just before the properties on Beach Way are under the jurisdiction of the Naval Postgraduate School (NPS).

Erosion rates in most of this Subregion are relatively low compared to other Subregions ranging from 11 to as high as 60-80 cm/year. The rates increase moving up-coast from the Del Monte Townhomes and are highest in this Subregion at the Monterey Beach Resort. The beach is wider here than further up the coast; however, it is narrower than in Subregion 1. Subregion 2 includes the highest concentration of both threatened sites and existing armoring in the southern Monterey Bay Region.

Subregion 2 is heavily used for recreational activities including walking on the beach, sunbathing, surfing, fishing, volleyball and beachcombing. This entire stretch is also part of Monterey State Beach under the jurisdiction of California State Parks. The dunes to the north of the Ocean Harbor House are known to support nesting snowy plover. Lateral access can be impeded in several areas of Subregion 2 during winter storms including at the Ocean Harbor House, Del Monte Lake outfall, the Monterey Beach Resort, and at the point where recreation trail is closest to the beach along Sand Dunes Drive approaching the Monterey Beach Resort.

Subregion 2 includes a portion of the Monterey Interceptor—between the Monterey Pump Station (located near the former City of Monterey treatment plant) and Tide Avenue—that was designated as high-risk in the assessment of threat to MRWPCA facilities completed in 2004. Other sections of the Monterey Interceptor in this Subregion were designated as moderate risk. This stretch also includes a section of Highway 1, near the Monterey Beach Resort, that is in closer proximity to the coast than in other Subregions.

This Subregion includes a former petroleum tank site located between the Ocean Harbor House condos and the Monterey Beach Resort; asphalt and remnants from old roads remain at this site. Another potential consideration is a plume of gasoline-contaminated groundwater located at the point where the recreation trail is in closest proximity to Del Monte Avenue, just beyond the Del Monte Beach subdivision. This plume is currently being observed, through funding by Chevron, to track its activity by a monitoring well in the vicinity.

There is a historical landfill in this Subregion, between Beach Way and the Monterey pump station, containing debris from the historic Del Monte Hotel fire. This landfill is currently being uncovered by storm waves.

The portion of Monterey State Beach from the Ocean Harbor House condos to the Monterey Beach Resort is potential snowy plover habitat.

Existing Coastal Protection Structures and Practices:

Armoring exists at the Del Monte Lake storm drain outfall, Ocean Harbor House condos, and Monterey Beach Resort.

Critical Erosion Sites Included:

Parts of Monterey Interceptor; Naval Postgraduate School Research Building; Old Monterey Treatment Plant; Del Monte Lake Storm Drain Outfall; Del Monte Beach Subdivision; Ocean Harbor House; parts of Sand Dunes Drive; Monterey Beach Resort; Roberts Lake/Laguna Grande Outfall; Part of Highway 1. There is also a warehouse located on the dunes at the Naval Postgraduate School property, however that building is sacrificial and will be removed if threatened by erosion. The recreation trail (bike path) is another sacrificial structure, that if threatened should be removed and relocated rather than protected.

Assessors Summary:

This area is about 7300 feet long, with 241 parcels. The total value of near oceanfront property (from the Assessors data) is \$107,814,546 with average values of \$477,363 per parcel and \$14,769 per foot of shore. This translates to \$48,454,724/km

2.2.2.1 Subregion 2 - Recommended Actions

Immediate term

- Implement a land use planning measures (1. Rolling Easements; 2. Conservation Easements 3. Fee Simple Acquisition of threatened structures with a hybrid lease back option for structures that are still suitable for habitation until they cease to be safe.; 4. Fee Simple Acquisition)
- Cessation of Sand Mining
- Implementation of an opportunistic beach nourishment program including use of clean sediment from dredging of Monterey Harbor to address critical erosion areas
- Other measures not evaluated in this report
 - Use of temporary structures (e.g. geotextile sand bags, K-rails) as an interim storm protection measure

Short term

- Structural adaptation underpinning and elevation of threatened structures
- Beach nourishment (large). It should also be noted that there are significant regulatory hurdles to implementing this in the Monterey Bay National Marine Sanctuary. It is NOT recommended that this option be considered without first ceasing sand mining from the beach.

Medium term

- Groins as a sand retention structure show positive net benefits over 100 years in this Subregion and is worth further investigation in a feasibility study.

Long term

- Managed Retreat
- Structural Adaptation or Relocation of transportation infrastructure

2.2.3 Subregion 3 – Monterey-Seaside Boundary to Tioga Ave

Subregion 3 begins at the border of Seaside and continues to Tioga Avenue in Sand City. It includes all of Seaside's beachfront property and parts of Sand City.

Erosion rates in this Subregion continue to increase from Subregions 1 and Subregion 2, and are highest near Tioga Avenue. Lateral access along the beach can be cut off during storm episodes and high tides at the terminus of Tioga Avenue.

Subregion 3 is used for recreational activities including walking on the beach, sunbathing, fishing, volleyball and beachcombing, although not as frequently as Subregion 1 and Subregion 2.

There is very little development in Subregion 3 and what does exist is infrastructure rather than commercial or residential development. This Subregion would benefit from cleanup of sites and potential retrofit or improvement of certain structures. While there is more area available for coastal retreat than the previous 2 Subregions, this Subregion has limited space with Highway 1 in proximity to the shore; therefore focus on keeping wide beaches might be appropriate.

Several threatened sites exist in Subregion 3, including a section of the Monterey Interceptor—between the Seaside Pump Station and the Monterey Beach Resort—that was designated as high-risk in the PWA threat assessment study conducted in 2004. The Seaside Pump Station, located only 75 feet from the shoreline, was also determined to be a high risk (PWA, 2004). PWA estimated that the facility may be threatened within 20 years and could be compromised by short-term episodic events even sooner. The estimated cost to replace this pump station is \$55 million dollars (Appendix 3).

Existing Coastal Protection Structures and Practices:

Seawall at Monterey Beach Resort

Critical Erosion Sites Included:

Parts of Monterey Interceptor; parts of Sand Dunes Drive; Seaside Pump Station; Part of Highway 1; Bay Street storm drain outfall; Sand City at end of Tioga Avenue; Monterey Beach Resort.

Assessors Summary:

This area is about 3360 feet long, with 225 parcels. The total value of near oceanfront property (from the Assessors data) is \$595,096 with average values of \$2,644 per parcel and \$177 per foot of shore. This translates to \$580,709/km.

2.2.3.1 Subregion 3 - Recommended Actions

Immediate term

- Implement land use planning measures (1. Rolling easements; 2. Conservation Easements 3. Fee Simple Acquisition of threatened structures with a hybrid lease back option for structures that are still suitable for habitation until they cease to be safe.; 4. Fee Simple Acquisition)
- Cessation of Sand Mining
- Implementation of an opportunistic sand placement program
- Other measures not analyzed in this report
 - Use of temporary structures (e.g. geotextile sand bags) as an interim protection measure

Short term and Medium term

- Structural adaptation of threatened structures
- Beach nourishment (large volume of 2 million c.y.) recognizing that this is only an intermediate and not long term solution. It should also be noted that there are significant regulatory hurdles to implementing this in the Monterey Bay National Marine Sanctuary. It is NOT recommended that this option be considered without first ceasing sand mining from the beach.

Long term

- Managed Retreat
- Structural Adaptation or Relocation of transportation infrastructure

2.2.4 Subregion 4 – Tioga Ave to Fort Ord

This Subregion begins just northeast of Tioga Ave. in Sand City and continues to the boundary of Sand City and Fort Ord. Erosion rates in this Subregion are higher than Subregions 1-3, with the highest rates near Tioga Avenue.

The land in this Subregion falls within the boundaries of Sand City and also includes a section of Monterey Regional Parks District (MRPD) parkland known as Landfill Dune Preserve. This preserve is located on the site of a previously located landfill for the Monterey Peninsula cities, which closed in 1955. The site then served as a go-cart racetrack which remained open until 1969. The land was acquired by MRPD in 1995 and underwent partial remediation during the next two years with the assistance of the California Integrated Waste Management Board. The landfill material was unearthed and sorted and the recoverable or recyclable materials were removed with the remaining debris being re-buried and covered with sand. Although the debris was buried beyond a projected 50-year erosion setback, sea level rise was not taken into consideration. The coastal dunes were subsequently restored with native vegetation and an extension of the Monterey Bay Coastal trail was constructed.

Subregion 4, although not heavily used for recreational activities compared to the previous Subregions, is used for walking on the beach, sunbathing, fishing, beachcombing, and surfing. This may change in the future as the transition in ownership from the military to California State Parks has opened this area up for recreational use.

This Subregion includes very little existing development. However, there are two proposed developments within its boundaries. Sand City, MRPD and California State Parks have a Memorandum of Agreement that establishes these two areas where development would be allowed seaward of Highway 1 in Sand City. The first site is the combined 7-acre Sterling property and the adjoining 23-acre McDonald property to the north. This project is under review by the Sand City. The other property is the 39-acres Ghandour project, located on an old sand mine between the large sand dune visible from Highway 1 and the north end of Sand City, adjacent to Fort Ord. The development proposal has been contested and the project review is continuing at the time of this report.

A portion of the Monterey Interceptor is also located within this Subregion; however it was determined by PWA not to be at high risk, as part of their assessment for MRWPCA (PWA, 2004). This area was identified in the CRSMP as one critical to maintain sediment supply through continued erosion of the dunes.

Existing Coastal Protection Structures and Practices:

There is limited coastal protection in this Subregion; however there is some “de facto” armoring caused by the dumping of concrete and construction rubble near the end of Tioga Ave. However, accelerated sea level rise was not considered in this 2004 analysis.

Critical Erosion Sites Included:

Parts of Monterey Interceptor (although not high-risk); debris and concrete on the dunes adjacent to Tioga Avenue

Assessors Summary:

This area is about 4835 feet long, with 9 parcels. The total value of near oceanfront property (from the Assessors data) is \$10,355,798 with an average value of \$1,150,644 per parcel and \$2,141 per foot of shore. This translates to \$7,024,278/km. It is our understanding that assessed values do not necessarily reflect developed fair market values and hence may not be accurate.

2.2.4.1 Subregion 4 - Recommended Actions

Immediate term

- Implement land use planning measures (1. Rolling Easements; 2. Conservation Easements 3. Fee Simple Acquisition of threatened structures with a hybrid lease back option for structures that are still suitable for habitation until they cease to be safe.; 4. Fee Simple Acquisition)
- Cessation of Sand Mining
- Implementation of an opportunistic sand placement program
- Assess potential for a Transfer of Development Credits program to remove development potential from erosion hazard zones and provide a densification of development within Sand City, perhaps through urban redevelopment
- Other measures not analyzed in the report
 - Application of any sand mitigation fees to Sand Bank

Short term and Medium term

- Structural adaptation of proposed structures (e.g. modular construction)
- Transfer of Development Credits of developable parcels
- Beach nourishment (large) recognizing that this is only an intermediate and not long term solution. It should also be noted that there are significant regulatory hurdles to implementing this in the Monterey Bay National Marine Sanctuary. It is NOT recommended that this option be considered without first ceasing sand mining from the beach.

Long term

- Managed Retreat
- Structural Adaptation or Relocation of transportation infrastructure (We assume that infrastructure function will be maintained however it is possible that changes in transportation needs would allow rerouting and demolition and not require reconstruction).

2.2.5 Subregion 5 – Ford Ord to Reservation Road

Subregion 5 encompasses Fort Ord Dunes State Park and parts of Marina State Beach. Steep narrow beaches with coarse sand, and high dunes characterize this Subregion. (Figure 4) Erosion rates in this Subregion are higher than the previous Subregions. This Subregion includes very little existing development along the shore; however the park does include more than 100 abandoned military buildings. The dunes in this Subregion vary in elevation between sea level and 140 feet above mean sea level, and are heavily vegetated with iceplant.

Subregion 5 includes very little existing development, and current state park plans call for removal of what does exist as it becomes threatened by coastal erosion. Although the erosion rates are significantly higher than many of the other areas within the Southern Monterey Bay region, with wide dunes and Highway 1 relatively far from the shoreline, this Subregion does not face the more imminent threats that the other Subregions must address. Accordingly, avoidance based responses such as managed retreat might be appropriate.



Figure 4 Subregion 5

Fort Ord Dunes State Park was opened in 2009 and includes four miles of shore along Monterey Bay. The property includes the remnants of fifteen small arms firing ranges, the former Fort Ord ammunition storage area that includes twelve bunkers, and other military era structures that are not in use, including a wastewater treatment plant. Fort Ord Dunes also includes an internal road system and utility lines. Several of the ammunition supply bunkers on the site will be used by State Parks for storage; however the structures will be removed as they become threatened by coastal erosion. State Parks uses a 700-foot setback zone in anticipation of the 100-year erosion line.

Subregion 5 is not as heavily used for recreational activities compared with the previous Subregions owing to limited access to the beaches guarded by high dunes. However, it has the potential for increased use due to its new State Park status, and is used to some degree for walking on the beach, sunbathing, fishing, beachcombing, and some surfing. The Fort Ord Dune State Park is accessed through Fort Ord. The main access point to Marina State Beach is at the west end of Reservation Road.

Three storm water outfalls that were previously causing severe erosion problems in this Subregion were removed from the beach by Fort Ord Reuse Authority in 2003. The outfalls were truncated and are now discharging to retention basins in the dunes. A fourth outfall structure that remains under the army's ownership has also been stabilized and will ultimately be phased out.

Several monitoring wells west of Highway 1 in Fort Ord also exist in Subregion 5 to monitor the progress of a waste plume that originated near 12 Street and is migrating seaward. These wells are part of a remediation program that also includes injection wells into which water from the plume, that has been treated, is pumped. Both the Monitoring wells and injection wells are currently in use, and are owned and operated by the Army Corps. of Engineers. At least one of the monitoring wells is seriously compromised by erosion, including one located at the top end of the bluff located due west of the abandoned wastewater treatment plant. The injection wells are located on the east side of the highway and are not threatened (Gray, 2006).

Critical Erosion Sites Included:

Monitoring wells at Fort Ord; Fort Ord Stormwater Outfalls

Assessors Summary:

This area is about 26,925 feet long, with 28 parcels. The total value of near oceanfront property (from the Assessors data) is \$596,221 with average values of \$21,293 per parcel and \$22 per foot of shore. This translates to \$72,168/km.

2.2.5.1 Subregion 5 - Recommended Actions

Immediate, Short, Medium and Long term

- Cessation of Sand Mining
- Rolling Easements implemented as conditions of approval for new or re- development
- Managed Retreat/Relocation/Demolition of any threatened structures
- Structural adaptation of any proposed structures (e.g. modular construction)

2.2.6 Subregion 6 – Reservation Road to Sanctuary Beach Resort

This Subregion is entirely encompassed within Marina State Beach. (Figure 5) There is a lack of existing development in Subregion 6. This area is probably highly impacted by the CEMEX sand mining operation up-coast. Therefore cessation of the mining operation would most likely have a positive effect on erosion and structure threats in this area. There is significant area available for coastal retreat in this area with substantial dunes and distance separating Highway 1 from the ocean, therefore managed retreat is probably a likely option in this Subregion.

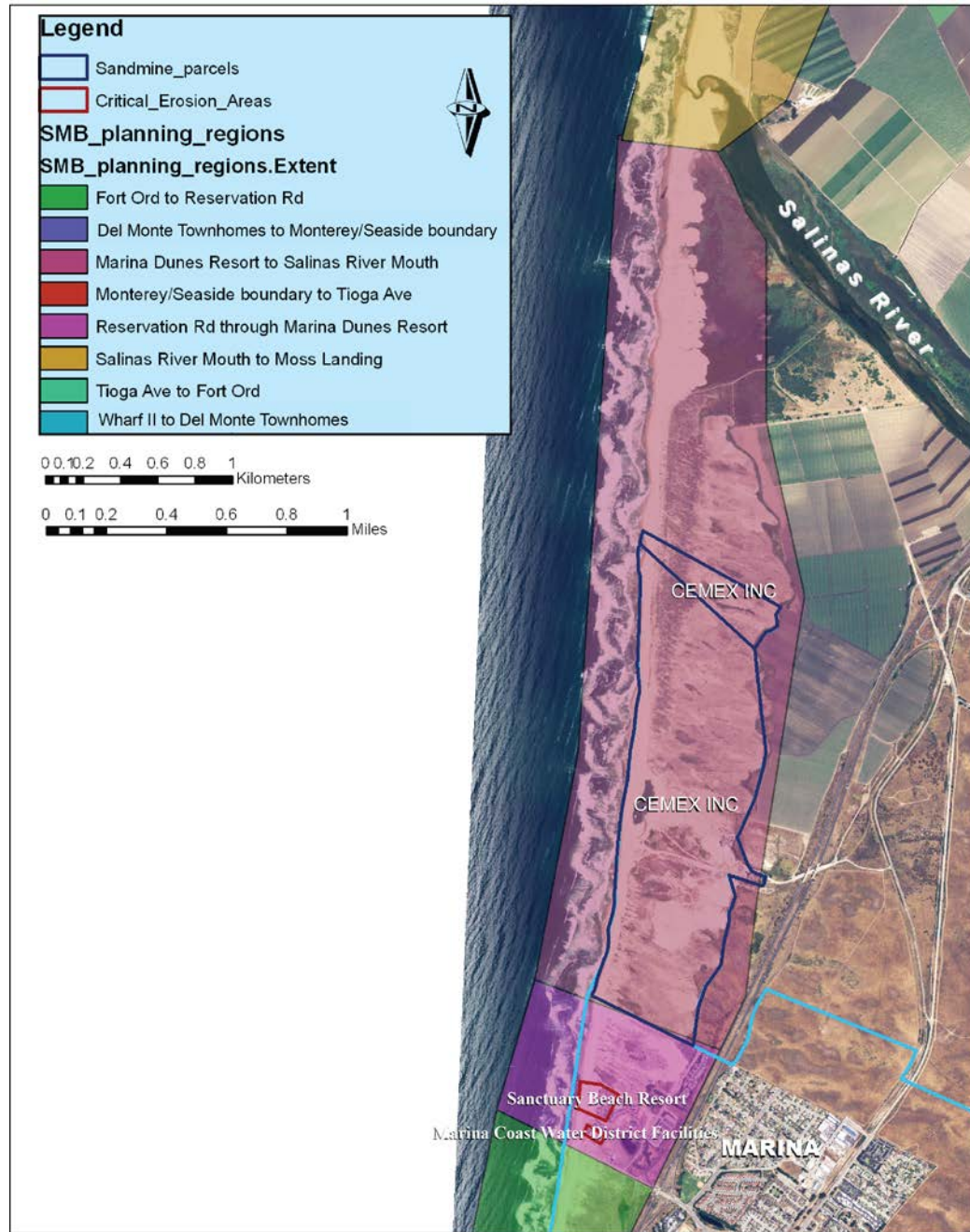


Figure 5 Subregion 6 and 7

The main access point to Marina State Beach is at the west end of Reservation Road. This access point includes a parking lot, restroom, and a boardwalk that leads through the Marina Dunes Natural Preserve. Also at the end of Reservation Road are the Marina Coast Water District (MCWD) facilities. The parking lot is one of the few points along the Monterey Bay shore where ocean viewing can be conducted from parked cars. MCWD has plans to remove and/or relocate the facilities.

The beach is known for hang-gliding, surfing, and surf fishing. The beach is a popular site for picnics.

Critical Erosion Sites Included:

Marina Coast Water District Facilities at end of Reservation Road; Reservation Road Parking lot, and Sanctuary Beach Resort

Assessors Summary:

This area is about 2,703 feet long, with 7 parcels. The total value of near oceanfront property (from the Assessors data) is \$26,728,303 with average values of \$3,818,329 per parcel and \$9,887 per foot of shore. This translates to \$32,437,664/km.

2.2.6.1 Subregion 6 - Recommended Actions

Immediate, Short, Medium and Long term

- Implement land use planning measures (1. Rolling Easements; 2. Conservation Easements 3. Fee Simple Acquisition of threatened structures with a hybrid lease back option for structures that are still suitable for habitation until they cease to be safe.; 4. Fee Simple Acquisition)
- Cessation of Sand Mining
- Managed Retreat/Relocation of any threatened structures
- Structural adaptation of any proposed structures(e.g. modular construction)

2.2.7 Subregion 7 – Sanctuary Beach Resort to Salinas River Mouth

Subregion 7 begins just north of the Sanctuary Beach Resort and continues until reaching the Salinas River Mouth. (Figure 5) This area includes wide dunes with very limited coastal development. Erosion rates in this Subregion are the some of the highest in Southern Monterey Bay and have increased significantly in the last twenty years presumably as the result of the significantly increased sand mining at the CEMEX site over this period of time (see Section 4.2.1).

The CEMEX sand mining operation is located on a 400-acre property along the Marina coast about a half-mile up coast from Reservation Road within this Subregion. This site has been actively mined since 1906, and does not have (nor is required to have) permits from the County of Monterey, City of Marina, California Coastal Commission, or the State of California. A reclamation plan was developed for the site, as required by the California Surface Mining and Reclamation Act of 1975. This plan was finalized in the early 1990's, and the reclamation program has been under the supervision of City of Marina since then. However, jurisdiction is currently being transferred to the State of California. Of the 400-acres on the property, 104 acres are disturbed by current mining operations. In the 1991 Reclamation Plan EIR, the previous owner estimated that mining operations at the site would continue for 50 years. After the site is

sufficiently mined, the parcel will be available for other coastal dependent or visitor-serving uses as allowed by the Marina Coastal Zone Land Use Plan.

Currently there are no proposals for future developments on the west side of Highway 1 in Marina; however there are two vacant parcels on the east side of the highway. There is the potential for 78.35-acres of the CEMEX property to be developed in the future; but this will not likely occur until after 2020. Potential future uses include a coastal resort hotel or RV park. While existing zoning regulations would set a maximum limit of 1,200 units for resort development of the site, with average unit size of 700sq. ft., the limited availability of information about the specific characteristics of the site render it virtually impossible to know whether any (and if so, what type of) development of the site is feasible under existing laws.

Critical Erosion Sites Included:
CEMEX sand mining operation.

Assessors Summary:
This area is about 15,144 feet long, with 12 parcels. The total value of near oceanfront property (from the Assessors data) is \$18,125,312 with average values of \$1,510,442 per parcel and \$1,197 per foot of shore. This translates to \$3,927,165/km.

2.2.7.1 Subregion 7 - Recommended Actions

Immediate, Short, Medium, Long term

- Rolling Easements
- Conservation Easements particularly on the 5 acre CEMEX property
- Cessation of Sand Mining
- Managed Retreat/Relocation of any threatened structures
- Transfer of development credits
- Other measures not analyzed in the report
 - o Application of any sand mitigation fees to Sand Bank
- Fee Simple Acquisition of Sand Mine

2.2.8 Subregion 8 – Salinas River Mouth to Moss Landing

Subregion 8 extends from the Salinas River Mouth north to the south jetty of Moss Landing Harbor (Figure 6). This Subregion was identified in the CRSMP as a stable to an accretional Subregion (i.e. not eroding). This Subregion is characterized by a dune backed shore with a backdune wetland complex created by the remnants of the Salinas River when it used to flow unconstrained and meet the ocean north of Moss Landing.

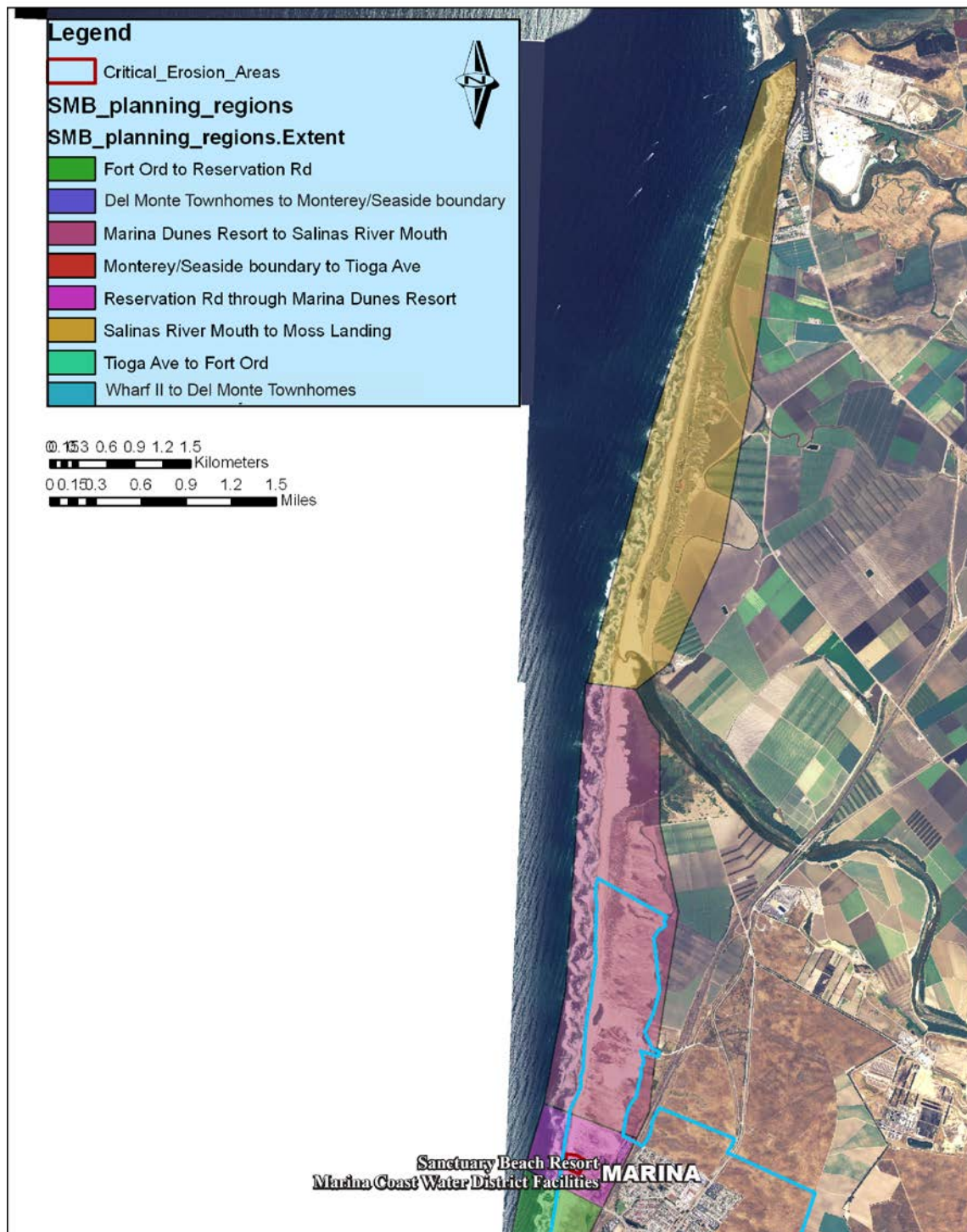


Figure 6 Subregion 8

Critical Erosion Sites Included:

No sites were identified although the Monterey Bay Aquarium Research Institute (MBARI) is located very near the active beach and could become threatened over time, especially as sea level rises and erosion accelerates.

2.2.8.1 Subregion 8 - Recommended Actions

Immediate term

- Implement land use planning measures (1. Rolling Easements; 2. Conservation Easements 3. Fee Simple Acquisition of threatened structures with a hybrid lease back option for structures that are still suitable for habitation until they cease to be safe.; 4. Fee Simple Acquisition)
- Conservation Easement acquisition on developable parcels
- Cessation of Sand Mining
- Managed Retreat/Relocation of any threatened structures

Short term to Long term

- Structural adaptation of any proposed structures including mobile construction

2.3 ADDITIONAL RECOMMENDED STUDIES

2.3.1 Conduct Planning Scale Sea Level Rise Coastal Hazard and Vulnerability Study

Evaluate future erosion hazard zones at a planning level considering sea level rise and climate change. Integrate both the erosion and flood hazards to predict medium to long term impacts. Improve existing erosion hazard zone calculations using specific data sets on erosion rates, and seasonal variability in beach morphology. Provide initial assessment of uncertainty by aggregating multiple scenarios to identify relative risk of various areas. Include tsunami risk mapping. Identify vulnerable infrastructure in revised hazard zones.

2.3.2 Improve Real Estate Database

Fact check and update current Assessors database with updated property values, ownership (public vs. private), structural improvements and zoning to improve planning level vulnerability assessment and provide more robust level planning data.

2.3.3 Improve Cost/Benefit Analysis

Incorporate results from the SLR studies, the improved real estate database and monitoring data (Sections 2.3.1, 2.3.2, and Appendix 2) into the present study cost benefit modeling and improve assessment of recreational benefits, and ecological costs and benefits into the future.

2.3.4 Evaluate Potential Interim Storm Protection Measures

It is recommended that a study be conducted to evaluate some potential interim storm protection measures (e.g. geotextile sand bags (Figure 7), etc.). Other potential options to evaluate could be the use of sacrificial timber bulkheads as an interim storm event protection (>5+years).

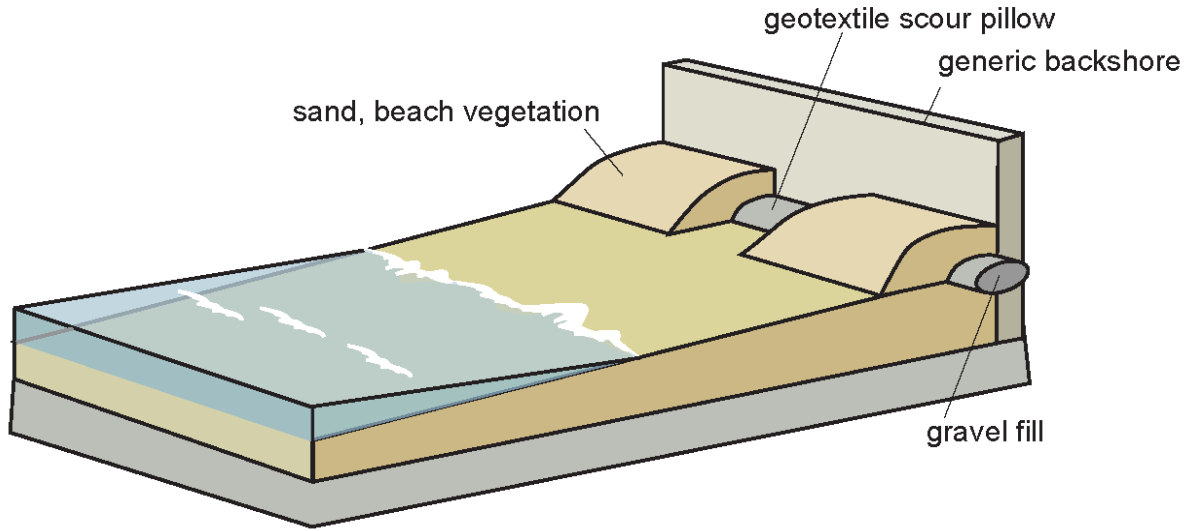


Figure 7 Conceptual temporary erosion mitigation device e.g. geotextile sand bag (also known as “geotextile scour pillow”)

2.3.5 Recreational User Study

Conduct baseline research and data collection on recreational uses in southern Monterey Bay including: subtidal, intertidal, dry sand, and dune to undeveloped lands. This could include a combination of online and site surveys, as well as video camera analytics to systematically document the number of recreational users.

2.3.6 Ecological Evaluation

Conduct comprehensive baseline surveys of the biota of beach and dune habitats of SMB.

Develop and conduct biotic monitoring programs that can be used to evaluate ecological responses to and impacts of different erosion control strategies as they are implemented in SMB (see Appendix 2 for more information on monitoring)

2.3.7 Cessation of Sand Mining from the Beach

This is a regional shore management issue that requires further attention (see Section 2.1 Regional Recommendations). We recommend additional legal research into the costs and means of implementing this recommendation. A first step may include a formal discussion with the sand miners to evaluate their interests and possible cooperative actions such as clarification of linkages between mining and erosion, alternative sand sources, and a cost – benefit analysis of the alternatives to present operations including cessation that come out of that formal discussion. Other means to implement this which have been identified include:

- Regulatory injunction
- 3rd party lawsuit
- Fee Simple Acquisition

3. METHODOLOGY

3.1 STANDARD SCALES AND ASSUMPTIONS

To assess the erosion mitigation measures and evaluate their effectiveness over various time scales, some standardizing assumptions about the appropriate planning horizons, spatial scales, climate change, and coastal management decisions, were made to facilitate the analysis. In addition, the evaluation criteria were refined following discussions with the SMBCEW.

3.1.1 Time Frames and Horizons

For this project, we attempt to assess the effectiveness of each mitigation measure over a variety of time frames. This enables results and mitigation measures to be identified for the planning horizon of interest, but with consideration of long term effects that will begin to identify appropriate adaptation strategies and options to enhance community resiliency to climate changes in the future:

- Immediate 0-5 years
- Short 6-25 years
- Medium 26-50 years
- Long 51-100 years

3.1.2 Spatial

The overall spatial scale is the regional littoral cell scale. However, recommendations will be made at a Subregional spatial scale to address critical erosion areas and identify appropriate strategies by time horizon. The Subregional alternatives must be considered together to ensure consistency and compatibility over the littoral (regional) scale. Cost estimating is done on a \$/km value to be applicable at a greater than parcel scale level.

3.1.3 Climate Change

The use of historical erosion rates implicitly ignores the effects of climate change and acceleration of sea level rise which are expected to increase erosion rates. For the purposes of this study, we recommend future work adopt the sea level rise scenarios from the California Climate Adaptation Strategy of 16 inches by 2050 and 55 inches by 2100 (CNRA, 2009). Sea level rise will likely increase erosion rates (PWA, 2009). The higher erosion rates will exacerbate previously identified critical erosion areas, making these sites more vulnerable to erosion and flooding impacts sooner, and potentially exposing new areas to flooding and erosion.

Recent climate change research indicates changes in wave climate, precipitation and sediment transport are possible but the changes are less certain than sea level rise (Allan and Komar 2006, Adams et al., 2008, Ruggiero, 2010). In this study, we implicitly assume that there will be no changes to either the long term sediment budget or wave climate by extrapolating historical erosion rates. Sea level rise is not addressed. In discussions with the SMBCEW it was decided that since a source of funding could not be

identified to address sea level rise in a timely manner for this study, it would best be considered in a subsequent study along with adjustments for expected future sand mining rates.

3.2 EVALUATION CRITERIA

To standardize the evaluation of each alternative so that they can be compared systematically, we applied several standardized criteria. Most of the criteria are based on previous efforts by the SMBCEW, with several new criteria added to provide a more thorough assessment of impacts, costs, and effectiveness. Criteria are categorized as Technical and Impacts, as follows:

Technical

- Effectiveness – reducing threat to upland
- Effectiveness – maintaining beach width
- Resiliency – adaptable to future conditions
- Certainty of success – scientific certainty that measure will function as intended

Impacts

- Environmental
- Recreation
- Safety/Access
- Aesthetics
- Cumulative – if all oceanfront parcels received treatment

3.3 EROSION MITIGATION MEASURES

The erosion mitigation measures have been divided into the following categories of tools: Land Use Planning, Non-Structural, Structural and Other. In general, the measures can be categorized as measures which avoid the risk to coastal hazards, measures that improve or enhance sand supply, and measures that hold the line in a fixed location. Managed Retreat in its broader context can include all alternatives, including hard armoring that is temporary, beach nourishment, development setbacks, etc. Here, Managed Retreat is treated as a local erosion hazard mitigation alternative that could be labeled Relocation.

Following consultations with the SMBCEW, the laundry list of alternative erosion mitigation measures was reevaluated based on new information and subsequent work completed during the RSM process. This led to the addition of several alternatives back to the list. In addition, Low Crested Structures were added to the list, as these represent new management approaches being tested in the European Union.

The following alternatives were evaluated for this project:

Land Use Planning Measures

- Managed Retreat (Relocation / Removal)
- Transfer of development credit
- Fee Simple Acquisition

- Rolling Easements
- Conservation Easements
- Present use tax incentive
- Structural Adaptation
- Habitat Adaptation
- Setbacks for Bluff-top Development
- Setbacks + Elevation for Beach Level Development

Non structural Measures

- Sand Mining cessation
- Opportunistic Sand Placement / Nourishment
- Beach Dewatering
 - o Active
 - o Passive
- Nourishment (evaluated in CRSMP and comparative benchmark for the Cost/Benefit Analysis)
 - o Beach Nourishment
 - o Nearshore Placement
 - o Beach Placement
 - o Dredge Sand from Deep or Offshore Deposits
 - o Dune Nourishment (adding both sand and vegetation)
 - o Potentially add ecological impacts/benefits of nourishment

Structural Measures

- Seawalls/Revetments
- Groins (including geotextiles)
- Emergent Breakwaters
- Artificial Reefs / Submergent Breakwaters / Low Crested Structures
- Perched Beaches
- Low Crested Structures

Measures that reduce factors which exacerbate erosion

- Native Plants
- Sand Fencing / Dune Guard Fencing
- Controlling Surface Run-off
- Controlling Groundwater
- Berms / Beach Scraping

3.3.1 Land Use Planning Measures

The approaches in this category primarily focus on allowing the natural coastal processes to operate unimpeded. These issues include Managed Retreat (relocation / removal), Rolling Easements, Conservation Easements, Transfer of Development Credits, Present Use Taxes, Fee Simple Acquisition, Structural Adaptation, or Setbacks.

In general, these mitigation measures have higher initial costs, long implementation timelines and high benefits. Some have limited application due to shortage of undeveloped parcels, and some simply put the problem off to a later date or the next generation.

3.3.2 Non Structural Measures

The alternatives in this category tend to be focused either on enhancing sediment supply and accretion processes, or reducing sediment losses. These alternatives include: cessation of sand mining, large scale sand placement, implementation of an opportunistic sand use program, and beach dewatering.

Implementing mechanisms for these types of alternatives will likely require the involvement of a regional planning entity (AMBAG coordinated with various jurisdictions and their respective departments – planning, public works, flood control, etc. Some of the tools here though are more site-specific and so will follow a more traditional local permitting process). In general, these measures replace eroded sand frequently and repeatedly. Cessation of sand mining is a special case that could be characterized as a Land Use Planning Measure as well as a Regional Strategy.

3.3.3 Structural Measures

Approaches that fall into this category involve the design and construction of structures to protect the coastline. These alternatives include: seawalls, revetments, groins, breakwaters, perched beaches, low crested structures and artificial reefs. While the stated objective of the SMBCEW is to avoid coastal armoring structures, because of the potential impacts to the beach and coastal recreation and habitats, several of the other structural engineering alternatives may also protect the beach and so are discussed in more detail.

Implementing these strategies will likely follow a relatively traditional permitting process involving the local permitting agencies, California Coastal Commission, California State Lands Commission, and for those located below Mean High Water (MHW) the Monterey Bay National Marine Sanctuary and the U.S. Army Corps of Engineers (USACE).

3.4 **TAKINGS CLAIM ANALYSIS**

Some of the hurdles to implementing some of the land use planning tools stem from the perception by local jurisdictions that a private property takings claim and resulting lawsuit could occur as a result of implementing certain measures. Based on conversations with SMBCEW, and local planning staff it was recognized that a brief analysis of regulatory takings was an important component of this study. As part of the analysis, five hypothetical case studies in the SMB region were selected representing a range of likely types of potential takings claims. These case studies and legal insights provide an initial discussion of considerations as they may arise during implementation of the land use planning mechanisms. This discussion is not to be used in lieu of legal counsel.

This approach to this work is outlined below:

- Review of takings, public trust, and key cases
- Assessment of the following Planning Tools:
 - Managed retreat
 - Setbacks
 - Rolling Easements
 - Conservation Easement
 - Transfer of Development Credits
- Assessment of five case studies based on different conditions:
 - Multiple unit pre-Coastal Act
 - Post Coastal Act – no seawalls condition of Coastal Development Permit
 - Undeveloped
- Assessment of each measure for comparison

3.5 COST BENEFIT ANALYSIS

Following the initial evaluation of erosion mitigation measures, SMBCEW requested a more robust cost benefit analysis of erosion management measures. In response, a quantified cost benefit analysis methodology was developed based on a simplified conceptual model of beach width and associated benefits, and the costs of beach and upland erosion. The cost benefit analysis included:

- A beach width index that changed over time and in response to each measure
- An initial assessment of ecosystem services in dollars linked to beach width
- An initial assessment of recreational benefits in dollars

Discussions with the SMBCEW helped to narrow the range of measures analyzed in detail under this cost benefit analysis and additional funds were provided by the MBNMS to support the improvements. The SMBCEW selected the following alternatives for more detailed cost benefit analysis:

- Managed Retreat (relocation / removal)
- Transfer of Development Credit
- Rolling Easements
- Conservation Easements
- Fee Simple Acquisition
- Structural Adaptation
- Setbacks (combined)
- Sand Mining
- Beach Nourishment (large scale nourishment in RSM)
- Revetments and Seawalls (as a benchmark)
- Groins
- Breakwaters
- Artificial Reefs

The SMBCEW decided to drop the following alternatives from the detailed cost benefit analysis:

- Dewatering Active (due to lack of scientific certainty and cost information)
- Dewatering Passive (due to lack of scientific certainty and cost information)
- Present Use Tax (due to lack of ability to mitigate erosion)
- Habitat Adaptation (due to lack of ability to mitigate erosion)
- Beach Dewatering – Desalination (due to lack of scientific certainty and cost information)
- Perched Beaches (due to lack of scientific certainty and cost information)
- Opportunistic beach nourishment (small nourishment in RSM due to lack of ability to mitigate erosion across an entire Subregion)

3.5.1 Cost-Benefit Analysis Methodology

The goal of the cost-benefit analysis was to set up a more holistic accounting scheme that includes ecosystem services (ecological, recreational, and storm damage reduction benefits) of the natural shore in addition to the costs and benefits traditionally considered (construction costs and benefits to private property and infrastructure services). The analysis extends over time, and considers site-specific characteristics of each Subregion, in order to inform planning decisions based on local conditions but also to facilitate a regional aggregation. The physical aspect of the methodology is illustrated conceptually in Figure 8 and the site specific characteristics are shown in Figure 9. We attempted to evaluate a quantitative cost benefit for specific erosion mitigation measures over the planning horizons.

We have developed a framework to account for the Costs and Benefits of the erosion mitigation measures over the various planning horizons 5, 25, 50, and 100 years. Our approach tracks various beach zone widths over time in response to the physical changes caused by coastal erosion that would occur under each mitigation measure. The underlying assumption is that the beach zone widths relate to ecosystem services, recreation and storm damage reduction benefits. Thus for each time step, the method tracks changes in beach widths and the resulting effect on recreational, ecological, and property damages. These beach zone width zones used in the analysis are shown in Figure 8, which illustrates the impacts of a revetment on the beach system over time. For each zone and time horizon we attempt to account for changes in values as a result of changes in widths resulting from erosion and construction. To account for the range of physical beach and coastal processes conditions in SMB we have relied on physical widths from 3 representative profiles along Del Monte Ave, Sand City, and Marina (Figures 10, 11, and 12). During this accounting process we attempted to identify projected changes in the physical widths through time as a result of each erosion mitigation measure.

The first step was to designate and define various widths or zones across a nearshore profile. Beginning offshore of Mean Lower Low Water (MLLW) is the surf zone recreational area or subtidal habitat area. Between MLLW and Mean High Water (MHW) is the intertidal recreation and habitat zone. Above MHW to the toe of the dune is the dry sand beach recreation and habitat zone. From the base of the dune to the inland extent of development is considered upland undeveloped or habitat zone. The final zone is from the ocean side line of development inland and is referred to as the developed width (Figure 8). It should be noted that these zone designations are generalized and do not entirely account for the complexity of the sandy beach ecosystem.

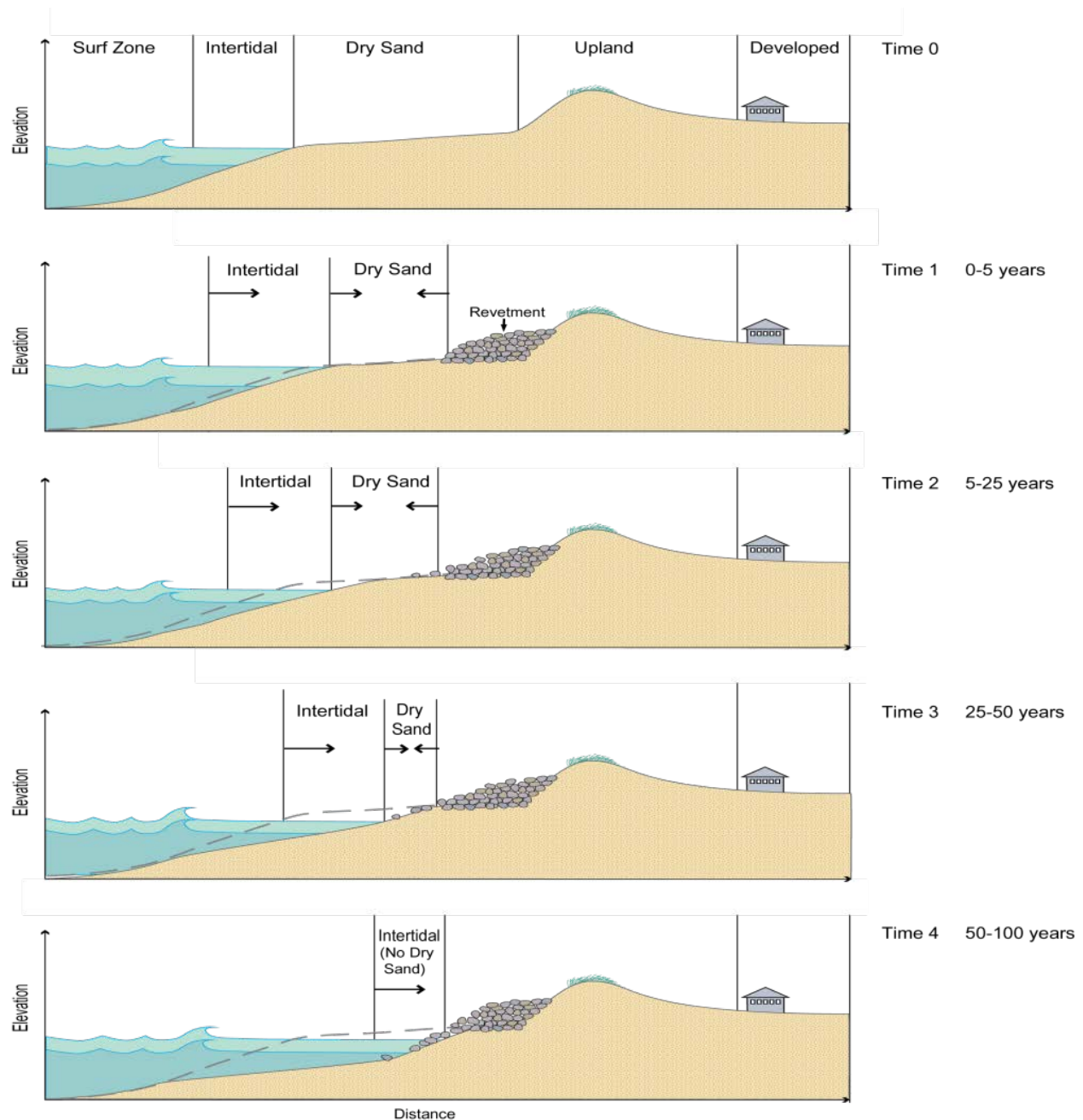


Figure 8 Conceptual Model of Accounting for changes to physical, ecological and recreational environments through time using the example of a revetment (baseline condition)

3.5.2 Cost-Benefit Analysis Assumptions

Assumptions were made for some parameters that were required for the analysis but were uncertain or unknown. In many cases, less than optimal data exists to conduct a complete and robust cost/benefit analysis. The authors of this report have conducted due diligence to understand the physical, ecological, and recreational information necessary to apply such a model, however, there remain outstanding gaps in our knowledge and metrics of human and ecological use of Southern Monterey Bay. To complete the assessment several assumptions were made by the authors, as agreed by the SMBCEW, based on

professional judgment, observations and experiences in Southern Monterey Bay and other places in California. These assumptions include the following:

- Analyses assume that physical changes in dry sand beach widths are related to changes in ecological function
- Analyses assume that physical changes in dry sand beach width are related to changes in recreational value
- *Managed Retreat and Structural Adaptation* measures assume that erosion processes would continue unimpeded
- *Setbacks* assume that erosion would continue until upland undeveloped within 20' of development then revetment is placed
- *Opportunistic Sand Placement (SCOUP)* – the smaller nourishment described in the CRSMP (~75,000 cubic yards) would add three feet of beach width every 5 years (for the Del Monte subcell)
- *Revetments and Seawalls* – Includes placement losses which reduce beach width at time of construction. Includes active erosion effects which accelerate beach loss when beach width narrows and wave run-up frequently reaches structure.
- *Beach Nourishment* – the large nourishment alternative described in the CRSMP (~2 million cubic yards on beaches in Monterey, Seaside and Sand City) would widen the beach by 100 feet every 25 years. *Groins, Artificial Reefs, Breakwaters* –Coastal engineering structures would be used in conjunction with the large beach nourishment alternative as a sand retention structure. The retention structures would essentially slow the rate of sand transport away from the nourishment area, thereby slowing the rate of beach width reduction. This effect is modeled as a reduction in width loss, using the concept of sand diffusion. Offshore emergent breakwaters are considered the most effective because wave sheltering and diffraction reduces sand transport directly. Artificial reefs or submerged breakwaters are considered less effective than emergent breakwaters because the wave sheltering is reduced by the lower crest height, which allows wave overtopping. Groins are considered the least effective because wave climate would not be reduced and rip current formation would cause offshore transport, bypassing and edge effects.
- All *Managed Retreat and Structural Adaptation* measures assume that erosion processes continue unimpeded and therefore have no ecological impacts
- With the *Transfer of Development Credit* measure, we assume that the value of the “receiver” site and its use is similar to the shore parcel that development credit is transferred from *Rolling Easements* assumes that there would be no public cost to acquire the easement and that the natural erosion process would continue unimpeded.
- *Conservation Easements* assumes that there would be some public cost to acquire the easement. This cost is selected to be 50% of fair market value. This cost is only applied to private property (e.g. not State Parks).
- *Fee Simple Acquisition* assumes that there a public purchase to acquire the property at fair market value
- *Structural Adaptation - Setbacks + Elevation for Beach Level Development* this also assumes that erosion processes would continue unimpeded. Cost estimates range from \$200-\$500 per square

foot with the smaller cost associated with smaller dwellings in the larger cost associated with large infrastructure such as Highway 1

- *Setbacks for Dune-top Development* assume that erosion would continue until upland undeveloped reaches within 15' of development then a revetment is placed. Placement loss would occur and ecological damages follow a linear decline corresponding to dry sand beach loss.
- *Cease Sand Mining* assumes that erosion rates are reduced by 60% (See Section 4.2.1; Figure 25). Cost varies from Fee Simple Acquisition at fair market value to a regulatory injunction at no public cost.

3.6 COST ESTIMATING

This section describes the construction cost estimating used for the cost benefit analysis (Sections 3.6.1 and 3.6.2). The estimated costs resulting from damages to the coastal sewer system are described in Section 3.6.3 and Appendix 3. Additional Information about the estimates is provided in Section 3.6.4.

3.6.1 Initial Estimates

PWA investigated the costs of structural measures to mitigate erosion in southern Monterey Bay. Construction costs were estimated per kilometer of shore as agreed upon with the SMBCEW. The Sand City Erosion Study⁵ provided estimates for confinement structures to enhance beach nourishment (breakwaters and groins), as well as seawalls and revetments. These costs were escalated using construction cost index data published by the Engineering News Record. The Coastal Regional Sediment Management Plan⁶ for the study area provides a conceptual description of large-scale beach nourishment consisting of about two million cubic yards deposited over a 3 to 4 mile section (southern most, Monterey through Sand City). This report also includes a description of a smaller nourishment volume characterized as “opportunistic” beneficial reuse of sand excavated for other purposes. A 75,000 cubic yard volume from the Monterey Marina Dredging project was used, but other inland sources of similar scale are also represented by this SCoup measure. PWA also contacted design firms to inquire about the costs of revetments, seawalls and artificial reefs, and reviewed available construction costs from recent projects. These other firms consulted included Haro Kucinich, Power Engineering, and ASR, Ltd.

The above data were reviewed and a range of costs were obtained. From the range, it was concluded that the range of costs was largely affected by location (exposure and erosion rate) and likely structure life. For the purposes of this study, a single representative value for each measure was desired. Values were selected using judgment assuming a 25 year structure life with no maintenance. After 25 years each structure was rebuilt at the previous cost of construction, using 2010 dollars (See Table 2). The following costs were selected:

⁵ Battalio & Everts, 1990, Moffatt & Nichol Engineers, Sand City Erosion Study.

⁶ PWA, 2008, Coastal regional Sediment Management Plan for southern Monterey Bay.

Table 2 Generalized Construction Cost Estimates

Item	Cost (\$/ foot or \$/sf)	Cost (\$M/ km)
Rock revetment	\$4,500	\$15
Seawall	\$5,900	\$20
Groins (with sand placement)	\$8,000	\$26
Reefs (with sand placement)	\$12,000	\$39
Breakwaters (with sand placement)	\$12,000	\$39
Sand Placement Large (about 2,000,000 cy)	-	\$3.3
Sand Placement Opportunistic (about 75,000 cy)	-	\$0.4
Structure Underpinning	\$200 / sf	-
Bridge / trestle to elevate roadway	\$500 / sf	-

A review of the estimated costs including a comparison with the prior Sand City Shore Erosion Study, led PWA to present the following opinions to the SMBCEW:

1. The estimates are concept level and very approximate. These should be considered more applicable in terms of relative costs per kilometer and not used for budgeting.
2. The beach nourishment costs may be under estimated.
3. Seawalls have become relatively less expensive over last few decades
4. It is difficult to estimate breakwaters and reefs although experts in reef design and construction were consulted (ASR, Ltd)
5. Actual costs are site and time specific, and depend on design criteria.

3.6.2 Revisions Based on August 5, 2010 SMBCEW Meeting:

PWA and team presented the first draft estimates and benefit / cost analyses to the SMBCEW for their consideration and comment. Estimates were revised based on our interpretation of the discussion and comments received. Revisions consist of a range rather than a single estimate. If the original estimate was considered high, a lower value was estimated and vice versa. The following Table 3 summarizes the results.

Table 3 Revised Generalized Construction Cost Estimates

Item	Cost (\$M/km)		Description of Changes
	Low	High	
Rock Revetment	\$15	\$18	Estimated high range by increasing low estimate by 50%.
Seawall	\$20	\$33	Estimated high range using Ocean Harbor House costs of about \$8M for 800 lineal feet of seawall ¹ which is \$10,000 / lf.
Groins (with sand placement)	\$17	\$26	Established low estimate as 67% of high estimate (so high estimate is about 50% higher than low estimate).
Reefs (with sand placement)	\$26	\$39	Established low estimate as 67% of high estimate (so high estimate is about 50% higher than low estimate).
Breakwaters (with sand placement)	\$26	\$39	Established low estimate as 67% of high estimate (so high estimate is about 50% higher than low estimate).
Sand Placement Large (about 2,000,000 cy)	\$3.3	\$5.0	Estimated high range by increasing low estimate by 50%.
Sand Placement Opportunistic (about 75,000 cy)	\$0.4	\$0.8	Estimated high range using trucking instead of marina hydraulic dredging. Used \$32/cubic yard, including mobilization and environmental costs. This compares to about \$27/cy discussed in 2005 for Ocean Harbor House sand mitigation fee ² .

¹ SMBCEW verbal comments at August 5 2010 meeting. Approximate value.

² California Coastal Commission staff report "Revised Findings for Coastal Development Permit" OHH-Th13a-1-2005, January 13 2005 hearing date for Ocean Harbor House shore protection and sand mitigation fee, etc.

Given that the level of funding for the project prevents detailed cost estimates, a range of values will be used to convey the sensitivity of the benefit cost evaluation to construction costs for structural measures. We defined the high cost as 50% higher than the low cost, which means that the low cost is about 67% of the high cost. Based on the comments from the SMBCEW, we assigned the original estimates as either low or high.

The SMBCEW indicated that the seawall costs seemed low, and recommended that the Ocean Harbor House seawall costs be considered as a recent relevant example: The Ocean Harbor House seawall costs were much higher. The City of Monterey indicated that they thought the hybrid alternatives (groins, reefs, breakwaters with sand) would cost less in the southern portion of the Bay because of the lower wave climate and erosion rates: This observation was generally supported. Several coastal engineers expressed doubts that the beach nourishment alternatives would remain functional for 25 years, and therefore the cost might be low: The shore modeling accomplished for this study and the prior regional sediment management plan indicates a widened beach life of closer to 20 years. Also, maintaining a net wider beach (minimum width) to mitigate storm damages may be a design objective. Therefore, the original beach nourishment estimate was assigned the "low" value and a higher estimate increased by 50% was established. Similarly, the opportunistic sand placement was based on Monterey Harbor dredging and was

considered to cost less than typical trucking options. An increased estimate based on land-based sand supply and a cost of about \$32 per cubic yard provided a high value that was roughly twice the low value.

3.6.3 Sanitary Sewer Transmission Damage Costs

The Monterey Peninsula Water Pollution Control Agency (MRWPCA) provided estimated replacement and failure costs for their sanitary sewer facilities along the shore. Additional information about the estimates is provided in Appendix 3: MRWPCA Costs. PWA used prior studies to identify when each component of the MRWPCA facilities would be impacted, triggering a cost^{7,8}. The selected threshold was a minimum protective summer / fall beach width of 65 feet, in order to provide an adequate buffer for winter conditions and severe erosion due to storms. A single width was selected for simplicity although different widths could be selected for each facility based on damage mode and location.

3.6.4 Additional Information about Cost Estimates

The information provided herein was developed to provide a standard basis for comparison between different shore erosion mitigation measures for the benefit of coastal zone management discussions. The information provided herein is neither intended nor authorized for any other use and should not be used for any purpose without prior written approval by PWA.

For planning purposes we have provided order of magnitude estimates to allow comparison of alternative erosion mitigation measures. These estimates are intended to provide an approximation of shore erosion, benefits and costs appropriate for the conceptual level alternatives comparison.

These estimates do not explicitly include consideration of all possible costs, such as design, environmental review, permitting, construction administration, monitoring, property purchase and other costs. In particular, significant costs can be expected for sand mitigation fees for coastal armoring projects. Please note that in providing opinions of probable costs, ESA PWA has no control over the actual costs at the time of construction. The actual cost of construction may be impacted by the availability of construction equipment and crews and fluctuation of supply prices at the time the work is bid. ESA PWA makes no warranty, expressed or implied, as to the accuracy of such opinions as compared to bids or actual costs.

These estimates do not consider all possible benefits and costs including indirect, consequential, aesthetic, and community health and well-being. Estimation of benefits is less certain than construction costs. Higher confidence is afforded recreational economics, while ecological values are inherently uncertain. PWA makes no warranty, expressed or implied, as to the accuracy of opinions of erosion rates. In particular, the erosion rates are not consistent with existing guidance on sea level rise which would tend to increase the rates of erosion.

⁷ Op cit.

⁸ PWA, 2004; Southern Monterey Bay Coastal Erosion Study, Memorandum to Robert Jaques, PE, PWA, Ref. # 1729, Nov. 24, 2004.

3.7 PHYSICAL CHANGES TO NEARSHORE WIDTHS

The second part of the cost/benefit analysis was to estimate future changes to the widths of the beaches and uplands of southern Monterey Bay for each of the prioritized erosion mitigation measures. To conduct the cost-benefit analysis we subdivided the littoral cell into three shoreline reaches based on similarity in erosion rates and jurisdictional boundaries (Figure 9). We assigned initial widths to each of the nearshore zones based on historic beach profile envelopes (Figures 10-12). The same erosion rates for SMB beaches that were identified in the CRSMP were used for this analysis.

For the Del Monte reach, we assumed the erosion rate was about -1.5 feet per year, with initial dry sand beach widths of 118 feet, and an upland total on average of 200 feet divided into undeveloped upland on average about 100 feet, and developed upland about 100 feet. The typical shore profile used to represent this reach is shown in Figure 10.

For the Sand City reach, we assumed the erosion rate was about -3.0 feet per year, with initial dry sand beach widths of 110 feet, and an upland total on average of 200 feet divided into undeveloped upland on average about 90 feet, and developed upland about 110 feet. The typical shore profile used to represent this reach is shown in Figure 11.

For the Marina reach, we assumed the erosion rate was about -4.5 feet per year, with initial dry sand beach widths of 127 feet, and an upland total on average of 275 feet divided into undeveloped upland on average about 75 feet, and developed upland about 200 feet. The typical shore profile used to represent this reach is shown in Figure 12.

The beach profiles shown in Figures 10 – 12 are cross-sections of the shore, and are considered representative of each reach. These beach profiles are based on field data collected over the last several decades under the direction of Dr. Ed Thornton.



Figure 9 Cost Benefit Reaches of Analysis

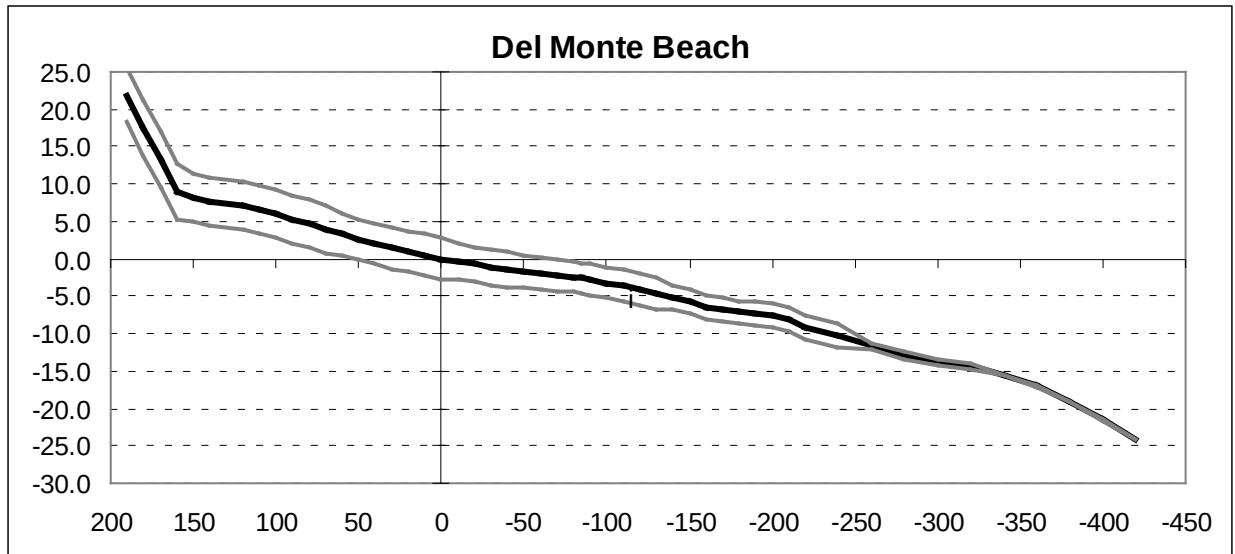


Figure 10 Del Monte Beach historic beach profile envelope (source Ed Thornton, unpublished data)

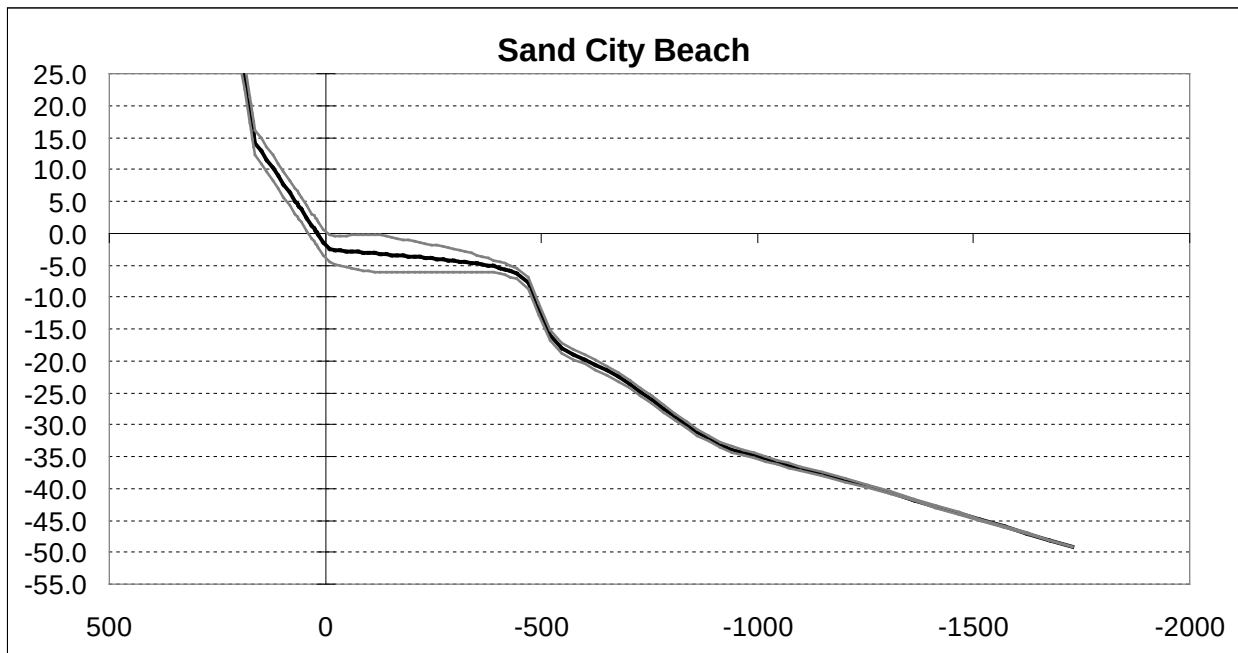


Figure 11 Sand City historic beach profile envelope (source Ed Thornton, unpublished data)

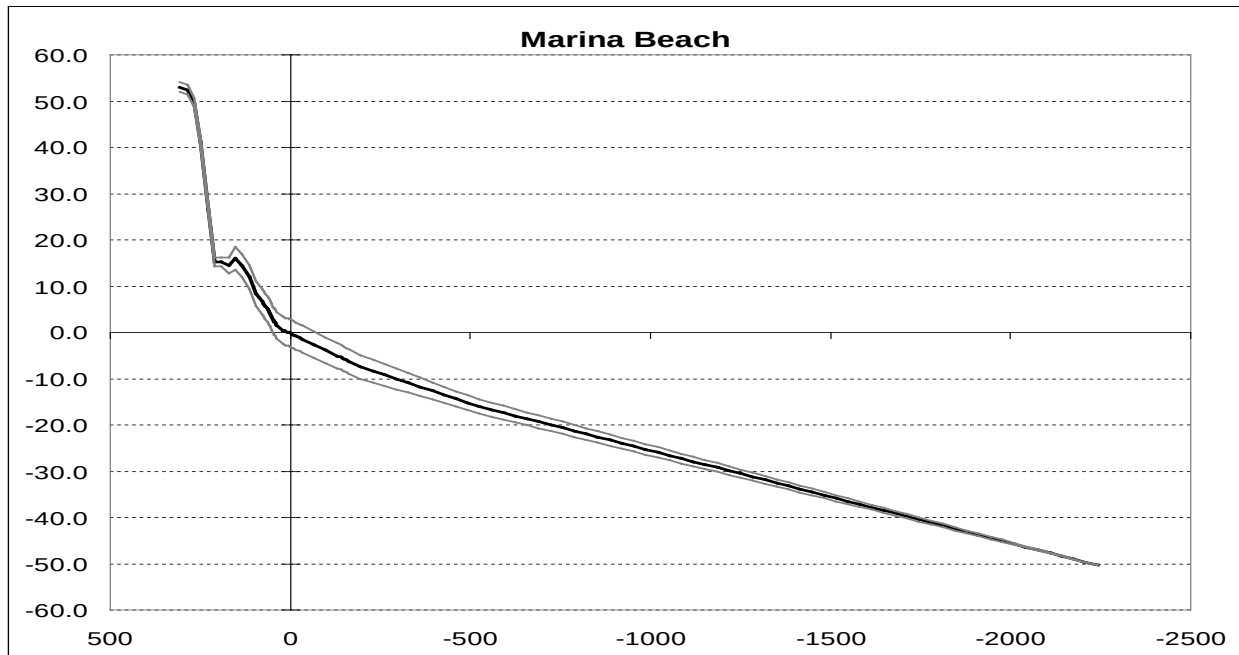


Figure 12 Marina historic beach profile envelope (source Ed Thornton, unpublished data)

3.8 SANDY SHORE ECOSYSTEM SERVICES

Ecosystem services are the benefits to humankind that arise from an intact and healthily functioning ecosystem. Obvious examples of various ecosystem services include production of oxygen, food production, water purification, protection from storms, or nutrient recycling. Unfortunately, it is difficult to put a “price tag” on these services and there is limited information about these benefits for sandy beaches or how to properly measure them. However due to the clear importance of the benefits that a healthy beach system can provide, it makes no sense to completely ignore ecosystem benefits in the assessment, as is often the case. In this cost/benefit analysis we attempt to incorporate an initial assessment of the ecological values of the sandy shores in SMB. This section discusses ecological function of sandy shores, focused on beaches. Section 3.9, The Economic Value of Beaches and the Coastal Zone, addresses the economic valuation of the ecosystem services.

For simplicity, we have focused primarily on beaches and dunes as the proxy for sandy shore ecological function. This is a significant simplification that is likely to lead to under-estimation of services, under-representation of impacts, and hence adds method uncertainty and bias to the analysis. However, this analysis is relatively less biased than prior analyses, and is a first step toward multi-objective shore management. A more complete description of the shore ecology of southern Monterey Bay is provided in the Coastal Regional Sediment Management Plan (PWA et al., 2008), including subtidal and terrestrial habitats.

Sandy beach and dune ecosystems exist at the narrow dynamic boundary of land and sea. Composed of unconsolidated sand from watersheds and coastal bluffs that is constantly shaped by wind, waves and tides, they are strongly influenced by marine and terrestrial processes. Although often under-appreciated,

the irreplaceable biodiversity, and unique ecological functions and resources supported by sandy beach ecosystems are important to consider in coastal management along with their high socio-economic values (Brown & McLachlan 2002, Schlacher et al. 2007). Intrinsic ecological values and functions of beach and dune ecosystems in SMB include: unique vegetation, rich invertebrate communities that are prey for shorebirds, fish and marine mammals, absorption of wave energy, the filtration of large volumes of seawater, nutrient recycling, and critical habitat (nesting and foraging) for declining and endangered wildlife, such as shorebirds and pinnipeds, and for a variety of threatened dune plants (McLachlan & Brown 2006, PWA 2008).

The structure and function of open coast beach ecosystems appear to be closely linked to press and pulse (trend and storm event) environmental drivers and human activities operating on a range of spatial scales (McLachlan & Brown, 2006, Defeo et al., 2009). Along with environmental drivers associated with climate change, evolution in beach and strand geomorphology, sediment dynamics, coastal and watershed perturbations, recreational activity, beach grooming, beach scraping, armoring, nourishment and beach front development have all been shown to affect these coastal ecosystems, the wildlife that depends on them, and the ecosystem function and services they provide.

The ecology of beaches of southern Monterey Bay has been addressed in prior reports such as project-level environmental impact reports. However, beach ecology in this region is not well studied and very little direct information is presently available for use in analysis and consideration of ecological responses to the alternatives presented in this report. Although there is some information on the distribution of limited features of a few threatened species, such as the locations of nests of western snowy plovers, the knowledge sufficient to evaluate impacts of different alternatives is lacking for almost all other groups and taxa, including a number of threatened species of plants and animals. For example, there have been no comprehensive surveys of beach and dune invertebrate communities in southern Monterey Bay. A general overview of California beach ecosystems is presented to provide some context for discussion.

Beach ecosystems provide habitat and resources for a diversity of species, ranging from invertebrates to birds, fish and marine mammals. Interstitial organisms (bacteria, protozoan and meiofauna) inhabit the spaces between sand grains. Larger intertidal invertebrates burrow actively in the sand and include representatives of many phyla, but are usually dominated by crustaceans, molluscs and polychaete worms. These taxa include suspension- and deposit feeders, detritivores, scavengers, and predators which can reach high abundance and biomass, particularly on many intermediate beach types, such as those in southern Monterey Bay. Most beach invertebrate species occur in no other coastal habitats, their unique adaptations for life in these dynamic ecosystems include: high mobility, rapid burrowing ability, rhythmic behaviour, specialized orientation mechanisms and behavioural plasticity (McLachlan & Brown, 2006).

Ecological zonation on exposed sandy beaches is extremely dynamic due to the highly unstable nature of the sandy substrate and the mobility of the intertidal animals and the resources on which these animals depend (McLachlan & Jaramillo, 1995, McLachlan & Brown, 2006). In general, three different intertidal zones inhabited by distinct groups of mobile animals are present on exposed sandy beaches, such as those in SMB (McLachlan & Jaramillo, 1995). These intertidal zones generally correspond to the

- relatively dry sand/substrate of the coastal strand and supralittoral zone at and above the drift line,
- the damp sand of the mid-intertidal and below the water table outcrop, and
- the wet or saturated sand of the lower intertidal and swash zone (Figure 13).

It is important to understand that these zones and the animals associated with them constantly move up and down the shore in response to tides and changing beach conditions. To maintain preferred environmental conditions (e.g. sand moisture, etc.), feeding opportunities and to avoid avian and fish predators and wave impacts, many beach invertebrates of the lower to mid shore migrate in the active swash across most of the intertidal zone with every high and low tide while upper shore invertebrates move over the exposed sand surface to access food resources and follow the high tide driftline up and down the beach. In winter conditions, adequate room to migrate up the shore to avoid storm waves and surges may be a key to the survival of both lower and upper shore invertebrates. Beach erosion and societal responses to erosion that induce changes in the relative proportions and condition of these zones can result in strong ecological responses that propagate up the food web (Dugan & Hubbard, 2006, Dugan et al., 2008).

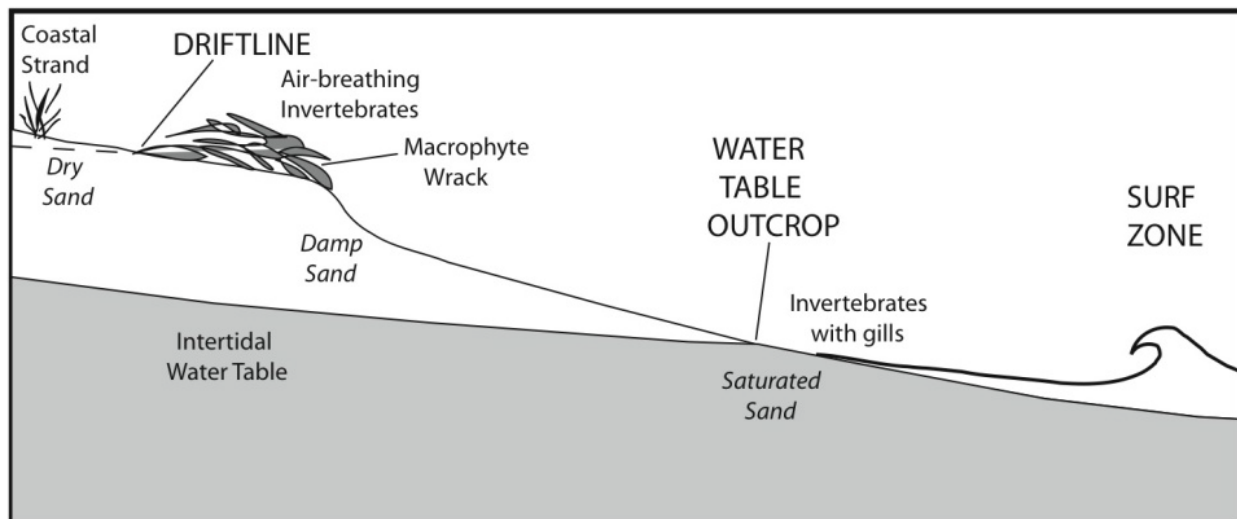


Figure 13 Generalized beach profile illustrating some of the major features of a sandy beach ecosystem

Open coast beaches are characterized by a lack of attached plants and the shifting sands support relatively low *in situ* intertidal primary production. The diverse invertebrates inhabiting California beach ecosystems depend almost entirely upon inputs of organic material from other marine sources, including ocean phytoplankton and macroalgae from coastal reefs (Figure 14). However, intertidal invertebrates can reach very high abundance ($>100,000$ individuals m^{-1} of shore) and biomass (>1000 g m^{-1} of shore) on California beaches, such as those in SMB. Suspension-feeding invertebrates that inhabit the wet lower zones, including sand crabs, clams, and a variety of smaller crustaceans and worms, depend primarily on phytoplankton delivered by the wave wash or swash. Many of these taxa have planktonic larval stages that enable dispersal among beaches and regions. In contrast, the upper shore invertebrates are significantly associated with drift seaweeds or wrack and avoid direct contact with the sea. These unique animals include talitrid amphipods, oniscoid isopods and a variety of insects, including flightless species.

The majority of these taxa have relatively low dispersal abilities, and all have direct development in the adult habitat with no planktonic lifestages. Thus, populations of these upper shore taxa can be particularly limited by distance from source populations and are quite vulnerable to disturbance, and the loss of or fragmentation of beach ecosystems.

Drift algae and seagrasses that are stranded on beaches as macrophyte wrack represent an important link between reef and kelp forests and beach ecosystems, especially in California where almost 40% of the invertebrate species of a beach can be associated with wrack most of which is accumulated at or above the driftline (Figure 14) (Dugan et al. 2003). The availability of dry sand habitat has been shown to affect the accumulation and retention of macrophyte wrack in beach ecosystems and on armored shores (Dugan & Hubbard, 2006, Dugan et al., 2008, Revell et al., 2011a). Beaches with high wrack input can support dense populations of invertebrate consumers in the upper intertidal zones that in turn attract a high diversity and abundance of wintering and migratory shorebirds (Hubbard & Dugan, 2003).

Simple Beach Food Web

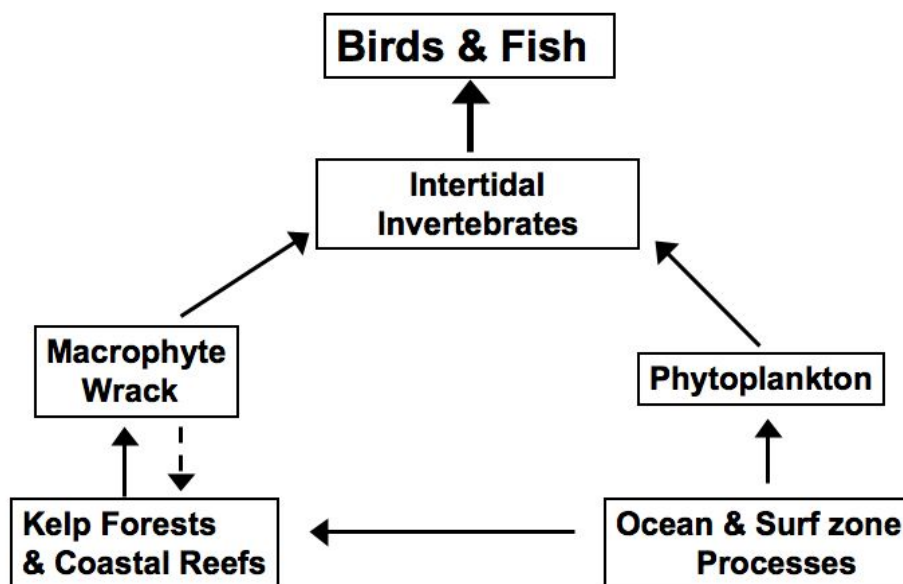


Figure 14 A Simplified Food Web for Southern Monterey Bay Beaches

Upper shore invertebrates are crucial to the important beach ecosystem function of wrack processing and subsequent remineralization (Lastra et al., 2008) providing a nutrient cycling linkage between the nearshore and shore environments (Dugan et al. in press). This important ecosystem service is strongly mediated by upper shore invertebrates that can consume large quantities of freshly delivered drift macrophytes, such as kelp. For example, it was estimated that upper beach invertebrate consumers processed >70% of the annual wrack input (>2 tonnes $\text{m}^{-1} \text{yr}^{-1}$, primarily kelps) on a South African beach (Griffiths et al., 1983). Dense populations of talitrid amphipods (>90,000 individuals. m^{-1}) were estimated to consume almost 20 kg of freshly stranded *Macrocystis pyrifera* $\text{m}^{-1} \text{month}^{-1}$ on a southern California

beach (Lastra et al., 2008). Recent studies have also found significant relationships between levels of dissolved nitrogen in interstitial and surf zone water with the mass of the standing stock of kelp wrack on beaches. This indicates additional water filtration benefits to water quality as a function of upper shore consumers and beach ecosystems in nearshore nutrient cycling (Dugan et al., in press).

Variation and changes in the availability of wrack have been shown to have strong bottom-up effects on beach ecosystems, altering the abundance and composition of the invertebrate community, and consequently the abundance of prey for higher trophic levels, such as shorebirds and fishes (Dugan et al., 2003). Thus, the wildlife support provided by beach ecosystems can be affected by the availability of macrophyte wrack and associated invertebrate prey. Results of recent research suggest that disturbance to wrack supply or availability to upper shore zones rapidly results in strong negative effects on these wrack-dependent invertebrates (Dugan et al., unpublished). However, results indicate that the ecological recovery of this key component of the beach ecosystem can require many months to years, even when wrack supply is abundant.

SMB beaches provide important resources and food web support for wildlife and fish (Figure 14). Shorebird use of beach ecosystems has been positively correlated with the availability of invertebrate prey, the amount and type of macroalgae wrack, beach slope and beach width (Dugan, 1999; Dugan et al., 2003; Neuman et al., 2008) on California beaches, including shores in the study region. The majority of prey biomass available for birds and fish on beaches in SMB is provided by intertidal invertebrates, such as sand crabs (*Emerita analoga*) whose populations can be strongly affected by beach conditions, as well as alteration of ocean currents delivering planktonic larvae. Another major prey resource on beaches in the study region are the intertidal wrack consumers, such as talitrid amphipods (*Megalorchestia* spp.), oniscoid isopods and insects, which are more available to birds during high wave and tide conditions than the lower intertidal beach animals. These populations are also strongly affected by beach conditions as well by the availability and production of drift macroalgae from kelp forests and reefs.

Shores are vital transitional zones linking terrestrial and marine realms (Polis & Hurd, 1996). Connectivity between beach and dune ecosystems facilitates important reciprocal exchanges of materials including sand, groundwater, nutrients, salt spray, organic matter and biota (McLachlan & Brown, 2006). Waves, tides and longshore currents transport sand, organic matter and plant propagules from the sea to the beach/foredune boundary. Winds transport marine sand from the dry beach into the dunefield, creating and modifying dune structure. Below the primary foredune the deposits of marine macrophyte wrack, driftwood and riverine organic matter delivered by waves can create a foundation for the formation of embryo dunes and hummocks and the subsequent colonization of coastal strand vegetation (Dugan & Hubbard, 2010). In SMB, the results of this active process and exchange between beaches and dunes provide the type of scattered cover, sparse vegetation, and open habitat required for successful nesting and chick-rearing by the western snowy plover. In storm or erosive events, foredunes can contribute sand to the intertidal zone reducing storm effects on biota and grain size (Revell et al., 2011b). A natural dune/beach interface can also enhance survival of beach invertebrates by providing space for temporary landward shifts in distributions to avoid direct storm impacts. At the same time macrophyte wrack, wood and other drift material deposited in the dunes during wave and storm events, provides the structure for

subsequent aeolian sand deposition and plant colonization. Mammals, birds and reptiles from the dunes and other terrestrial habitats also access the intertidal beach and strandline for foraging.

Threatened birds, such as the western snowy plover (*Charadrius alexandrinus nivosus*), nest and rear chicks on SMB shores (Lehman, 1994, Page et al., 1995, PWA et al., 2008) making use of the dry sand and coastal strand and dune habitats, zones where geomorphic and ecological impacts of erosion and human interventions and activities can be strongly expressed (Dugan & Hubbard, 2010, Dugan et al., 2008). Seabirds, including gulls, terns, brown pelicans, and cormorants, also regularly roost on beaches, sometimes in large numbers. Fish, such as the California grunion, depend on the vulnerable uppermost intertidal zones of open sandy beaches for spawning, burying their eggs at the driftline for incubation on selected beaches in the SMB region (Thompson, 1918, Martin, 2006). Finally, pinnipeds, including elephant seals, sea lions, fur seals and harbor seals, haul out, pup and raise their young on sandy beaches, again primarily using upper beach zones.

Our understanding of the sensitivity of beach and dune ecosystems to disturbance, including anthropogenic disturbance, greatly lags that of other shore habitats. A prevailing assumption is that beach ecosystems and functions recover rapidly from press or pulse disturbances. That assumption is not supported by recent studies and syntheses of data from California beaches which indicate that recovery times for some intertidal taxa (clams, upper shore invertebrates) may extend over years and even decades (Dugan et al., unpublished, McLachlan et al., 1996). This critical lack of understanding of recovery dynamics and trajectories for beach ecosystems suggests a precautionary approach to addressing beach erosion concerns in SMB is justified and warranted.

3.8.1 Limitations of the Evaluation of Ecosystem Services

Dry beach width vs. ecological value

For shores that experience disturbance, such as grooming, vehicle use, profile contouring, scraping, berm building or nourishment, dry beach width, as defined for these analyses, does not represent a reliable or useful proxy of beach ecosystem condition. Anthropogenic activities such as these create dry sand zones which have relatively little ecological value. For example, groomed beaches often appear to have a wide dry sand zone, however this zone is, in fact, composed of degraded coastal strand and dune habitat, where the native vegetation and topography have been eliminated by the mechanical disturbance and wrack removal associated with grooming. This habitat and biodiversity impact has been documented for groomed beaches in southern California where unvegetated dry sand zones were four times wider, macrophyte wrack cover was >9 times lower, and native plant abundance and richness were 15 and >3 times lower, respectively, compared to ungroomed beaches (Dugan & Hubbard, 2010). The lower ecological value of these wide groomed beaches is also indicated by their reduced species richness, abundance and biomass of wrack-associated invertebrates and lower shorebird diversity and abundance, compared to ungroomed beaches (Dugan et al., 2003). The ecological impacts of nourishment actions, including opportunistic sand placement⁹ and other fill activities, are of particular relevance to SMB.

⁹ also known Sand Compatibility and Opportunistic Use Program (SCOUP), as defined by the Coastal Sediment Management Workgroup.

While nourishment or fills of beaches can create wider dry sand zones, the ecological value of nourished shores does not scale with dry beach width. This is due largely to the intense disturbance and mortality of intertidal fauna associated with fill activities, including burial and the direct impacts of heavy equipment and sand manipulation (Speybroek et al., 2006). Recovery of ecological value of beaches, including impacted biotic communities and ecosystem functions, following nourishment episodes may be protracted, requiring years, even decades in some case. Ecosystem recovery can be strongly inhibited, if the fill material is too fine, too coarse or poorly sorted compared to native sand (e.g. Peterson et al., 2006).

Affects of Erosion Mitigation Measures on ecosystem function

For the vast majority of the erosion mitigation measures analyzed in this report, there is little to no information on the affects of the measures to ecosystem function. It is likely that ecosystem impacts scale with the size and intensity of the impact. Furthermore, there have been few if any baseline monitoring studies of the sandy beach and dune ecosystem in SMB. While there have been some studies done on Western Snowy plover, this is but one shorebird amongst a rich biodiversity found on these beaches. This is an area recommended for further study.

3.9 THE ECONOMIC VALUE OF BEACHES AND THE COASTAL ZONE

Ecosystem services have value to people, but it is difficult to quantify this value. This section provides an overview of the economic value of beaches including a background on methods economists use to value services, reviews some of the scientific literature, and then discusses relevant case studies in California. The application of this body of knowledge to southern Monterey Bay is then described in Section 3.9 with detailed results and values shown in Section 4..

3.9.1 Types of Economic Values

Beaches and nearby coastal parks and other publicly accessible property provide a variety of services which have economic value ranging from recreational value to providing a buffer against storm damage along the coast to providing various ecological services. Since beaches (below the mean high tide line) in California are public property, there is no market price for this land or for a day at the beach. Thus it is more difficult to estimate the value of beaches to society and economists rely on a variety of techniques to estimate the “non-market value” of beaches. These non-market values fall into a number of quite distinct categories depending upon the type of economic service. Economists have devised an overall framework to group these services, which is illustrated in Figure 15 below. Total economic value is first divided into use value and non-use value and then subdivided further as illustrated in the figure. Although in theory non-use values are important, in practice they are extremely difficult to measure and are largely theoretical constructs for now.

Total economic value				
Use value		Non-use value (Passive use value)		
<i>Direct</i>	<i>Indirect</i>	<i>Option</i>	<i>Quasi-option</i>	<i>Existence</i>

Figure 15 Total Economic Value of a Natural Resource

On the other hand a great deal of attention has been paid to estimating the use value of natural resources. As the name implies, direct use value measures services that flow directly from the resource, for example timber from a forest, or bird watching at a wetland. Indirect use values are more difficult to define and measure, but generally involve ecological services, discussed below. In practice, the distinction between direct and indirect use values is sometimes arbitrary. Figure 16 below indicates how one would divide the services of a wetland into direct and indirect use value.

For beaches, by far the most important direct use value is recreation, though other direct use values may also exist (e.g., sand mining). Although estimating the value for non-market activities such as beach recreation presents challenges, there are a number of standard techniques that can be applied and there is now at least general agreement among economists within a reasonable range what the appropriate value is for a day at the beach. Measuring the economic value of beach recreation is more challenging than measuring the value of market goods that are bought and sold. The economic value of a market good is the sum of what individuals are willing to pay for it in the marketplace. Economists consider beach recreation a consumer good. However, the State of California provides beaches for free (though some beaches charge a small fee for parking). Consequently, there are no explicit prices that can be used to compute the value individuals receive from visiting a beach or the total economic benefit (consumer surplus) that accrues to all visitors to that beach.

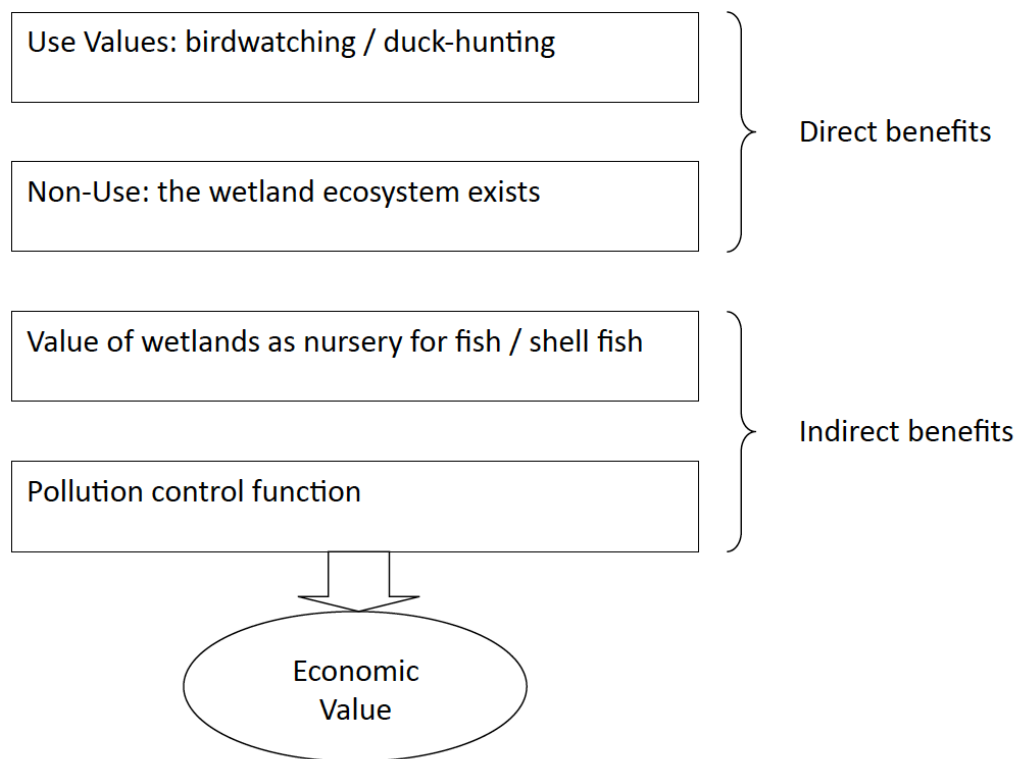


Figure 16 An Illustration of Direct and Indirect Benefits for Wetlands

3.9.2 Techniques for Valuing the Economics of Beaches

However, economists have developed several techniques for estimating the economic value of a day at the beach. The two most common techniques involve either stated preferences, where people are asked how much they are willing to pay (e.g., to go to a specific beach for the day) and revealed preferences, where economists analyze people's actual behavior to estimate their willingness to pay. Contingent valuation (CV) is the general methodology for stated preferences. The chief criticism of CV is that people may not state what their actual preferences are or may misunderstand the question. Designing a sophisticated CV study is also expensive.

Revealed preference models vary in sophistication. The simplest models use travel cost (time and expense) to estimate consumer's willingness to pay (WTP). For example King (King, 2001a, King, 2001b) finds that a day at the beach at Carpinteria and San Clemente is worth between \$30 and \$45 a day. One downside of the travel cost method is that it is hard to adequately account for substitution—if San Clemente beach were to close (e.g. due to an oil spill) many people would simply go to a different beach. Random Utility Models (RUMs) are a more sophisticated version of travel cost models that look at trips to multiple beaches and account for these substitution effects. Not surprisingly, estimates of WTP from RUMs tend to be lower than simple travel cost methods since most beaches in California have reasonably close substitutes. One serious weakness of RUMs is that they only account for individual substitutions (e.g., if I decide to go to Santa Monica rather than Venice Beach). However, should a large beach close, thousands of people will need to make alternative plans and the capacity of nearby beaches to absorb all

of the substitution, in particular increased parking and traffic congestion, is questionable. Thus it is possible that welfare estimates made with RUMs are too low.

The most comprehensive examination of the consumers' valuation of beach visitation was the Southern California Beach Valuation study, which used a RUM to examine beach visitation in Orange and Los Angeles Counties. The results of this study are consistent with an earlier valuation made for the American Trader oil spill case and were not inconsistent with the day use valuations employed by the US Army Corps of Engineers. Unfortunately, none of these models takes into account changes in beach width even though it is a key amenity.

More recently, King, Mohn, Pendleton, Vaughn and Zoulas (King et al., 2010) estimate welfare benefits of enhanced beach width in a random utility model based on data from the southern California beach project (Orange and Los Angeles counties). They find significant welfare benefits from enhanced beach width. Further, they find that water users (e.g., swimmers and surfers) as well as people on the pavement also benefit from increased beach width, though after a point the welfare benefits of increased beach width diminishes. In a related paper, Pendleton, King, Mohn, Webster, Vaughn and Adams use the same data set to estimate welfare losses at southern California beaches when beach width decreases due to erosion and storm surges (Pendleton et al., 2010).

A small number of studies also examine the welfare benefits of increased beach width at beaches on the east coast of the US. Huang and Poor (Huang & Poor, 2004) use stated preference methods to examine the value of protecting against beach loss in the states of Maine and New Hampshire. Although they focus on preserving the status quo rather than changing beaches, they find a general dislike by the public for many of the consequences of beach armoring (e.g., building seawalls or sand retention structures such as groins). Landry, Keeler, and Kreisel (Landry, Keeler, & Kreisel, 2003) examine a Georgia island community using a hedonic model to quantify benefits to property owners and stated preference techniques to determine the benefits of beach preservation and enhancement strategies. They find that in general people prefer wider beaches and they don't like armoring strategies.

Parsons, Massey, and Tomasi (Parsons, Massey, and Tomasi, 2000) use revealed preference data to look at beaches in New Jersey and Delaware, using models, which account for familiarity and favorites, and consider three categories of beach width. They find that, in general, people prefer wider beaches, but only up to a point (about 250 feet in width). Whitehead, Dumas, Herstine, et al. (Whitehead, Dumas, Herstine, et al., 2006) use a random effects Poisson model combining revealed preference and stated preference data and find that people prefer increased beach width, although width is only examined using the Stated Preference data.

All of the studies above are site-specific and most of the beaches in the current study were not included in any of the studies cited above. Also, to be consistent one should use a standard model which is reasonably tractable. The standard methodology in economics is to use a benefits transfer (BT) approach which allows one to apply estimates from similar beaches to a different site. In practice BT is much cheaper (e.g., the Southern California beach study cost well over \$1 million) than other methods and also has the advantage of consistency.

For BT to work properly, one must create a methodology for assessing the recreational value of a particular beach. Several federal agencies, most notable the USACE, have developed a scale from 1-100 to assess the value of a recreation day with certain amenities assigned a subtotal of the total 100 points (Table 4). This methodology is described in USACE (USACE, 2004).

Table 4 U.S. Army Corps of Engineers Point Values for Beach Recreation

USACE Benefits Transfer Methodology	
Criteria	Total Possible Points
Recreation Experience	30
Availability of Opportunity	18
Carrying Capacity	14
Accessibility	18
Environmental	20
Total	100

The USACE criteria indicate out how to assign point values to each beach (or other recreation site) depending upon the criteria. One serious limitation of the USACE criteria is that dry sand beach width (generally above the still water level such as Mean High Water, (MHW) is not specifically accounted for, although “carrying capacity” depends in part on beach width. Another problem with the above scheme is that, since it is additive, one can score a zero on a particular criterion and yet still earn a relatively high day use value. For example, if the recreational experience is zero or low, it matters little whether the site is accessible or has an adequate carrying capacity. Another issue with the USACE methodology is that additional recreation points are given if multiple recreational opportunities are available, but, in practice some beaches cater only to one type of recreation (e.g., surfing, bathing) but do so extremely well—e.g., Trestles for surfing or Carpinteria for families—and the USACE methodology may undervalue these types of recreation.

3.9.3 Coastal Sediment Benefits Analysis Tool

The Coastal Sediments Benefits Analysis Tool (CSBAT) was developed by the Coastal Sediment Management Workgroup (CSMW) to facilitate beach nourishment. The tool considers the costs of sand placement along with hazard reduction and recreational benefits. The effects on the environment are not valued but rather treated as “considerations”. CSBAT was applied as part of the CRSMP for southern Monterey Bay (PWA et al., 2008). This CSBAT approach avoids some of these issues associated with the point system by assuming that the value of each amenity is multiplicative - that is, one should rate each amenity on an appropriately defined scale and then multiply each amenity’s point value to derive a final index. The index can then be translated (as the USACE methodology is) to a day use value. CSBAT uses these criteria to assess the recreational value of beaches for Southern California. The following six criteria were included in the analysis:

1. Weather: Typically California beaches are overcast early in the morning and clear before noon, though some beaches remain overcast for a significant number of days. In assessing the weather, the number of sunny days, average temperature of the air and water, currents, and wind could all be considered. For example, Monterey suffers from a large number of foggy days, windy and cold weather and colder than average water temperature.
2. Water Quality/Surf: Water Quality has become a critical issue for California, leading to temporary or permanent closures of many beaches. This factor will be revised in future studies and model updates since waves and water quality are quite different attributes, as pointed out by some reviewers.
3. Beach Width and Quality: Beach width is an important criterion, particularly in an examination of the use of opportunistic sediment for beach nourishment. While wider is not always better, as a general rule, everything else equal, people prefer wider beaches. Most beaches in southern California have good sand quality (and little cobble except near shore), so sand quality is not an important issue for this study.
4. Overcrowding: Previous surveys of beach goers generally indicate that overcrowded beaches are considered less desirable (King 2001). Crowding can be measured in a number of ways. Typically, it is measured by the amount of sand available per person, though crowding can also occur in the water, in parking lots, snack bars, etc.
5. Beach Facilities and Services: In addition to criteria 1 to 4 above, beach goers generally prefer restrooms, trashcans, and lifeguards. Most (but not all) also prefer some food facilities and other shops.
6. Availability of Substitutes: If similar beaches are available within a short distance, a beach is less valuable – in particular it may not make sense to nourish a beach if another similar beach is available nearby. However in making an assessment of substitutes one must keep in mind the differing preferences of beach users, e.g., some prefer a City beach with an urban ambiance while other prefer a more “natural” beach. One other critical issue often overlooked in studies of California beaches is congestion and availability of parking. In particular, Los Angeles, San Diego and Orange County have plenty of beaches with similar amenities, but virtually all of these beaches are crowded on summer weekends and parking is often unavailable after noon. For the beaches in this Monterey study, parking is considerably less of an issue, but future model expansion into other geographic areas will analyze parking in more detail.

The functional form used in the CSBAT analysis is a Cobb-Douglas utility function, which is standard in economics. The equation is of the general form:

$$\text{Value of a Beach Day} = M * A_1^a * A_2^b * A_3^c * A_4^d * A_5^e * A_6^f \quad (\text{A.4})$$

where: M is the maximum value for a beach day

$A_1 \dots A_n$ represent each beach amenity (rated on a scale of 0 to 1)

a...f are the weighting of each amenity value

$$a + b + c + d + e + f = 1.$$

The CSBAT model has been calibrated with data from existing studies. The Cobb-Douglas function exhibits diminishing marginal utility with respect to dry sand beach width (e.g., adding 50 ft of sand to a narrow beach has a larger welfare benefit, other things being equal, than adding 50 ft to a wider beach) which is consistent with all empirical studies and anecdotal evidence. In addition, the CSBAT model employed here caps beach width benefits at 300 ft, which is consistent with a number of studies indicating that beaches can, in fact, be too wide. However, wider beaches also lower congestion and the benefit of less crowding at wider beaches is taken into account in the model.

The key issue in calibrating the CSBAT model is how beach width increases (or decreases) visitors' willingness to pay. In particular, King finds that doubling the beach width of a typical (somewhat eroded) beach in Southern California increases the value of a beach day by 15-20% (King, 2001a; King, 2001b). The maximum value for a beach day is \$14, which is consistent with Chapman and Hanneman's (Chapman & Hanneman, 2001) estimate for the value of a day at Huntington Beach as well as the US Army Corps of Engineers (USACE, 2004) benefit transfer protocol.

3.9.4 Application of the CSBAT Model to the Study Area

We conducted several site visits to the area, interviewed lifeguards, representatives from Surfrider Foundation, and other people with expertise on coastal recreation. From these site visits and interviews we drew a number of conclusions:

1. Although the weather in the area is cooler and has far fewer sunny days than many southern California beaches, nevertheless these beaches are quite popular on warm sunny days and traditional beach activities constitute a significant part of the overall recreational benefits.
2. Walking, hiking, and bird watching are significant activities along the entire study area and the beaches and nearby coastal area provide these activities year round.
3. Surfing is a significant activity at a number of spots in the area, in particular at areas in Sand City, Reservation Road, and Moss Landing. Increasing use of Fort Ord Dunes State Park has occurred as California State Parks has opened the area for visitors.
4. As with most beaches and parks, recreational activity tends to cluster around certain access areas, generally near entrances and parking facilities. The densest recreational activity is at the southern end, at Del Monte Beach. Other significant clusters center around the Best Western hotel and the Sanctuary resort (both of which have a public lifeguard at peak times and ample public parking).
5. Official attendance estimates are only available for certain spots (mostly State Parks). However our site visits and interviews with lifeguards indicate that the official estimates are almost certainly too high. King found that attendance estimates at smaller beaches are often overstated. For example, the CRSMP for southern Monterey Bay reported that Monterey State Beach had an average visitation of 644,677 per year (King, 2001c). To be conservative, we used an estimate of 300,000 per year for each reach.

Although the CSBAT model allows one to distinguish between recreation types and seasonality, given the study limitations, we decided to apply one estimate which represents an average of all types of recreation.

In this study area, it is important to note that recreational use of the beaches in the study area can also be compartmentalized based on the changes to varying nearshore widths. For example, the subtidal areas are visited by surfers and kite surfers, while the intertidal zone is used primarily by beach combers and surf fishermen. The dry sand beach which was the focus of this analysis has typical family oriented types of recreation, bird watching and walking. Finally the dunes are used by hikers as well as hang gliders especially along the Reservation Road area. However given the lack of availability of information on the actual numbers and types of uses, we focused primarily on the dry sand beach width use.

In addition, beaches and dunes can provide important services as storm reduction buffers. Wider beaches reduce storm damages to public and private property inland, reducing inland erosion, property damage, and damages to inland habitat such as lagoons and coastal wetlands. These “hazard mitigation” benefits are typically estimated as the cost of damages avoided. These hazard reduction benefits are included in our analysis as described elsewhere.

3.9.5 Economic Impacts of Recreational Use

The economic and tax revenue impacts of beach use and changes in beach width (or elimination of certain beaches) were also estimated for this paper. The analysis used attendance estimates from the CSBAT model and spending estimates from King and Symes (King & Symes, 2004). The key variable here is the percentage of day trip visitors versus out of town visitors (who spend more). For each site we relied either on existing data or interviews with knowledgeable people to estimate the percentage of day trippers vs. overnightriders.

In addition, we assumed that spending per visitor did not change as beach width changed—thus all of the economic and tax revenue impacts estimated in this paper are a result of estimated changes in beach attendance. It is also possible that changes in beach width could affect the composition of overnight/day trip visitors, which would also affect spending/tax estimates, but this impact was considered secondary and not estimated. Tax revenue impacts were based on spending estimates combined with data from the *California Statistical Abstract* (2009).

3.9.6 Indirect Uses and Ecological Value of Beaches and the Coastal Zone

Although beaches are best known for their recreational value, it is by no means clear that other non-use and ecological values are less important or less valuable, particularly considering the fact that many beaches in California (especially as one moves north) do not provide the recreational services of a beach like those in the more densely populated southern California. California’s beaches provide habitat for a number of threatened species of flora and fauna such as the Least Tern and Western Snowy Plover; beaches also provide spawning opportunities in the intertidal zone for grunion and many other species. Reducing the size of beaches reduces this habitat and potentially reduces biodiversity. Schlacher et al. (Schlacher et al., 2007) find that human activity on beach habitat has already significantly reduced their capacity to provide ecological services. See Section 3.8 Sandy Shore Ecosystem Services.

Unfortunately, much less is known about these benefits or how to properly measure them. However it makes no sense to completely ignore them. One common parameter used in many studies of beaches,

wetlands and other natural resources providing ecological and other services is to place a value per hectare or per acre and use the total area of the resource to derive an economic value. This methodology is not without problems, particularly when one is examining a change in the area of the resource, since ecosystem services may exhibit diminishing returns or certain habitats may also exhibit threshold effects where reducing habitat below a certain level leads to species extinction (Brander, Florax and Vermaat, 2006).

Costanza et al. (Costanza et al., 2006) use an analysis of 94 peer-reviewed papers and 6 other studies, Hedonic analysis and spatial modelling to estimate the economic values of seven types of biomes (including beaches) and the cumulative ecosystem services of New Jersey. They estimate that New Jersey's beaches deliver \$42,147 per acre per year in economic/ecological services.

The most comprehensive study of wetland valuation to date was conducted by Brander, Florax, and Vermaat (Brander, Florax and Vermaat, 2006) who examined over 200 studies of the economic value of wetlands. These studies include recreational value, water quality improvements, amenity improvements and habitat/biodiversity value.

Brander, Florax and Vermaat find that the average biodiversity value of a wetland per hectare per year is \$17,000 (about \$6800 per acre) and habitat value is about \$2000 per hectare. They also estimate that wetlands provide \$4000 per hectare per year in flood relief, a value that is likely low compared to beaches.

For this study, we decided to use a conservative value of \$20,000 per acre (less than the value of a New Jersey beach in a National Marine Sanctuary), which represents a midpoint between Costanza's estimate and some other estimates. We applied this estimate to the beach area and to the undeveloped area behind beaches (e.g., the dune areas) which represents part of the ecosystem. We did not apply this estimate to the developed areas even though there is certainly ecological value there as well. Further, we did not evaluate the changes to ecosystem services caused by a number of factors such as: 1) armoring devices which may limit the mobility of fauna in the tidal zone, 2) the impacts of nourishment on ecosystem services, 3) non-linear effects, and disturbance associated with sand placement. Therefore our model assumes that ecosystem services are proportional to dry sand area but the true relationship is likely to be much more complicated. One approach would be to value natural beaches higher than constructed (or nourished) beaches: In this study, a uniform valuation was applied by acre of dry beach.

Given that the valuation of ecological services is in its infancy, extreme caution should be taken when applying these estimates, since the actual value of these ecological services may be significantly higher or lower than the estimate we applied. Indeed, one could argue that given the uncertainty surrounding these estimates that no number should have been applied. However, policy makers are being asked now to make important decisions based on limited data and science and completely ignoring ecological value is likely to have a greater distortionary effect on the decision making process than using a number which lies in the midrange of current estimates. This is an area that would benefit enormously from future research.

3.9.7 Analysis of Property in the Upland Developed Areas

In contrast to the non-market values generated at beaches and in the undeveloped coastal zone, it is possible to use market data to estimate the value of private property (land and structures) in the developed area. Further, although much of the land and structures are owned by government or quasi-government agencies or by non-profit organizations, it is still possible to make meaningful inferences about the market value of this land, since some transactions data do exist.

Upland erosion places both land and infrastructure at risk to economic damages. We evaluated upland losses in the developed areas by using county parcel data used in the assessment of property for tax purposes. For each reach and erosion mitigation measure, and at each of the four outlined planning horizons (see Section 1.1.3), we estimated the value of the parcels that would be lost as well as losses to the structures on the land due to erosion or inundation.

The general approach applied was to import (County) parcel data into ArcGIS® to identify assets at risk to upland erosion given the analysis provided by ESA PWA. A GIS shapefile that spatially delineated all unique parcels in Monterey County was secured from AMBAG. The entire County parcel layer was clipped based on a 300 foot proximity to the shore. We employed spatial analysis techniques to evaluate if expected upland erosion will intersect with a parcel, thereby placing a parcel at risk to damage. The existing toe of the back beach provides a stationary reference for measuring upland erosion damages within GIS. The distance from a parcel's seaward edge to the toe line was tabulated and compared to projected extent of shore erosion.

In order to simplify the analysis, we adopted the following assumptions when translating erosion inputs to parcel damage functions:

- All parcels parallel the shore; and
- All parcels are perfect squares

These assumptions combined with inputs on a parcels distance to the toe of the beach, parcel area, and future upland erosion rates can be used to tabulate the percent of a parcel at risk. Parcel characteristic data is necessary to translate the extent of expected erosion risk to monetary damages for at risk properties. We were able to identify property characteristics for at risk parcels with county assessor records. These records, commonly known as assessor secure rolls, are designed for tax purposes and part of the public record. Unique field codes, known as assessor identification numbers (AINs) allowed us to link at risk parcels identified in GIS with detailed parcel characteristic records provided by the county assessor.

3.9.8 Valuing At Risk Assets

To assess a property's tax burden, California counties record a parcel's land value and improvement value. Land value represents the total appraised value of the land, including any upgrades or improvements. Improvement value represents the total appraised value of structures, including any upgrades or improvements. California's division of assessed value into land and improvements (structures) appears to provide a streamlined method to tabulate upland erosion damages. Yet, this

valuation technique has numerous shortcomings that undermine an accurate appraisal of expected upland erosion damages:

1. In California, Proposition 13 results in property being reassessed only when it changes ownership (improvements are also added to the structure value). Future increase to a property's assessed value are capped at two percent, which leads to a discrepancy between assessed value and actual market value since property values in Monterey have risen at a far greater rate than two per cent a year over the past several decades. In effect, Proposition 13 results in assessed property values that may be far below their respective market value, especially for properties which have not changed hands for many years.
2. County assessors appraise structures with depreciation factors. Depreciation accounts for the remaining economic life of a structure as a function age and character.¹⁰ In this report, we value structures using full replacement value—the cost of reconstructing a new but similar structure in the same region.¹¹
3. To account for land damages, we attempted to estimate the full market value of the land (which literally falls into the ocean, and cannot be replaced). As a consequence of Proposition 13, the assessed value of properties that have not been sold recently will fail to fully estimate the true market value of land.
4. County assessor recorded land and improvement values are developed for tax purposes. Because institutional properties (e.g., governmental, non-profit) are in many cases exempt from property taxes, county assessors record land value and in some cases improvement value at zero. However this property is clearly valuable.

Over ninety percent of the at-risk parcels are zoned for residential and institutional (governmental) uses. Given limited financial resources and time, attention was focused on re-estimating the land value and structure values for residentially zoned parcels and the land value for undeveloped government properties.

3.9.9 Residential Land and Structures

At-risk residential parcels were spatially clustered, with each cluster containing similar land use designations (e.g., single-family, multi-family), structure types (e.g., single-family dwelling, condo, townhouse) structure size and lot size. To fill existing data gaps, where no data was available for the value of land and structures, we assumed these values were similar (per sq. ft.) to adjacent property/structures

¹⁰ We investigated the possibility of using depreciated replacement value. However, there were significant data gaps for the condition and/or character of buildings (as was the case in this analysis), depreciation value is calculated only as a function of building age. In our case, the resulting estimates vastly underestimate values of older home in average and/or good condition.

¹¹ For evaluating flood damages, the USACE measures depreciated replacement costs while FEMA generally uses full replacement costs. The primary rationale for FEMA's use of full replacement costs lies in FEMA's commission to allocate the finances required to repair or replace damages assets apart from an asset's existing economic condition. In the event of erosion, land will and structures will literally fall into the ocean, presenting a different paradigm to valuing replacement costs.

To calculate a structure's full replacement value, we applied assessor structure characteristic inputs (e.g., size, type) to mean cost per sq ft replacement values. These values, identified by the National Institute of Building Sciences (NIBS), represent average nationwide costs. The cost of construction (e.g., wages, material, transportation) varies by region. To account for the difference of national construction costs to those in the Monterey region, we secured region-specific building cost indices maintained by Engineering News Report (ENR). We adjusted NIBS values with indices from the San Francisco region and accounted for inflation from the reported 2006 base year to the present (2010). Accounting for both region-specific building costs and inflation, NIBS cost per sq ft factors increased by nearly 30 percent.

Residential land value is affected by location and classification among many other variables. Location-based variables (e.g., urban/rural, parks, roads, air quality) and classification-based variables (e.g., single-family/multi-family, commercial, institutional, mixed use) can be both static and dynamic. Teasing out the relative contribution of these variables respective to a parcel's total land value is difficult, often requiring the use of hedonic modeling efforts that were not feasible for this level of analysis.

Lacking data to make reasonable inferences for estimating residential land we used multiple listing services (MLS) to evaluate recent home sales and pending home sales adjacent to at risk property. Properties at risk were generally clustered allowing us to relate and extrapolate bundled (i.e., land and improvement value).

To estimate the value of the land, we subtract our estimates of structure value from the identified total property value. For parcels where no data were available, we used lot size data in conjunction with estimates from similar property values to produce estimates of land values per sq. ft. factors.

3.9.10 Other Structure and Land Values

Governmental publicly owned parcels at risk from upland erosion are primarily undeveloped. As discussed, tax exemptions result in county assessors recording the land value of these parcels at zero. Yet, from an economic framework, these undeveloped parcels have economic value. To estimate the value of government land in the developed upland area, we evaluated recent land trust transactions along the California coast. The sale price of these transactions ranged from \$1 to \$20 per sq. ft. These prices, while wide-ranging, are well below market value. In many cases, land trusts transfer their deed of ownership to a public agency for future management and vice versa. To estimate the value of government owned parcels, we assume that these parcels will remain undeveloped and under the county's ownership or be transferred to a local land trust for management. We conservatively estimate the value of these parcels at \$2.50 per sq ft. It should be considered a possibility, notwithstanding existing land use provisions (e.g., development rights, easements), this undeveloped land could be sold in an open and competitive market. If this were the case, the cost per sq. ft. would greatly exceed our default value.

For all additional parcels at risk, we use recorded assessed values to estimate structure and land loss. Some parcels at risk to erosion support commercial and industrial facilities, agricultural production and recreational hunting. In future analyses, we encourage an evaluation of these damages, focusing on

potential economic impact losses for these industries as well as an incorporation of changes to coastal hazards resulting from rising sea levels.

In addition we accounted for two additional infrastructure costs in our analysis. First the Monterey Regional Water Pollution Control Authority (MRWPCA) has several pump stations and a pipeline (the Monterey Interceptor), much of which runs on the beaches in this study. We obtained information on the replacement cost of this infrastructure and its location by reach from the MRWPCA (Appendix 4). The total replacement cost is approximately \$130 million. Our analysis assumes that the infrastructure would be removed/replaced if and when the dry sand beach width reaches 65 feet.

Streets and Roads also represent a significant infrastructure cost. We estimated the total area of these streets and roads and assumed they would have to be moved or replaced during the planning horizon when erosion occurs in the developed area. We selected \$200 per sq. ft. (could be higher, say up to \$500 per sq. ft.) (see Section 3.6) as a cost for movement/replacement/elevation for the purposes of this cost-benefit analysis. We did not estimate the costs of replacing local electric, sewage and water lines (other than MRWPCA) or other municipal infrastructure. Some or all of this cost should be implicitly part of the market price of structure/land lost that we did incorporate into our analysis.

Property Damage Functions

Land and structure values assigned to each at-risk parcel are applied to erosion damage functions to estimate losses to each reach over our future planning horizons (0-5, 5-25, 25-50, and 50-100). We estimated the losses by introducing the following damage functions for all management strategies less setbacks:

- Developed parcels face a complete loss of structure and land value when intersecting an erosion hazard zone.
- Undeveloped parcel damage is a function of the percent of parcel (surface area) within the erosion hazard zone, regardless of parcel size.

In modeling costs following the use of setbacks, we made use of the following assumptions:

- Erosion continues unimpeded until it reaches 20 ft. of a developed parcel.
- When erosion is within 20 ft. of a developed parcel, revetments are constructed.
- Parcels landward of setbacks will not face land or structure damages.
- Incurred damages (costs) reflect the capital construction cost of a revetment, \$4,500 per linear ft (see section 3.6 Cost Estimates).
- Revetment construction, other structural measures and beach nourishment were assumed to occur roughly every 25 years, at time frames of 0-5, 26-50 and 51-100. Note that the last action at year 100 was not included (that is, three constructions at 25 year intervals but not a fourth). This favors the structural measures and beach nourishment measures and biases the analysis against the land use management measures.

To estimate final damages, damage functions were linked to parcel characteristic data, re-estimated land and structure values for the aforementioned categories, and inputs on the percent of a parcel within expected erosion zones.

3.9.11 Benefit/Cost Analysis and Baseline

All of the above data were incorporated into a benefit/cost analysis over a 100 year planning horizon. Future benefits and costs were discounted at a rate of 5% per year and all estimates reported are 2010 present values representing the entire 100 year time horizon. All estimates are in real 2010 dollars. The recreational and ecological benefits were estimated and discounted for each year over the 100 year period. The costs of nourishment and armoring devices such as seawalls are estimated and discounted during the year the cost is incurred, following the construction cost estimates (see Section 3.6). The replacement cost of the MRWPCA was estimated during the year when the beach width reached 65 ft. (if it ever did). The analysis of land and building losses as well as street/road losses was assigned to the beginning of the planning horizon in which the loss was estimated to occur.

The baseline scenario for the benefit/cost analysis was selected to represent the most likely actions to occur within the existing coastal zone management framework. We have defined the base line conditions as construction of revetment to protect development. While this may not be the outcome that many desire, it is consistent with historic and recent actions and expected trends in the area. Thus if the benefits of one particular policy response (e.g., nourishment) exceed the costs (implying a benefit/cost ratio greater than one) that should be interpreted as meaning that the policy is an improvement upon the status quo (do nothing). If the benefits are lower than the cost (i.e., the B/C ratio is less than one) that implies that the particular policy is worse than the status quo. All of the B/C analysis was done over the entire planning horizon since it would not make sense to examine a policy (e.g., nourishment) on a shorter horizon when the costs/benefits should be amortized over the life of the project (100 years in this case). Looking over a shorter time horizon would effectively throw out part of the analysis and render the results less meaningful.

It is important to note that this benefit – cost analysis attempts to include the value of the natural ecology and other ecosystem services. At present, most shore management decisions consider these parameters in a regulatory context, that is, as qualitative elements to be protected. The regulated restrictions on impacts to the public, including the environment, would still govern over the benefit cost analysis. This is particularly important because, for example, protection of endangered species habitat at a particular location is a legal matter largely unfettered by lost opportunity or other costs.

The benefit – cost analysis is applied to multiple coastal erosion mitigation measures. The benefit-cost results are described in Section 6 for each erosion mitigation measure analyzed.

4. DETAILED EVALUATION

The following section provides an overview of each erosion mitigation measures being assessed in the cost benefit analysis. The erosion mitigation measures are divided into three (3) measures: Land Use Planning Measures, Non Structural Measures, and Structural Measures

In this section, each erosion mitigation measure is defined, analyzed for effectiveness and benefit costs, and discussed using the evaluation criteria described in Section 3.2.

4.1 LAND USE PLANNING

Land Use Planning is an approach to addressing erosion that encompasses a wide range of creative and evolving techniques designed to encourage development and redevelopment landward of coastal hazards. Where coastal development exists on eroding shores, land use planning typically includes some form of managed retreat. It is a way to phase or manage infrastructure relocation as portions of the built environment are affected by the natural process of erosion. This approach is supported by natural resource managers and cited in various policy recommendations, guidance documents and climate change adaptation strategy reports. This study includes five (5) types of managed retreat under a larger, broader definition of a managed retreat approach: Managed Retreat (relocation / removal), Fee Simple Acquisition, Rolling Easements, Conservation Easements, and Transfer of Development Credits.

For example, the California Coastal Commission's (Commission) Regional Cumulative Assessment Project (ReCAP) identifies measures such as conservation easements, Rolling Easements, transfer of development credits, Fee Simple Acquisition, structural adaptation and setbacks based on an economic lifetime of 75 to 100 years as recommendations for improving the management of coastal hazards. The Commission's Beach Erosion and Response guidance document also cites the use of various managed retreat techniques as a way to minimize armoring of the shore, including transfer of development credits, habitat adaptation and setbacks. Pursuant to the Governor's Executive Order requiring state agencies to plan for sea level rise and climate impacts, the California Natural Resources Agency oversaw the development of California's Climate Adaptation Strategy. This report includes discussion of managed retreat techniques such as structural adaptation, setbacks and Rolling Easements. The ReCAP report found that current day coastal policies are resulting in the loss of public shore due to protection of private property.

Levina et al. (Levina et al., 2007) reviews some of the climate impacts and vulnerability driving managed retreat issues affecting the Gulf of Mexico shore. They point out in agreement with Titus (Titus, 1998) that managed retreat is a land use strategy that is operationalized mainly on the local level. The authors suggest a strategy of restricting land use to prevent development. First, the authors suggest using land use planning through setbacks, density restrictions, and rezoning. The authors acknowledge legal feasibility and cost issues including alleged property takings if all economic value of the properties is removed. Next, they discuss purchase of development rights as another expensive alternative, and mention that this option is of limited utility because of the cost. Drawing from Titus (Titus, 1998), a purchase of land area the size of the state of Maryland would be required to preserve coastal lands within the flood plain for the

entire US. They further point out that Rolling Easements pose fewer takings problems than setbacks or other more intrusive alternatives.

It is important to note that managed shore retreat and realignment is an integrated land use management strategy for addressing erosion, an otherwise natural process, within the context of the human built environment. It is a new, holistic approach to protecting and/or relocating current development, and ensuring that future development is located away from known and anticipated coastal hazards such as erosion. Erosion and the processes it is influenced by, takes place at a large regional geographic scale. Managed retreat, therefore, adopts this same viewpoint and considers all public and private costs and benefits within to inform decision-making.

The longer-term and wider view perspective of managed retreat stands in stark contrast to traditional erosion mitigation techniques. Historically erosion mitigation occurred at a very small geographic scale, with decisions often times based on protecting a single structure, and with a view only to the short-term impacts.

4.1.1 Managed Retreat (Relocation / Removal)

Description

Managed Retreat is a broad strategy that can encompass the use of all erosion mitigation measures while allowing long term shore recession over time. Often, managed retreat is really “retreat and then manage” over a period of decades until erosion hazards become significant again. This nuance and the negative connotation of the word “retreat” has led some to use the term “Managed Realignment.” Herein, the concept of Managed Retreat refers to the gradual removal or relocation of structures away from unstable erosion-prone areas. Managed shore retreat and realignment allows shore migration and mitigate coastal hazards by limiting, altering or removing development in hazardous areas. The CRSMP for Southern Monterey Bay recommends allowing erosion to continue in undeveloped areas, thereby supplying sand to the littoral cell, and limiting erosion in developed areas (PWA et al., 2008).

Managed Retreat is most effective in situations where erosion threats have been anticipated and plans made well in advance of an imminent threat to structures. Figure 17 below is a schematic of managed retreat. The top figure (Current) depicts existing conditions with coastal development within the erosion hazard zone and shore armoring. The shore is narrow with limited ecosystem services. As erosion progresses and sea level rises, the coastal hazards become more severe. Hence, with managed retreat, the development and armoring are removed as soon as practicable, the natural shore geometry is restored and the natural ecology recovers (Post – middle). The next schematic shows different shore conditions as recession continues and the shore responds to storms (Eroded). Over time, the shore recedes but the beach ecosystem services are maintained at the expense of upland areas. Management activities include monitoring, planning for future realignments of development and actions desired over the short term. One perspective is to consider planning and management actions related to a moving framework defined by the shore and coastal hazard zones. Fixed property and infrastructure are affected as the shore management zone moves toward them, requiring advance planning and action to minimize costs and maintain ecosystem services and equitably allocate benefits and costs, including consideration of private property and public infrastructure. Therefore, some short term actions could include beach nourishment,

dune planting, public purchase of private property, and other land use erosion mitigation measures. Armoring can also be used but typically only as a temporary measure to allow time to implement the retreat strategy, including planning, funding, design, permitting and legal activities. An example can be found in Pacifica State Beach where a critical sewer and flood management pump facility was not relocated but rather protected with a seawall, with a plan to relocate at the earliest practicable opportunity. Similarly, a private restaurant on piles was left in place with the expectation that it will be relocated landward when coastal hazards exceed the foundation design criteria or if the owner is willing to sell the property to the public.

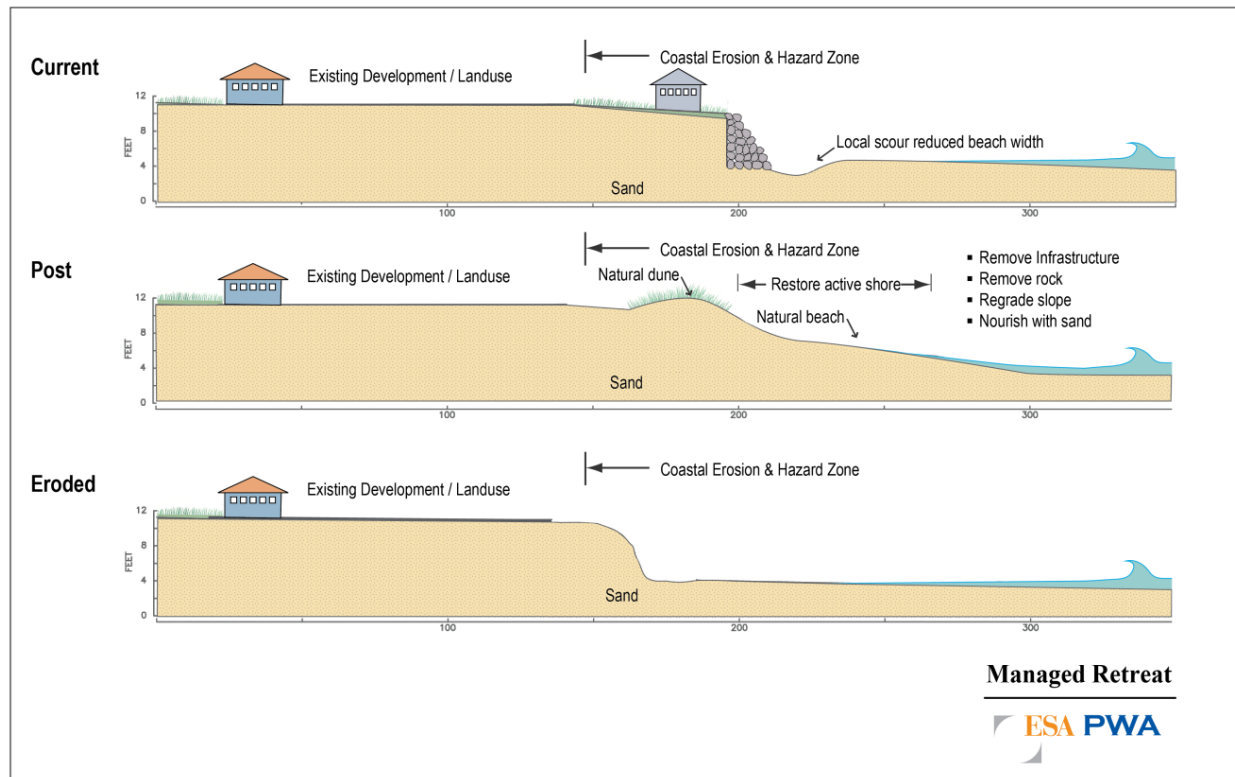


Figure 17 Managed Retreat (Relocation / Removal)

The concept of managed retreat and shoreline realignment often creates confusion because it is both an over-arching long term shoreline management strategy as well as a short term erosion mitigation measure. For example, armoring over the short term combined with purchase of private property by the public would not be included in an erosion mitigation measure but would be allowed in a longer term strategy. Through multiple projects, ESA PWA has applied managed retreat strategies by phasing removal of infrastructure as both funding, political will, and acceptability of risk are identified.

In prior work by the SMBCEW, Managed Retreat and Realignment was treated as an erosion mitigation measure rather than a strategy that could employ multiple measures. The managed retreat and realignment measure described in the following section is consistent with the prior SMBCEW definitions but would more accurately be called abandonment of property, removal of structures and relocation of people and infrastructure functions. Hence, the erosion mitigation measure analyzed in detail is called “Managed Retreat (relocation / removal)”. A summary of evaluation criteria for managed retreat is shown in Table 5.

General Applicability

Managed Retreat (relocation / removal) is generally applicable to all privately or publicly owned development located in coastal erosion hazard zone, which is defined by unstable areas threatened by coastal erosion and flooding over the planning time frame.

Specific Applicability

The strategy of managed retreat and realignment is appropriate for all of southern Monterey Bay (see discussion, above), but the erosion mitigation measure defined by the SMBCEW of Managed Retreat (relocation / removal) is considered most applicable to reaches with limited development in the coastal hazards zone. Therefore this measure is most relevant for application to Subregions 5, 6, 7 and 8 to address critical erosion areas at the Sanctuary Beach Resort and the Marina Coast Water District facilities.

There are few documented examples of the Managed Retreat (relocation / removal) hazard mitigation measure as defined by the SMBCEW. The following examples are more akin to the managed retreat and realignment strategy, as they employed Fee Simple Acquisition of private property and limited redevelopment in the future coastal hazard zone, as well as other erosion mitigation measures.

In the City of Monterey, the Window on the Bay Park is a good example of a managed retreat strategy that was initiated in the 1970s to enhance community identity. This project has the two-fold purpose of providing waterfront and recreational access, and allowing the City to make traffic safety improvements to the central portion of Del Monte Avenue (City of Monterey, 2012). The City of Monterey, with financial support from the Coastal Conservancy and other funders, purchased numerous industrial sites and privately owned parcels along the waterfront and removed the infrastructure while enhancing the recreational and ecological function of the area. The City has been negotiating to obtain the remaining privately owned parcels along this waterfront area (City of Monterey, 2012). This park is an obvious centerpiece for the largely visitor serving community and a reminder of the connection that the city has with Monterey Bay.

A good example of a managed retreat erosion mitigation measure occurred at Stillwell Hall, an officers' club located on the dunes at Ford Ord. As erosion encroached on the property, the Army constructed a revetment to protect the structure. Over time as erosion continued the beach fronting the revetment was lost as a result of passive erosion (Figure 8). When Fort Ord was decommissioned and California State Parks received the property, the structure was demolished and the revetment removed. Within three years, the beach was restored through natural erosion processes (Figure 18).



Figure 18 Stillwell Hall on Fort Ord. Photo on left taken in 2002 shows the building and revetment, and photo on right from 2005 shows the site, with recovered beach, after the removal of building and revetment. Photos from California Coastal Records Project

Table 5 Summary of Evaluation Criteria for Managed Retreat

Evaluation Criteria	
Reduce threat to existing structures	No
Maintain Beach Width	Yes
Environmental Impacts	No Generally reduces impacts by moving development away from sensitive coastal lands
Recreational	Yes
Safety and Public Access	Yes
Aesthetics	Yes
Adaptability to Future Conditions	Highly adaptable
Cumulative Impacts	None. Reduces impacts of development
Certainty of Success	Highly certain

Discussion

Although this may be the most straightforward method for protecting development that is under imminent or long-term threat of being damaged or destroyed, it is often assumed to be technically or financially infeasible. Often there is not sufficient space or land available for the structure to be relocated, and the property owner is often responsible for the full cost of the relocation. Accordingly, this approach has been most typically used for public property and by government agencies such as the California Department of Parks and Recreation in this region.

Potential variations to the measure definition include:

- building relocation incentives
- managed retreat strategy including other measures
- relocation easements
- rebuilding restrictions
- purchase and lease back

Effectiveness – Maintaining beach width vs. protecting upland property

With Managed Retreat (relocation / removal), and the land use planning tools that permit erosion to continue, the dry sand width remains constant as the beach migrates inland, eroding the upland property (Figure 19). The increasing erosion rates are represented as steepening slopes of the upland lines for all three reaches. The triangles in the plot show the point at which upland development is likely impacted on average for each reach. Prior to that point in time, upland erosion is only affecting undeveloped land, after that point in time, the erosion affects development.

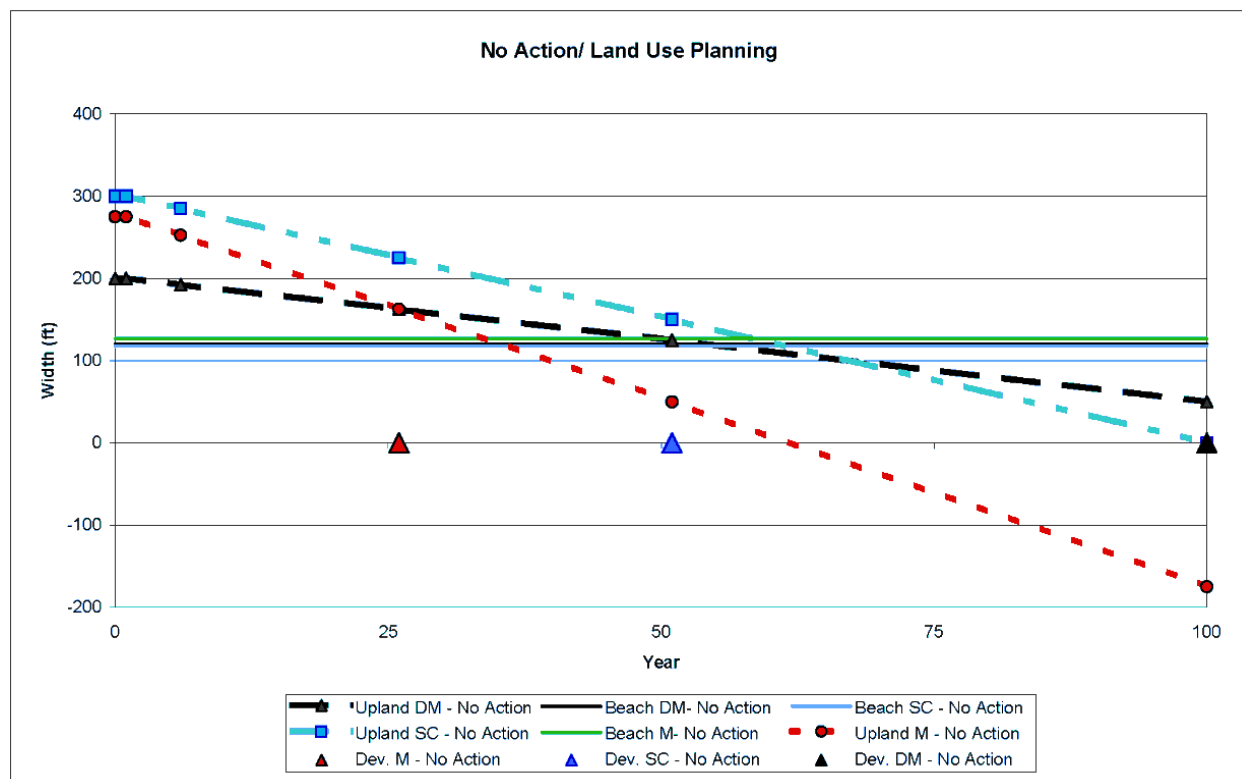


Figure 19 Effectiveness of Land Use Planning Measures at maintaining dry sand beach widths and upland property

Examples of Managed Retreat in California

The Pacifica *State Beach Improvement Project* is an example of managed retreat constructed between 2002 and 2004. To address flood threats to homes and businesses, the City removed the most vulnerable structures. In 2002, the City partnered with the Pacifica Land Trust and the California Coastal Conservancy to purchase two homes and their surrounding acreage for \$2.2 million. The city plans to relocate the one remaining shore structure—a Taco Bell restaurant—to the other side of Highway 1 as part of a planned retreat strategy being phased in over time. The project is considered a strong success, having weathered seven years of Pacific storms and swells while providing an improved recreational experience for beachgoers. This application of “managed retreat” allowed beach restoration with a relatively small quantity of sand and cobble placement, and flood and erosion control without massive structures. The project was awarded Best Restored Beach 2005 by the American Shore and Beach Preservation Association.

Surfer's Point at the mouth of the Ventura River is another example of a managed retreat project that is currently under construction. Erosion during the 1997-98 El Niño damaged a bike path and threatened a parking lot. In response, through an engaged local surfing stakeholder community, relocation of the parking lot off the upper beach was combined with cobble nourishment and dune creation. This project will result in an additional 250' of natural beach habitat, and enhance resiliency to storms and sea level rise as well as improve recreational and ecological functioning of the beach.

Example of Managed Retreat from the United Kingdom

In the United Kingdom, managed realignment has been pursued as a result of the loss of the natural shore ecosystem following shore armoring to protect development. (Shih & Nicholls, 2007). Historically, sea walls and levees have been built and re-fortified to guard against flood risk. An expenditure of over \$6.25 Billion dollars will be required to maintain existing levels of tidal defense standards and account for climate change related to SLR and increasing storm surges. Managed realignment would allow defenses to be moved back and thereby allow space for estuarine habitat. The United Kingdom Department of Environment Food and Rural Affairs (DEFRA) first introduced managed realignment as a system of flood defense in 1993. DEFRA recognized the need to incorporate managed realignment as part of an overarching strategy to protect both property and habitats. Loss of natural shores harms the robustness of coastal defenses because they play an important role in dissipating wave energy. The major obstacle to managed realignment in the UK is the poor integration of national flood and coastal defense policies with local land use planning (Shih & Nicholls, 2007). In some cases managed realignment has been linked to Fee Simple Acquisition, with the government purchasing flood prone land and then leasing the land back to the original owners. As risk increases, or events reduce the utility of the properties, the lease is not renewed, and the government manages the land for natural flood defenses.

Regulatory Viability

Existing regulations would not affect the ability to develop and implement managed retreat projects. However, the potential for court challenges over takings/ eminent domain exists, depending upon the specific approach used to implement relocation. See Section 5 for discussion of regulatory risk and takings issues.

Ecological Impacts

Generally, this mitigation measure has little to no impact on the sandy beach ecosystem unless erosion rates are so rapid or extensive that conditions and ecology change. It is possible that inland habitat could be impacted unless it can also spread inland over time. Therefore, Managed Retreat (relocation / removal) can be optimized by considering ecological criteria including habitats inland of the beach such as dunes and lagoons.

Cost and Benefits

The cost of Managed Retreat (relocation / removal) depends on the type and value of existing development and their locations relative to the coastal hazard zone and its rate of inland migration. See Section 3.5.2 for assumptions used in this measure. The overall cost can be the summation of the value of property and development. This cost is compensated by the benefit of ecosystem services. One of the most difficult elements of this measure is uncertainty over who pays and who benefits, and quantification

of benefits. Typically, this measure is part of a strategy that includes public cost to rebuild public infrastructure and compensate private property owners for their property net the costs associated with shore armoring.

4.1.2 Transfer of Development Credit (TDC)

Description

Transferable Development Credit (TDC) programs allow the transfer of the development rights from one parcel to another parcel (Figure 20). TDC programs are tools used by land use planners to direct development away from certain sensitive areas (source sites) and into areas that can better accommodate it (receiver sites).

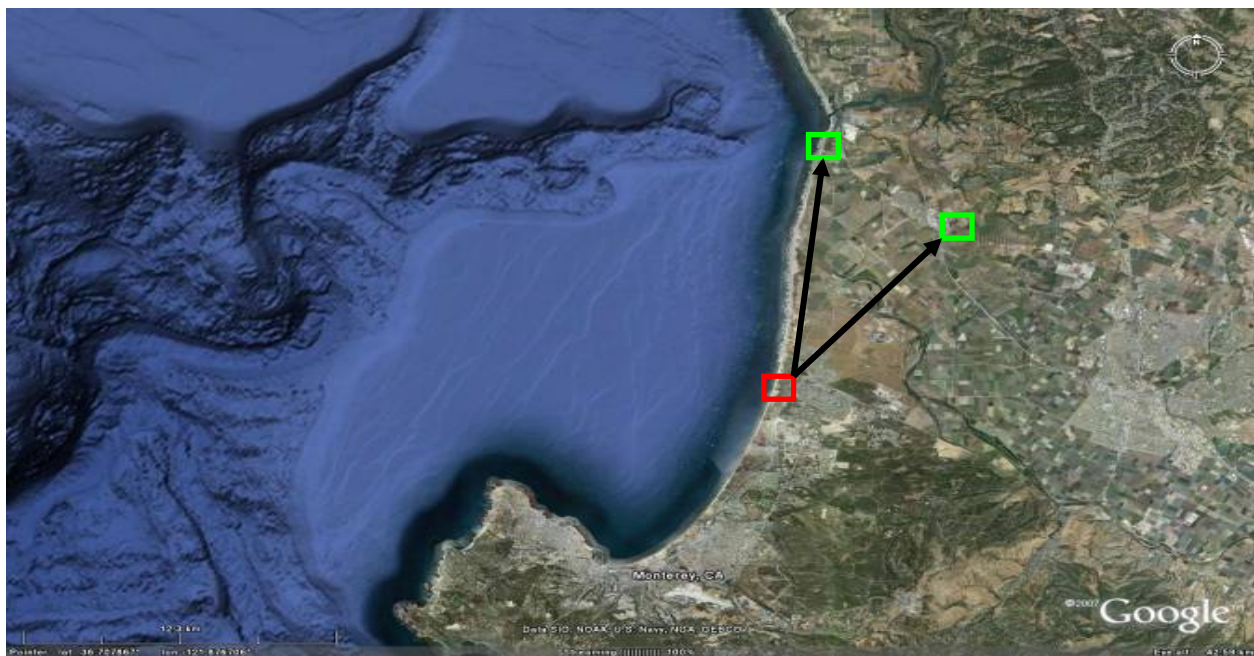


Figure 20 Transfer of Development Credits

General Applicability

TDC, also known as Transferable Development Rights, could be applied where undeveloped sensitive or hazardous parcels exist (to transfer potential development from) and desirable areas to transfer potential development to are available. TDC programs are widespread throughout the country and vary based on local land use planning priorities and needs. While the design specifics are left to the discretion of a local government, in general a TDC program identifies source sites (from which a TDC is taken away) and receiver sites (to which a TDC is added). The owner of a source site can sell a TDC to the owner of a receiver site. The seller typically retains ownership of the “sending” property, but relinquishes the right to develop it, while the buyer is able to intensify development on the receiver site more than would otherwise be permitted under existing zoning. Source or sending sites may be sensitive land areas such as endangered species or wetlands habitat, or areas prone to coastal hazards such as erosion or landslides. Owners of source sites receive monetary compensation from the sale of the TDC and in the form of potentially smaller property taxes, while owners of receiver sites have assurance of future development

rights on their site. TDC programs may provide a higher level of certainty over traditional zoning efforts because of the specificity of the amount and location of future development.

Specific Applicability

This management alternative is most relevant for application to Subregion 4 (Table 6).

In the case of Southern Monterey Bay, there are only 3-4 ocean front parcels that are zoned for development. Therefore, this measure would likely require transfer to inland properties rather than a direct exchange of similar property. While transferring development to areas inland of the hazardous areas is attractive, there are several potential complications. For example, transfer from one municipality to another (e.g. Sand City to Seaside) would have a net effect on tax revenues and expenditures for the two municipalities.

Table 6 Summary of Evaluation Criteria for TDC

Evaluation Criteria	
Reduce threat to structures	Yes – relocates future development before it becomes a hazard
Maintain Beach Width	Yes
Environmental Impacts	No
Recreational	Yes – transfer of coastal development allows recreation on the shore where development would have been
Safety and Public Access	Yes – Precludes safety issues associated with development in coastal hazard zone and allows public access
Aesthetics	Yes, Increased due to reduced shore armoring / development.
Adaptability to Future Conditions	Highly adaptable
Cumulative Impacts	Net Positive for coast.
Certainty of Success	Highly Certain

Discussion

Monterey County has implemented one of the most effective TDC programs in the country along the Big Sur Coast. In order to protect the scenic viewsheds along Highway 1, the county set up a program that transfers development from the west (ocean) side of the highway to the east (landward) side. Along the Big Sur Coast, the TDC program was implemented through revisions to the zoning code that established source sites on buildable viewshed lots (on the west/viewshed side of Highway 1) and receiver sites (on the east/non-viewshed side) after a noticed public hearing. Source sites were deemed to have an allocation of two TDCs per site. Receiver sites cannot exceed an overall density of more than one residential unit per net acre, nor increase density more than twice the requirements of the Big Sur Coast Land Use Plan. A TDC is transferred when there is a binding commitment between the buyer and seller in the form of a private contract. A TDC transfer is validated when the receiver site is issued a development permit reflecting the increased development, and the source site has a permanent, irrevocable scenic easement (scenic easement can make exceptions for agricultural or recreational use, but must preclude residential or

commercial development). The county also established a revolving fund to purchase and retire TDCs (County of Monterey, 2009).

A local government entity designs and administers the program and must take into consideration how suitable source and receiver sites will be established and regulated, the development of an allocation system, how much market demand exists, if the program is mandatory, and the extent of its role in brokering transactions and validation of transfers. If transactions cross local jurisdictions, agreements for tax revenue sharing and royalties also need to be devised (Kwasniak, 2004).

TDC programs do, however, require extensive planning and sustained implementation and enforcement over the long term. An integral key to success will be the willingness of the local community to participate in such a program, which will undoubtedly be linked to financial incentives made available. Some potential complications can occur if transfers are between jurisdictions, one jurisdiction could lose part of its tax base and also lose part of its developable land inventory. Some consideration of the net benefit to the community (e.g. tax receipts vs. required government services) may be needed. Other considerations could include access to services, water limitations, agricultural conversion and zoning changes.

A good example of a large, multi-jurisdictional TDC program exists in the New Jersey Pinelands National Reserve. This program is administered by the New Jersey Pinelands Commission (Pinelands Commission). Established by the New Jersey legislature, the Pinelands Commission implements the 1979 New Jersey Pinelands Protection Act and the Federal National Parks and Recreation Act of 1978 via the Pinelands Comprehensive Management Plan (CMP). The CMP features a TDC program that spans over a million acres and 56 municipalities in an effort to plan development consistent with protecting its ecological, archaeological, agricultural, historical, recreational and scenic resources. The Pinelands Commission is made up of 15 members, appointed by a combination of the governor, the Pinelands counties and the U.S. Secretary of the Interior, and holds monthly public hearings to discuss specific development projects and regulatory issues. The Pinelands Commission designated specific source and receiver sites and determined that TDCs would vary according to development potential. For example, one TDC per 39 acres for uplands and woodlands; two TDCs per 39 acres if located above a watershed; 0.2 TDCs per 39 acres for wetlands in which development threat was low; two TDCs per 39 acres for wetlands used for commercial harvesting of cranberries and blueberries. One TDC in the receiver site allows the owner to build an additional four residential units beyond the density threshold. The Pinelands Commission created scarcity by making the receiver sites twice as abundant as the total number of TDCs, thus ensuring market demand (Mittra, 1996).

TDC programs have been challenged in court and have withstood legal scrutiny. In *Ojavan Investors, Inc. v. California Coastal Commission* litigation against the Coastal Commission was filed questioning its capacity as manager of a TDC program. Landowner Bogart in Malibu's Latigo Canyon sued the Commission in response to a cease and desist order issued by the Commission when it discovered that Bogart had sold 19 lots subject to TDC development restrictions without telling the buyers about the restrictions. The landowner challenged the TDC restrictions on both statutory and constitutional grounds.

Both the trial court and appellate court found in the Commission's favor, and large civil penalties were imposed on Bogart.

There are two ways to run a TDC Program, both of which require fairly extensive planning as well as administrative oversight—each costly functions for local government. First, local government will have to establish parameters for sending and receiving areas. In particular, government will have to decide where denser development would be acceptable (i.e., determine receiving areas), and what types of development would be unacceptable in the conservation, or sending, areas. The government then has to assign credits according to some metric (e.g., conservation criteria, development potential) to each parcel in the sending area. Organizing a TDC system takes skilled land use planners, because the incentives created must be adequate to encourage the sale and purchase of credits in a functional market system. For example, the metric chosen for the credits must reflect some real value of the land so that sellers will sell, and the receiving area must be an attractive place for buyers to increase density. Additionally, a TDC program must operate within an economic and policy framework that manages long-term growth to ensure that the value of credits will be predictable. (For example, if public services/resources aren't sufficient to support density growth in a receiving area, the value of the credits will fall. Sufficiently increasing public services/resources in the sending area could have costs for local government). Setting up the TDC system thus will have upfront costs for local government.

In addition, managing the TDC system will result in recurring administrative costs to local government. Under the first option for managing a TDC system, developers purchase credits through an open market system, but still must present evidence of purchase to the local government and receive approval from government to increase density. Government's facilitation and authentication has continual administrative costs. Under the second TDC option, local government brokers the purchase of credits between parties, or manages a TDC bank. (This is the system developers sometimes prefer.) The second option has even greater administrative costs.

Regulatory Viability

The success of numerous and varied TDC programs across the country is evidence of its regulatory viability.

Ecological Impacts

The beach and dune ecology is maintained. Net ecological impacts vary on a case-by-case basis, however impacts are generally reduced assuming that the receiver site is selected appropriately and the project is implemented within regulatory requirements.

The cost of TDC depends on willing property owners and the net compensation by public entities who may broker a TDC to a lower value receiver site. See Section 3.5.2 for the assumptions used in this measure. There may be costs in terms of reduction of tax revenues and potential development sites.

4.1.3 Conservation Easements

Description

A conservation easement is a legally enforceable agreement attached to the property deed between a landowner and a government agency or a non-profit organization that restricts development “for perpetuity” but allows the landowner to retain ownership of the land (Figure 21).

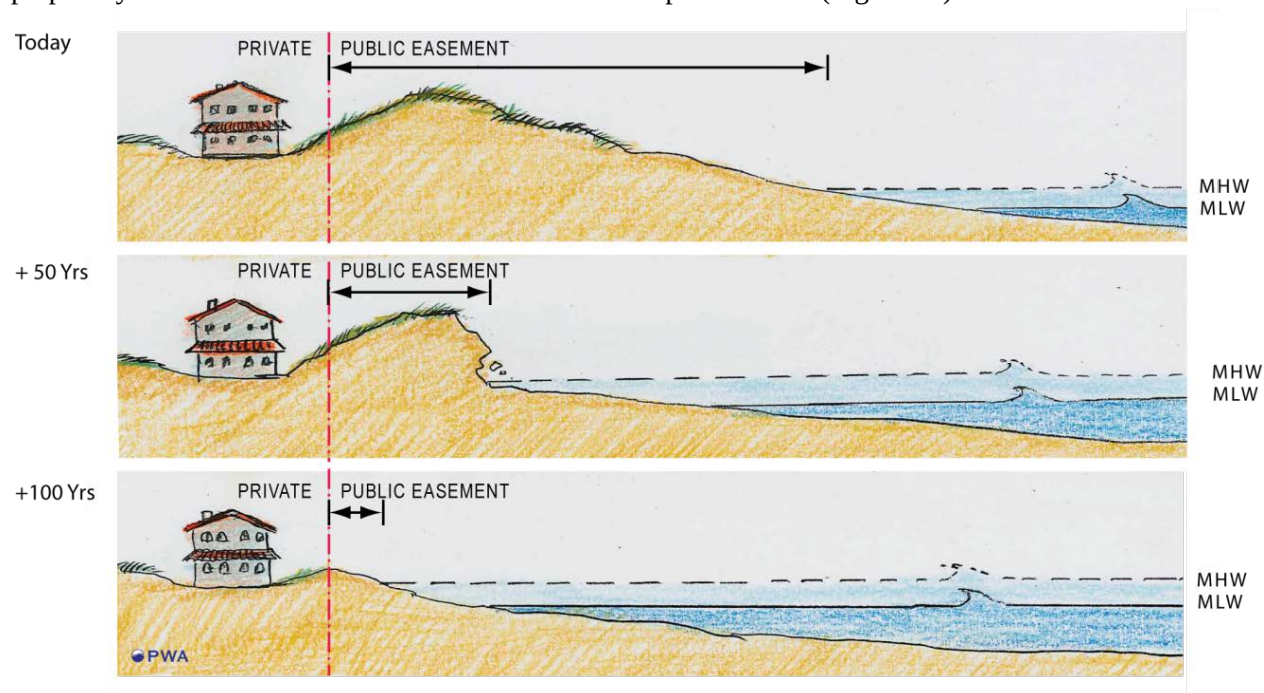


Figure 21 A Conservation Easement

General Applicability

Conservation easements can be applied to any coastal parcel, but typically where a large and or valuable parcel with environmentally sensitive elements exists, and the landowner is willing to enter into the agreement.

A comparison of the relative ecological, agricultural and public recreation benefits of conservation easements versus fee-simple holdings purchased in the San Francisco Bay Area was conducted recently. Researchers found that 190 organizations hold 24% of the land base in some sort of protected status, and that conservation easement holdings comprise a larger area than fee holdings on average. Easements were more often used to protect grasslands, oak woodlands, and agricultural land, while fee-simple properties were more often used for chaparral and scrub, redwoods, and urban areas. While easements help connect existing open space, they are less likely to allow for public recreation. Lastly, the researchers identified the need for centralized spatial analytical tools for assessment of conservation contributions (Rissman, 2008).

Specific Applicability

This management alternative is relevant for application all Subregions to address critical erosion areas located in the back of the beach or in sensitive dune habitats (Table 7).

In Southern Monterey Bay, some specific sites where conservation easements could be applied include: the sand mine site owned by CEMEX, the proposed EcoShore resort, and/or potentially part of the Naval Postgraduate school campus.

Table 7 Summary of Evaluation Criteria for Conservation Easements

Evaluation Criteria	
Reduce threat to structures	Yes. In terms of preventing development in the easement
Maintain Beach Width	Yes
Environmental Impacts	No. Reduces likelihood of environmental impacts
Recreational	Yes. Reduces likelihood of recreational impacts or improves
Safety and Public Access	Yes. Maintains existing levels unless easement includes access clause in which case can improve
Aesthetics	Yes
Adaptability to Future Conditions	Yes. Maintains portions of upland property undeveloped
Cumulative Impacts	None
Certainty of Success	Highly Certain

Discussion

A conservation easement is a strictly voluntary endeavor undertaken by a landowner who either sells or donates the rights to develop that land. While the conservation easement remains the landowner's private property, the development restrictions are permanent because they are attached to the deed and "run with the land". These restrictions continue in perpetuity no matter how many times the property is bought and sold in the future. This development restriction causes the value of the property to fall, however it can result in various tax advantages for the landowner at the federal and state level.

The government agency or non-profit organization to which the conservation easement is donated or sold to becomes the easement holder. Easement holders are responsible for the monitoring costs associated with the compliance and enforcement of its legal terms. Conservation easements are devised on a one-off basis and the specific legal parameters agreed to by both parties may vary considerably. While the general purpose is to preserve private land in an undeveloped state, an easement can also grant public access rights.

Conservation easements are sometimes required by state or local land use planners as a condition of issuing a development permit. This requirement is typically used to mitigate for the impacts of the development.

It is this wide variance in the type of design, enforcement and easement holders that precludes general summaries or trends regarding the efficacy of conservation easements across the country. As there is no national registry or system in place to track the identity of the easement holders, there is very little feedback regarding the impact to ecological and social resources available as a consequence. It is thought that conservation easements became more popular than Fee Simple Acquisitions because of a private property backlash against governmental management (Merenlender, 2004). These concerns are reinforced by another study that concluded major improvements in quality of design, ease of tracking and

monitoring, standards for termination and amendment, and other standardized management tools are needed across the board. This study also emphasized the need for local governments to consider the lifetime monitoring costs of an easement as opposed to a Fee Simple Acquisition (Pidot, 2005).

The formulation of conservation easements can be improved by considering long term erosion and the effect of sea level rise. Acquisition could be made more strategically, rather than opportunistically, with an eye towards connectivity, critical habitat and community participation. It is possible to allow for climate change adaptation within conservation easement agreements by drafting flexibility into the design. Including performance standards, best management practices as they evolve over time and termination or modification can be useful (Land Trust Alliance, 2009).

Regulatory Viability

As conservation easements are voluntary by definition, the only regulation needed is enforcement of the legal terms. There would appear to be a wide range of enforcement, which probably results in a wide range of impact effectiveness and overall viability of the easement.

Ecological Impacts

The ecological impact is beneficial by definition.

Cost and Benefits

The cost of conservation easements depends on willingness of seller, costs associated with maintenance and monitoring of easements, as well as the implementing mechanism. See Section 3.5.2 for the assumptions used in this measure.

In general, someone has to file, hold, and enforce a conservation easement on the sending parcel to ensure that future land use planning bodies cannot decide to allow development in the sending area. Either local government or a third party (e.g., an NGO) could hold the easement. Filing/management/enforcement of the easement can have costs.

There may not be a public cost to acquire the easement if the easement is included as a condition to a coastal development permit for some related development activity.

There may be administrative cost to filing, managing the holding of, and enforcing the easement, depending on whether the local government or a third party (e.g., an NGO) holds the easement. Also, there could be lost property tax revenue and altered property values.

Benefit Cost Analysis

Tables 8 through 10 presents the benefit and cost analysis for conservation easements. The baseline scenario includes the use of a revetment and the recreational and ecological benefits represent the differences between the baseline scenario of a revetment. Similarly the cost estimates net out the differences between the costs involved with a measure versus a revetment. A positive cost represents an additional cost over the baseline (revetment). Recreational and habitat values were estimated every year over a 100 year period and discounted at a 5% rate. Similarly the MRWPCA cost represents the present

value of replacement of the sewer component in the year in which we estimated failure/replacement/movement would occur (if applicable), which was when estimated beach width reached 65 feet. The other costs, structural adjustment costs, and private and public property losses, comprise estimates of losses during the planning horizon. The net benefits subtract costs from benefits—a higher value is better. The benefit/cost ratio represents the ratio of net benefits to costs. In some cases the costs or benefits are negative, yielding a negative B/C ratio, which is meaningless and represented as NA (not applicable).

There is limited generalized data on the costs of conservation easements. In actuality, easements vary widely and depend on site characteristics, types of sensitive resources, ease of development and desirability of location. In general, governments and private agencies can purchase conservation easements at substantially below market value. Consequently, for this analysis, we assumed that private land/structures could be purchased at half (50%) the market cost. Since much of the public land has already been purchased at well below market rates, we used these lower purchase prices instead.

Table 8 Present Value of Benefits and Costs for Conservation Easements: Del Monte

Planning Horizon (Years)	0 to 5	6 to 25	26 to 50	51 to 100	0 to 100
Total Recreational Value above Baseline	\$ 2,649,094	\$ 7,362,147	\$ 5,508,566	\$ 3,093,987	\$ 18,613,794
Total Habitat Value above Baseline	\$ 838,842	\$ 1,971,606	\$ 2,267,272	\$ 657,134	\$ 5,734,853
Sum Benefits	\$ 3,487,936	\$ 9,333,753	\$ 7,775,838	\$ 3,751,121	\$ 24,348,648
Structural Adjustment Costs	0	0	0	0	0
MRWPCA	0	0	\$ 10,277,227	0	\$ 10,277,227
Cost of Private Property Compensation	\$ 500,000	\$ 1,296,000	\$ 1,917,500	\$ 913,500	\$ 4,627,000
Cost of Pubic Property Compensation	\$ 30,235	\$ 104,492	\$ 44,597	\$ 32,101	\$ 211,425
Construction/Nourishment Cost	\$ -	0	\$ -	\$ -	\$ -
Revetment Cost	\$ (43,200,000)	\$ -	\$ (12,757,080)	\$ (4,879,666)	\$ (60,836,746)
Total Cost	\$ (42,669,765)	\$ 1,400,492	\$ (517,756)	\$ (3,934,065)	\$ (45,721,094)
Net Benefits	\$ 46,157,701	\$ 7,933,261	\$ 8,293,594	\$ 7,685,185	\$ 70,069,742
Benefit/Cost Ratio	NA	NA	NA	NA	NA

Table 9 Present Value of Benefits and Costs for Conservation Easements: Sand City

Planning Horizon (Years)	0 to 5	6 to 25	26 to 50	51 to 100	0 to 100
Total Recreational Value	\$ 10,331,640	\$ 18,929,245	\$ 8,068,351	\$ 3,086,197	\$ 40,415,432
Baseline	\$ 7,409,916	\$ 8,413,408	\$ -	\$ -	\$ 15,823,324
Total Habitat Value	\$ 16,933,333	\$ 25,930,217	\$ 7,750,579	\$ 2,829,750	\$ 53,443,878
Baseline	\$ 13,722,100	\$ 19,850,290	\$ 6,269,418	\$ 2,398,093	\$ 42,239,901
Sum Benefits	\$ 6,132,956	\$ 16,595,763	\$ 9,549,512	\$ 3,517,853	\$ 35,796,085
Structural Adjustment Costs	0	0	0	\$ 23,642,591	\$ 23,642,591
MRWPCA	0	\$ 25,970,041	0	0	\$ 25,970,041
Cost of Private Property Compensation	\$ 104,100	\$ 372,756	\$ 315,847	\$ 954,320	\$ 1,747,023
Cost of Pubic Property Compensation	\$ 93,608	\$ 366,571	\$ 164,061	\$ 93,863	\$ 718,103
Construction/Nourishment Cost	\$ -	0	\$ -	\$ -	\$ -
Revetment Cost	\$ (180,000,000)	\$ -	\$ (53,154,499)	\$ (20,331,941)	\$ (253,486,440)
Total Cost	\$ (179,802,292)	\$ 26,709,368	\$ (52,674,591)	\$ 4,358,833	\$ (201,408,682)
Net Benefits	\$ 185,935,249	\$ (10,113,604)	\$ 62,224,102	\$ (840,979)	\$ 237,204,767
Benefit/Cost Ratio	NA	NA	NA	NA	NA

Table 10 Present Value of Benefits and Costs for Conservation Easements: Marina

Planning Horizon (Years)	0 to 5	6 to 25	26 to 50	51 to 100	0 to 100
Total Recreational Value	\$ 10,446,180	\$ 19,139,101	\$ 8,157,800	\$ 3,120,411	\$ 40,863,493
Baseline	\$ 7,512,217	\$ 8,275,750	\$ -	\$ -	\$ 15,787,968
Total Habitat Value	\$ 21,357,208	\$ 31,537,626	\$ 10,675,252	\$ 4,083,353	\$ 67,653,439
Baseline	\$ 15,709,559	\$ 12,889,172	\$ -	\$ -	\$ 28,598,731
Net Benefits	\$ 8,581,612	\$ 29,511,804	\$ 18,833,052	\$ 7,203,765	\$ 64,130,233
Structural Adjustment Costs	0	0	0	0	0
MRWPCA	0	\$ 2,525,340	0	0	\$ 2,525,340
Cost of Private Property Compensation	\$ 1,376,487	\$ 2,310,244	\$ 14,246,730	\$ 913,500	\$ 18,846,962
Cost of Pubic Property Compensation	\$ 1,072,797	\$ 3,739,491	\$ 1,677,756	\$ 32,101	\$ 6,522,145
Construction/Nourishment Cost		\$ -			\$ -
Revetment Cost	\$ (250,200,000)	\$ -	\$ (73,884,753)	\$ (28,261,398)	\$ (352,346,152)
Net Cost	\$ (247,750,716)	\$ 8,575,075	\$ (57,960,268)	\$ (27,315,797)	\$ (324,451,706)
Net Benefits	\$ 256,332,328	\$ 20,936,729	\$ 76,793,320	\$ 34,519,562	\$ 388,581,939
Benefit/Cost Ratio	NA	NA	NA	NA	NA

Benefit Cost Results

The results of the cost benefit analysis shows that Conservation easements have a net positive cost benefit primarily as a result of avoidance of the construction costs associated with the revetments (Tables 8, 9, 10). There are positive net benefits of this measure at each planning horizon except at Sand City in the 6 to 25 year horizon when the MRWPCA costs are triggered. The total benefits over the entire study for the 100 year planning horizon total about ~\$695 million with that made up of ~\$106 million in recreation and ecosystem benefits.

The main benefits of conservation easements in the tables above are that they do not require building a revetment or other shore protection measure and thus one saves hundreds of millions of dollars. There are unknown costs of monitoring of the easement conditions that are not factored into the cost benefit analysis.

Land use measures entail other costs in the form of private and public property losses as well as the eventual replacement of the coastal sanitary sewer system. Tables 8 – 10 indicate that conservation easements have higher net benefits than the baseline of shore armoring. Note that the net costs are negative in specific time periods (e.g. the 6-25 year period) when the extent of erosion reaches development, triggering a loss of land and infrastructure.

4.1.4 Fee Simple Acquisition

Description

In the context of this study, Fee Simple Acquisition is the purchase of vacant or developed land in order to prevent or remove property from the danger of coastal hazards such as erosion.

As an erosion avoidance measure, this technique would transfer the erosion risks from the current property owner to the group or entity willing to acquire the property. Normally, the Fee Simple Acquisition is done to remove the property from being developed and prevent the construction of buildings or other capital improvements that would eventually be in danger from erosion. Fee simple acquisition is not likely to be effective when the property is in public ownership. However, one hybrid approach could include a fee simple purchase followed by a lease or rent back option until the property becomes inhabitable. This hybrid may enable public investment to recover some of the initial purchase cost.

General Applicability

Fee simple acquisition refers to buying property and can apply to any property that is available for purchase.

Specific Applicability

This management alternative is most relevant for application to Subregions with private property (Subregions 1, 2, 4, 6 and 7) to address critical erosion areas where structures exist or can be developed (Table 11).

Fee simple acquisition was used to purchase property at Window on the Bay (See section 4.1.1 for additional information). The City of Monterey bought the property from private landowners and converted it into a public park. Perhaps the best use of Fee Simple Acquisition would be the outright purchase of the sand mine through Fee Simple Acquisition.

Table 11 Summary of Evaluation Criteria for Fee Simple Acquisition

Evaluation Criteria	
Reduce threat to structures	Yes, if development is not permitted or is removed
Maintain Beach Width	Yes
Environmental Impacts	No.
Recreational	Yes
Safety and Public Access	Yes
Aesthetics	Yes.
Adaptability to Future Conditions	Yes, depends on new owner limiting/not developing
Cumulative Impacts	None
Certainty of Success	Highly Certain

Discussion

Fee simple acquisition is typically the purchase of private property by a local government in an attempt to defray the current or future costs of erosion prevention that is currently or will be borne by the public. This alternative is a local solution to a local erosion risk. Therefore, the various elements of the acquisition plan will vary.

In one case study in South Carolina, it was shown that moving development away from the beachfront is a difficult form of erosion management due to the high cost and the potential for a takings lawsuit. Hawes (Hawes, 1998) states that the federal Constitution might require fee acquisition in case of a takings determination.

In another example, a local governmental agency in the United Kingdom was able to design an acquisition plan that included a partial repayment of some of the costs. DEFRA purchased land that was prone to flooding and leased back the least risky areas to the original owners. Over time, as the risk increased or natural events reduced the usefulness of these properties, fewer leases were renewed. Eventually, there were no private landowners and the DEFRA now manages the land for natural flood defenses.

The City of Pacifica, as part of an overall managed retreat strategy used Fee Simple Acquisition, acquired 2.2 acres of beachfront property at fair market value on Linda Mar Beach in order to remove or relocate structures in danger of erosion. Several homes were demolished, while others are being readied for relocation (Pacifica Land Trust, 2003).

One potential hybrid that could be considered would be Fee Simple Acquisition of the property with a lease or rent back option. This would enable the jurisdiction or public entity to recover some of the purchase cost. An example of such an approach could potentially be the Ocean Harbor House where the City of Monterey already owns several units and rents them under the Section 8 (low income) program. Should the City acquire more properties, this may be a way to enable the most vulnerable properties to be acquired, rented for a period of time, and then abandoned or removed once they become damaged or unusable.

Regulatory Viability

Land purchase is a well-defined practice that is typically viable from a regulatory perspective.

Ecological Impacts

Generally little to no ecological impacts unless development occurs, or human disturbance is increased to the area.

Cost and Benefits

Potentially high based on perception of developed land value, potential loss of tax revenues, transfer of legacy burdens. For this alternative, we assumed that parcels were purchased at Fair Market Value (see section 3.5.2 for the assumptions used in this measure). Conceptually this is likely to require the highest upfront costs although the cost may be less when a parcel is threatened by erosion and the owner is considering constructing shore armor rather than after the property is damaged.

Benefit Cost Analysis

The benefit cost analysis for Fee Simple Acquisition (Tables 12 – 14) yield similar results compared to conservation easements. The only difference is that here we assume that a government or other agency must acquire all the land/property at market value. In practice, though the additional costs are smaller relative to other costs although a local government agency would save money using conservation easements initially, although if including the long term cost of monitoring the easement, the cost/benefit is less certain. Note that the net benefits rise when revetment construction is expected in the baseline, because there is a cost savings (no revetment) for the fee simple purchase measure. However, losses to property occur more continuously as the shore erodes. It should be noted that the cumulative net benefits and the ratio of benefits to costs are always positive. This indicates that purchasing property at fair market value is competitive with shore armoring in terms of benefits and costs if ecosystem services and recreation are included. Of course, most shore armoring projects do not include ecosystem services in their objectives, and the cost benefit is typically limited to the cost of armoring relative to the loss of property.

Table 12 Present Value of Benefits and Costs for Fee Simple Acquisition: Del Monte

Planning Horizon (Years)	0 to 5	6 to 25	26 to 50	51 to 100	0 to 100
Total Recreational Value above Baseline	\$ 2,649,094	\$ 7,362,147	\$ 5,508,566	\$ 3,093,987	\$ 18,613,794
Total Habitat Value above Baseline	\$ 838,842	\$ 1,971,606	\$ 2,267,272	\$ 657,134	\$ 5,734,853
Sum Benefits	\$ 3,487,936	\$ 9,333,753	\$ 7,775,838	\$ 3,751,121	\$ 24,348,648
Structural Adjustment Costs	0	0	0	0	0
MRWPCA	0	0	\$ 10,277,227	0	\$ 10,277,227
Cost of Private Property Compensation	\$ 1,000,000	\$ 2,592,000	\$ 3,835,000	\$ 1,827,000	\$ 9,254,000
Cost of Pubic Property Compensation	\$ 60,470	\$ 208,984	\$ 89,193	\$ 64,203	\$ 422,850
Construction/Nourishment Cost	\$ -	0	\$ -	\$ -	\$ -
Revetment Cost	\$ (43,200,000)	\$ -	\$ (12,757,080)	\$ (4,879,666)	\$ (60,836,746)
Total Cost	\$ (42,139,530)	\$ 2,800,984	\$ 1,444,340	\$ (2,988,463)	\$ (40,882,669)
Net Benefits	\$45,627,466	\$ 6,532,769	\$ 6,331,498	\$6,739,584	\$ 65,231,317
Benefit/Cost Ratio	NA	NA	NA	NA	NA

Table 13 Present Value of Benefits and Costs for Fee Simple Acquisition: Sand City

Planning Horizon (Years)	0 to 5	6 to 25	26 to 50	51 to 100	0 to 100
Total Recreational Value	\$ 10,331,640	\$ 18,929,245	\$ 8,068,351	\$ 3,086,197	\$ 40,415,432
Baseline	\$ 7,409,916	\$ 8,413,408	\$ -	\$ -	\$ 15,823,324
Total Habitat Value	\$ 16,933,333	\$ 25,930,217	\$ 7,750,579	\$ 2,829,750	\$ 53,443,878
Baseline	\$ 13,722,100	\$ 19,850,290	\$ 6,269,418	\$ 2,398,093	\$ 42,239,901
Sum Benefits	\$ 6,132,956	\$ 16,595,763	\$ 9,549,512	\$ 3,517,853	\$ 35,796,085
Structural Adjustment Costs	\$ -	\$ -	\$ -	\$ 23,642,591	\$ 23,642,591
MRWPCA	\$ -	\$ -	\$ 25,970,041	\$ -	\$ 25,970,041
Cost of Private Property Compensation	\$ 208,199.48	\$ 745,511.77	\$ 631,694.56	\$ 1,908,640.08	\$ 3,494,046
Cost of Pubic Property Compensation	\$ 187,216.07	\$ 733,141.86	\$ 328,122.00	\$ 187,725.40	\$ 1,436,205
Construction/Nourishment Cost	\$ -	\$ -	\$ -	\$ -	\$ -
Revetment Cost	\$ (180,000,000)	\$ -	\$ (53,154,499)	\$ (20,331,941)	\$ (253,486,440)
Total Cost	\$ (179,604,584)	\$ 1,478,654	\$ (26,224,641)	\$ 5,407,016	\$ (198,943,557)
Net Benefits	\$ 185,737,541	\$ 15,117,110	\$ 35,774,153	\$ (1,889,162)	\$ 234,739,642
Benefit/Cost Ratio	NA	NA	NA	NA	NA

Table 14 Present Value of Benefits and Costs for Fee Simple Acquisition: Marina

Planning Horizon (Years)	0 to 5	6 to 25	26 to 50	51 to 100	0 to 100
Total Recreational Value	\$ 10,446,180	\$ 19,139,101	\$ 8,157,800	\$ 3,120,411	\$ 40,863,493
Baseline	\$ 7,512,217	\$ 8,275,750	\$ -	\$ -	\$ 15,787,968
Total Habitat Value	\$ 21,357,208	\$ 31,537,626	\$ 10,675,252	\$ 4,083,353	\$ 67,653,439
Baseline	\$ 15,709,559	\$ 12,889,172	\$ -	\$ -	\$ 28,598,731
Net Benefits	\$ 8,581,612	\$ 29,511,804	\$ 18,833,052	\$ 7,203,765	\$ 64,130,233
Structural Adjustment Costs	0	0	0	0	0
MRWPCA	0	\$ 2,525,340	0	0	\$ 2,525,340
Cost of Private Property Compensation	\$ 2,752,975	\$ 4,620,489	\$ 28,493,460	\$ 1,827,000	\$ 37,693,923
Cost of Public Property Compensation	\$ 2,145,594	\$ 7,478,982	\$ 3,355,511	\$ 64,203	\$ 13,044,289
Construction/Nourishment Cost	\$ -	\$ -	\$ -	\$ -	\$ -
Revetment Cost	\$ (250,200,000)	\$ -	\$ (73,884,753)	\$ (28,261,398)	\$ (352,346,152)
Net Cost	\$ (245,301,432)	\$ 14,624,811	\$ (42,035,782)	\$ (26,370,196)	\$ (299,082,599)
Net Benefits	\$ 253,883,044	\$ 14,886,994	\$ 60,868,834	\$ 33,573,960	\$ 363,212,833
Benefit/Cost Ratio	NA	NA	NA	NA	NA

Benefit Cost Results

The results of the cost benefit analysis shows that Fee simple acquisition has a net positive cost benefit primarily as a result of avoidance of the construction costs associated with the revetments (Tables 12, 13, 14). There are positive net benefits of this measure at each planning horizon. The total benefits over the entire study for the 100 year planning horizon total about ~\$665 million with that made up of ~\$106 million in recreation and ecosystem benefits.

4.1.5 Present Use Tax Incentive

Description

A Present Use Tax Incentive occurs when local government assesses property taxes based on a property's present use, also referred to as its current use, rather than its market value to reward landowners with undeveloped land. The idea is that market value can reflect potential developed values, and taxing at this higher value actually encourages development.

General Applicability

The Present Use Tax Incentive measure is applicable to any parcel with a market value and taxed value in excess of its existing use.

Specific Applicability

This management alternative is most relevant for application to the following Subregions 1, 2, 4, 6, and 7 to address critical erosion areas where structures exist or can be developed (Table 15).

One example in Monterey County is the CEMEX Corporation which owns two parcels 376 and 26 acres (Figure 5). The larger which has the structural improvements is assessed at \$15.1 million (\$40,000 / acre) while the smaller at \$73,222 (\$2,800 / acre). Assuming the difference in value per acre is development, raising the value and tax rate on the smaller property would potentially incentivize development while maintaining taxes at the undeveloped rate would be a Present Use Tax Incentive. (Note: These values were obtained from information provided to us that has not been verified: An assessment of property values was not accomplished in this study.)

Table 15 Summary of Evaluation Criteria for Present Use Tax Incentives

Evaluation Criteria	
Reduce threat to structures	No except for lowering expectations of ROI and reducing likelihood of build out on undeveloped parcels
Maintain Beach Width	Yes, unless existing development applies for structural protection
Environmental Impacts	No change from existing land use
Recreational	No change from existing land use
Safety and Public Access	No change from existing land use
Aesthetics	No change from existing land use
Adaptability to Future Conditions	Slightly improves because no increase in development intensity
Cumulative Impacts	None, except reduction in tax revenues
Certainty of Success	Moderately Certain

Discussion

Local governments define the types of property that qualify for a present use tax assessment. This typically includes agricultural and forestlands, wetlands and various types of open space, but will vary based on local regulations. As evidenced across the nation, an increase in population and urban sprawl usually leads to an increase in property taxes as land becomes scarce and its value increases especially along the urban fringe. Families that retain large portions of land over generations often struggle to meet rising property taxes as the value of their land skyrockets. If a landowner qualifies for a present use tax assessment, the tax burden will be reduced and allow the landowner to avoid subdividing and selling off property in order to pay increasing property taxes. The benefit to the public is twofold as open space or sensitive habitats are preserved and an increase in density avoided.

In California, the Williamson Act was passed in 1965 and functions as a Present Use Tax Incentive. This statute taxes agricultural land for its present use and thus discourages agricultural conversion and a change in land use to more intensive development. Qualifying properties must encompass an area of at least 100 acres and be designated as an agricultural preserve. A contract is then drawn up between a local government and a private landowner that restricts the use of their land to agricultural or open space use. Landowners cede some use rights but are taxed at low open-space rates rather than at full market value. In addition to the public benefits cited above, local governments also receive a subsidy from the state (according to formula including quantity and quality of land preserved) that compensates them for

revenues lost. The contract is a rolling term ten-year contract with an automatic yearly renewal unless either party files a notice of nonrenewal. Cancellation and exit of the contract before the ten-year minimum has elapsed is possible under limited circumstances, but the landowner will incur a penalty. Currently there are over 16 million acres of open and agricultural spaces currently preserved under the Williamson Act program.

The Mills Act, passed by the California Assembly in 1976, is another statute that functions as a Present Use Tax Incentive. This Act reduces the property tax on historic structures to discourage the destruction of historic buildings and redevelopment of parcels. Qualifying historic property owners are individuals who actively participate in the restoration and maintenance of their property. Qualifying properties are appraised based on income potential rather than full market value. A rolling term ten-year contract is drawn up between a local government and the property owner that stipulates the tax relief allowed in return for the maintenance of historic aspects of their property. Local governments do not receive subsidies from the state to reimburse them for lost revenues.

Regulatory Viability

Requires state law changes, likely inconsistent with Prop 13, but existing precedent with Williamson and Mills Act. Without a specific change to state laws, the regulatory viability of this is not likely to support a present use tax for oceanfront parcels which could reduce their land value and discourage build out.

Ecological Impacts

No adverse effects to the coast ecology are anticipated. By definition, this measure would not be pursued unless the potential for adverse impacts is reduced.

Cost and Benefits

The cost of Present Use Tax Incentives is probably limited to the cost of negotiating the incentive and reduction in tax revenues to local jurisdictions.

4.1.6 Rolling Easements

Description

Rolling Easements are open space or conservation easements that move or ambulate with some identified reference feature (Figure 22). As the coast retreats the easement line migrates along with it, inland on a parcel, then any development is removed and becomes part of that easement. This approach ensures maintenance of beach width and protection of the natural shoreline by requiring humans to yield the right of way to naturally migrating shores. Rolling easements may be implemented by statute or, more typically, by specifying that a conservation easement “roll” or move landward as the shore erodes.

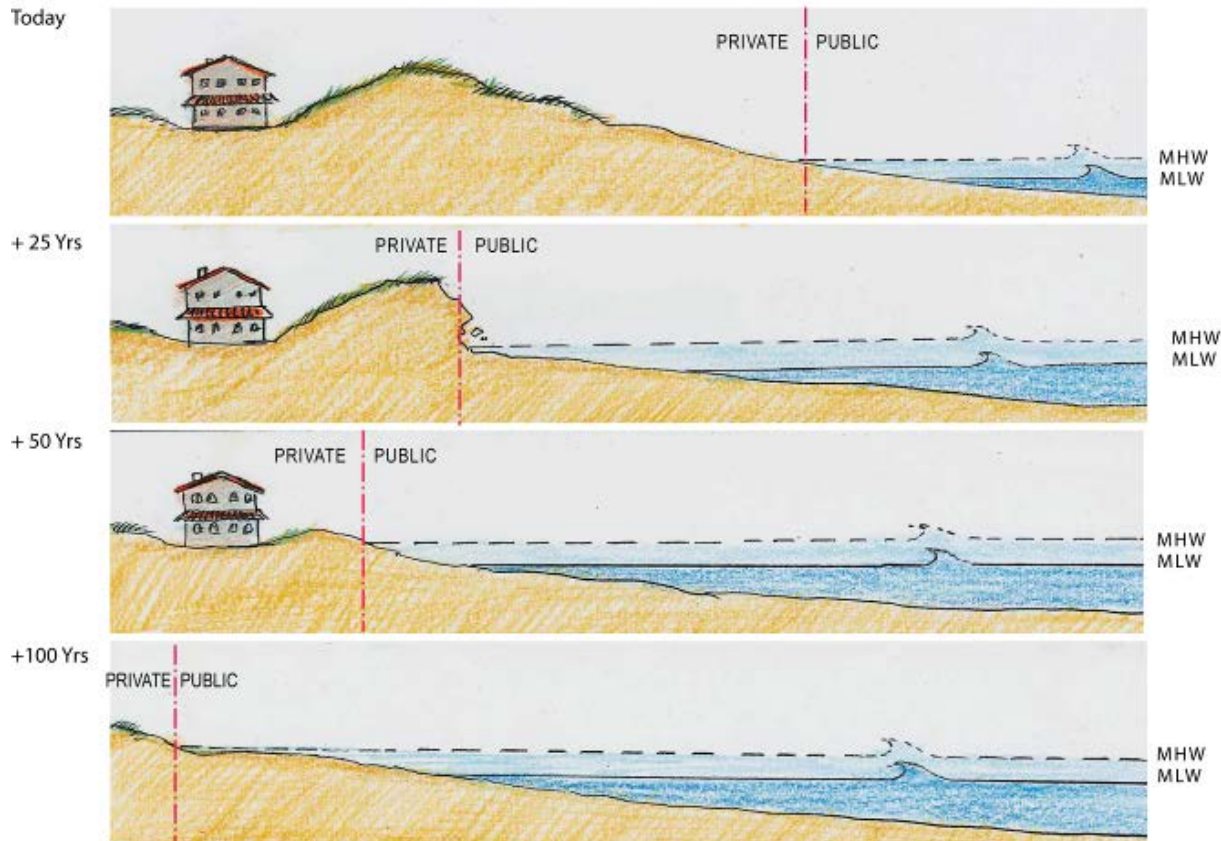


Figure 22 A Rolling Easement that follows an ambulatory shoreline

General Applicability

Rolling Easements are generally applicable to any parcel bounded on one side by a movable natural boundary (Table 16).

Specific Applicability

This management alternative is most relevant for application to Subregions 1, 2, 4, 6, and 7 to address critical erosion areas where structures exist or development can occur (Table 16).

Table 16 Summary of Evaluation Criteria for Rolling Easements

Evaluation Criteria	
Reduce threat to structures	No
Maintain Beach Width	Yes
Environmental Impacts	No
Recreational	Yes
Safety and Public Access	Yes.
Aesthetics	Yes.
Adaptability to Future Conditions	Yes
Cumulative Impacts	None
Certainty of Success	Highly Certain

Discussion

Rolling easements are based on some of the general concepts of common law regarding public and private ownership of land. California considers the mean high tide water line (MHW) a demarcation of the division of public and private land determined by the average of high tides over 18.6 years. This demarcation naturally fluctuates over time, by negligible amounts over the short-term but by large amounts over the long-term. In the long-term, this demarcation will retreat inland and encroach on private property. This landward encroachment of the MHW and the increased vulnerability of some coastal structures to inundation during high tide and/or storm events are often used to justify coastal armoring. Coastal armoring is an attempt to force the MHW to remain in a fixed location.

The practice of armoring the shore to protect private property impacts the public in several ways. First, it essentially permanently demarks the MHW line because coastal armoring remains in a fixed location while the beach erodes around it, causing the public beach area to eventually vanish. The impact of this permanent demarcation is to artificially continue to claim private property rights in an area that would normally become public property under the public trust doctrine. This situation normally results in decreased public access to the shore or total elimination of public access along and to the shore in specific areas. Second, armoring the shore increases the otherwise natural erosion rate to adjacent areas. The impact of this is a further loss of public beaches. Third, coastal armoring alters ecosystem function along the shore and potentially seaward as the coastal armoring affects physical and biological processes in the area of the armored shore.

A different approach to the encroaching MHW would be to implement a rolling easement approach. For example, the most seaward ten-feet of a landowner's property could be designated as a rolling easement, or +10 ft. above MHW. Similar to a conservation easement, this rolling easement could be donated or sold by the property owner to a government agency or non-profit organization, or the landward progression of the MHW over time simply could be recognized by the state as having altered the private/public property boundary along the shore, requiring no payment to the property owner. The landowner continues to own his/her property, but may not install coastal armoring to encumber the delineation of the private/public property line. The explicit or implicit rolling easement remains ten-feet wide at all times by moving landward as the shore (private/public boundary) retreats. This approach prevents the loss of wetlands and other important coastal zone habitats because they are allowed to naturally migrate inland. Rolling easements should discourage reinvestment in structures built on the property that are likely to be encumbered by the advance of the rolling easement as there is an acknowledged impermanence to the parcel's current size and condition. Over time, as the easement encompasses structures on the landowner's property, these structures would be required to be removed at the landowner's expense, as they may not remain within an easement without specific agreement. The rolling easement would lead to the eventual removal of the development in close proximity to the coast within the area covered by that easement. This approach is obviously less expensive for a local government than Fee Simple Acquisition and also allows the landowner to remain on and use the property for some amount of time and remove structures incrementally. Rolling easements that are established and/or recognized explicitly prior to landward construction should encourage the development of structures designed for cost effective incremental removal.

Rolling easements have both costs and benefits. More transaction costs can be anticipated in densely developed coastal areas. Like all easements, Rolling Easements will require some regular inspection and potential enforcement

Titus (1998) posits that Rolling Easements are an efficient means of adapting to rising sea levels because they impose no costs until the MHW moves, they have plenty of time to be incorporated into reasonable investment-backed expectations of property owners, and they may foster consensus on coastal development policies because property owners are compelled to admit the existence of sea level rise before they can argue that they should not be subjected to Rolling Easements.

Local governments can modify their planning policies to discourage the loss of public tidelands. Specifically, they can change their master plans and zoning regulations to explicitly indicate which areas of the coast could be armored and which should remain natural; include sea level rise projections and historical erosion rates into land use decisions regarding subdivisions of coastal property; and begin to plan the types of armoring that will be used in areas designated for protection (Titus 1998).

While California statutory law is silent on the topic of Rolling Easements, the state Coastal Commission has begun to impose a “no future seawall” condition on Coastal Development Permits for ocean front properties. This approach has arisen due to a provision in the state’s coastal statute that prohibits new development from requiring armoring when it is approved or in the future. The “no future seawall” conditions serve an important means of notice to property owners and should adjust their investment-backed expectations regarding the development potential of their ocean front properties.

Regulatory Viability

Rolling easements are highly viable in a regulatory context if voluntarily agreed to; viability is uncertain if the government relies on operation of the common law to recognize rolling easement. One of the attractive aspects of Rolling Easements is that they arguably allow states to reclaim title to property without incurring liability for a regulatory taking under *Lucas*. Caldwell & Segall argue that the public trust and other common law principles that underlie Rolling Easements are background principles under *Lucas*, and therefore, Rolling Easements should not pose takings problems (Caldwell & Segall, 2007). Kleinsasser concurs, finding that the public trust doctrine “underlies modern takings analysis.” Thus, the public trust doctrine provides a strong basis for states to claim title to newly submerged lands as the mean high tide moves inland. Although not yet challenged in court, requiring a rolling easement as a condition of approval would appear to meet both the nexus and proportionality requirements stipulated by the US Supreme Court and allow California to impose Rolling Easements on a case by case basis (Caldwell & Segall, 2007).

States like California that read the public trust expansively are best positioned to implement Rolling Easements in terms of both the geographic scope of the doctrine and the public rights it protects. Moreover, the California Coastal Act contains an express policy of expanding public access to the beach to the greatest extent feasible. To achieve this goal, the State may require dedication of easements or payment of mitigation fees as a condition of building permits. The ability to require easements gives the State significant powers to expand public beach access as long as the required dedications meet the

Supreme Court’s essential nexus test from *Nollan*. It should be noted, however, that the California Coastal Act includes a provision that suggests that coastal property owners have a qualified right to defend existing structures on their properties. California courts have found that this provision does not in fact accord an unqualified statutory right to defend a littoral property that overrides the Coastal Commission’s general permitting authority and ability to deny armoring permits. Nonetheless, uncertainty remains over whether the qualified right to armor *existing* structures under the Coastal Act would functionally prevent implementation of a rolling easement program for certain properties. (Peloso and Caldwell, 2010).

Ecological Impacts

Unknown, but likely beneficial to the sandy beach ecosystem with site specific impacts to sensitive dune habitats and species.

Cost and Benefits

Cost of Rolling Easements (Tables 17 – 19) depends on implementing mechanism, purchase price, and when the easement is acquired or imposed. See section 3.5.2 for the assumptions used in this measure. It is likely to reduce tax revenue from waterfront properties if ocean front properties experience devaluation due to easements. However, this approach may result in maintaining stronger property values for non-waterfront properties in the community (Kriesel & Friedman, 2002).

There may not be a “cost” to acquiring the easement if the government prevails against a challenge on a public trust or related common law theory, but such resolution may require litigation, which could involve significant legal costs. Alternatively, the functional rolling easement (in the form of a “no future armoring” policy) is implemented using a condition to a coastal development permit (CDP), and thus is considered “costless.”

Ultimately, the rolling easement could result in lost property tax revenue and decreased property values—but this is decades away. Also, one can assume there will be administrative costs associated with enforcing a rolling easement. Many of these were not factored into the analysis.

Table 17 Present Value of Benefits and Costs for Rolling Easements: Del Monte

Planning Horizon (Years)	0 to 5	6 to 25	26 to 50	51 to 100	0 to 100
Total Recreational Value above Baseline	\$ 2,649,094	\$ 7,362,147	\$ 5,508,566	\$ 3,093,987	\$ 18,613,794
Total Habitat Value above Baseline	\$ 838,842	\$ 1,971,606	\$ 2,267,272	\$ 657,134	\$ 5,734,853
Sum Benefits	\$ 3,487,936	\$ 9,333,753	\$ 7,775,838	\$ 3,751,121	\$ 24,348,648
Structural Adjustment Costs	0	0	0	0	0
MRWPCA	0	0	\$ 10,277,227	0	\$ 10,277,227
Cost of Private Property Compensation					
Cost of Pubic Property Compensation					
Construction/Nourishment Cost	\$ -	0	\$ -	\$ -	\$ -
Revetment Cost	\$ (43,200,000)	\$ -	\$ (12,757,080)	\$ (4,879,666)	\$ (60,836,746)
Total Cost	\$ (43,200,000)	\$ -	\$ (2,479,853)	\$ (4,879,666)	\$ (50,559,519)
Net Benefits	\$ 46,687,936	\$ 9,333,753	\$ 10,255,691	\$ 8,630,786	\$ 74,908,166
Benefit/Cost Ratio	NA	NA	NA	NA	NA

Table 18 Present Value of Benefits and Costs for Rolling Easements: Sand City

Planning Horizon (Years)	0 to 5	6 to 25	26 to 50	51 to 100	0 to 100
Total Recreational Value	\$ 10,331,640	\$ 18,929,245	\$ 8,068,351	\$ 3,086,197	\$ 40,415,432
Baseline	\$ 7,409,916	\$ 8,413,408	\$ -	\$ -	\$ 15,823,324
Total Habitat Value	\$ 16,933,333	\$ 25,930,217	\$ 7,750,579	\$ 2,829,750	\$ 53,443,878
Baseline	\$ 13,722,100	\$ 19,850,290	\$ 6,269,418	\$ 2,398,093	\$ 42,239,901
Sum Benefits	\$ 6,132,956	\$ 16,595,763	\$ 9,549,512	\$ 3,517,853	\$ 35,796,085
Structural Adjustment Costs	\$ -	\$ -	\$ -	\$ 23,642,591	\$ 23,642,591
MRWPCA	\$ -	\$ -	\$ 25,970,041	\$ -	\$ 25,970,041
Cost of Private Property Compensation					
Cost of Pubic Property Compensation					
Construction/Nourishment Cost	\$ -	\$ -	\$ -	\$ -	\$ -
Revetment Cost	\$ (180,000,000)	\$ -	\$ (53,154,499)	\$ (20,331,941)	\$ (253,486,440)
Total Cost	\$ (180,000,000)	\$ -	\$ (27,184,458)	\$ 3,310,650	\$ (203,873,808)
Net Benefits	\$ 186,132,956	\$ 16,595,763	\$ 36,733,970	\$ 207,203	\$ 239,669,893
Benefit/Cost Ratio	NA	NA	NA	NA	NA

Table 19 Present Value of Benefits and Costs for Rolling Easements: Marina

Planning Horizon (Years)	0 to 5	6 to 25	26 to 50	51 to 100	0 to 100
Total Recreational Value	\$ 10,446,180	\$ 19,139,101	\$ 8,157,800	\$ 3,120,411	\$ 40,863,493
Baseline	\$ 7,512,217	\$ 8,275,750	\$ -	\$ -	\$ 15,787,968
Total Habitat Value	\$ 21,357,208	\$ 31,537,626	\$ 10,675,252	\$ 4,083,353	\$ 67,653,439
Baseline	\$ 15,709,559	\$ 12,889,172	\$ -	\$ -	\$ 28,598,731
Net Benefits	\$ 8,581,612	\$ 29,511,804	\$ 18,833,052	\$ 7,203,765	\$ 64,130,233
Structural Adjustment Costs	0	0	0	0	0
MRWPCA	0	\$ 2,525,340	0	0	\$ 2,525,340
Cost of Private Property Compensation					
Cost of Public Property Compensation					
Construction/Nourishment Cost	\$ -	\$ -	\$ -	\$ -	\$ -
Revetment Cost	\$ (250,200,000)	\$ -	\$ (73,884,753)	\$ (28,261,398)	\$ (352,346,152)
Net Cost	\$ (250,200,000)	\$ 2,525,340	\$ (73,884,753)	\$ (28,261,398)	\$ (349,820,812)
Net Benefits	\$ 258,781,612	\$ 26,986,465	\$ 92,717,805	\$ 35,465,163	\$ 413,951,045
Benefit/Cost Ratio	NA	NA	NA	NA	NA

Benefit Cost Results

The results of the cost benefit analysis shows that Rolling Easements have a net positive cost benefit primarily as a result of avoidance of the construction costs associated with the revetments (Tables 17, 18, 19). There are positive net benefits of this measure at each planning horizon. The total benefits over the entire study for the 100 year planning horizon total about ~\$738 million with that made up of ~\$106 million in recreation and ecosystem benefits.

4.1.7 Structural Adaptation

Description

Structural Adaptation is the modification of the design, construction and placement of structures sited in or near coastal hazardous areas to improve their durability and/or facilitate their eventual removal (Table 20). This is often done through the elevation of structures or specific site placement. Structural Modification: Reconfiguring development to withstand progressively increasing coastal hazards. Examples are pile foundations that allow wave run-up and erosion to progress without damage to structures, and waterproofing or reinforcing for severe events.

General Applicability

Structural adaptation can be applied to any parcel or infrastructure although the cost and technical feasibility of an effective modification would be required (Table 20).

Specific Applicability

This management alternative is most relevant for application to Subregions 1, 2, 4, 6 and 7 to address critical erosion areas where structures exist or can be developed.

Theoretically, this could be done to elevate development such as the Ocean Harbor House, or Sanctuary Beach resort to reduce the risk to the structures. In fact, prior to the seawall construction, the seaward buildings were underpinned with columns and beams. This could also be applied to the Highway 1 corridor or Del Monte, adapting to higher water levels and erosion by elevating the roadway onto a causeway .

Most applicable to SMB is the elevation of roads on piles to enable erosion and shoreline transgression, particularly along vulnerable stretches of coast such as may be needed along Del Monte or stretches of Highway 1.

Table 20 Summary of Evaluation Criteria for Structural Adaptation

Evaluation Criteria	
Reduce threat to structures	Yes, although not permanently
Maintain Beach Width	Potentially
Economic Costs	Depends on adaptation likely increases costs
Environmental Impacts	Depends on type of adaptation and site characteristics
Recreational	Maintains
Safety and Public Access	Maintains
Aesthetics	Potential impact depends on type of adaptation
Regulatory Viability	Yes, may require revisions to construction or architectural standards
Adaptability to Future Conditions	Yes, potentially limited over long term
Cumulative Impacts	Potential impact to aesthetics
Certainty of Success	Certain

Discussion

Structural adaptation encompasses a wide range of ways to address the impacts of rising sea level and coastal hazards on structures. For existing structures that are or will be subjected to these threats, structural adaptation includes relocation, modification (such as elevating a road or a house). For structures yet to be built, structural adaptation focuses on modification of the traditional design and placement of structures to anticipate future environmental conditions. Examples include building structures on stilts or placing structures further landward than required by regulations.

Communities that participate in the National Flood Insurance Program must adopt and conform to building restrictions based on flood risk. For example, development in the “high velocity” V-zone of wave run-up and wave propagation must be constructed on piles with the lowest structural member above the 100-year flood elevation. Existing properties may be required to upgrade (structural modification) if significant improvements such as house remodel are accomplished.

Another structural adaptation approach could be to build the structure in a modular unit manner or to construct the foundation such that the structure could be readily moved away from hazardous areas.

Regulatory Viability

Structural modification is viable in the regulatory context if implemented through building codes and development standards in much the same way that structures must meet seismic standards.

Ecological Impacts

Little is known about the potential effects of structural adaptation in SMB. Effects would likely be site specific. Generally, the elevation of structures and roadways that would enable habitats to migrate landward would have a less damaging effect on the sandy beach ecosystem and maintain sand supply.

Cost and Benefits

The benefits and costs of structural adaptations have been modeled in a simple way in this analysis. See section 3.5.2 for the assumptions used to analyze this measure. We examined the loss of major roads using the lower end of the cost estimates which ranged from \$200 to \$500 a square foot. Using air photo analysis, we estimate the approximate square footage of the roads and costs of elevating on piles portions of Del Monte Ave, Highway 1, and some of the frontage roads

4.1.8 Habitat Adaptation

Description

Habitat Adaptation prepares for future shore retreat by designing habitats compatible with anticipated changes to environmental parameters. This provides habitats room to transgress, dunes that rollover, or migrate inland and upslope under a passive approach, or a more active adaptation approach in which habitats or more salt tolerant vegetation (crops) could be planted (Table 21).

General Applicability

Habitat modification is generally applicable to habitats that have continuity with undeveloped adjacent lands.

Specific Applicability

This measure has limited applicability to sand beaches in southern Monterey Bay, except to allow erosion to occur which is addressed in other measures. This management alternative is most relevant for application to Subregions 1, 2 and 3. Agricultural crop adaptation would be most relevant to Subregions 7 and 8.

Table 21 Summary of Evaluation Criteria for Habitat Adaptation

Evaluation Criteria	
Reduce threat to structures	Yes, although not permanently
Maintain Beach Width	Potentially
Economic Costs	Depends on adaptation, likely increases costs, potentially large increase if need to purchase upland adjacent lands
Environmental Impacts	Depends on type of adaptation and site characteristics
Recreational	Maintains
Safety and Public Access	Maintains
Aesthetics	Potential impact depends on type of adaptation
Regulatory Viability	Yes, may require revisions to construction or architectural standards
Adaptability to Future Conditions	Yes, potentially limited over long term
Cumulative Impacts	Potential impact to aesthetics
Certainty of Success	Certain where applicable

Discussion

A passive form of habitat adaptation occurs as wetland or shore habitats transgress or move inland and upward in response to sea level rise, although this is only possible when adjacent upland properties are undeveloped. A more planned strategy is to actively design and plant transitional flora, or flora that can thrive in both the current and future environmental setting. This strategy may include planting this transitional flora over time as needed and can be viewed as an adaptive management technique.

One key element of habitat adaptation is the maintenance of habitat connectivity as an essential part of climate change adaptation, which points to the need for continuous monitoring of conditions for which species are suited to shift with climate change or continuing erosion (Oregon Global Warming Commission, 2008). This connection between beaches and dunes is also crucial during storm events as much of the sandy beach ecosystem seeks refuge during high wave events.

For example, on agricultural lands habitat adaptation efforts may be to switch to more salt tolerant crops as there is a rise in sea level or sea water intrusion.

Wetlands and marsh habitats can be expanded by introducing sand, sediment and/or planting seagrass. EPA gives an overview of climate impacts in coastal areas and reviews adaptations options, including some habitat-related efforts (USEPA, 2009).

Regulatory Viability

Habitat adaptation is generally considered viable within a regulatory context except where impacts to existing valuable habitats might occur, especially with protected species.

Ecological Impacts

By definition, habitat adaptation would only occur if there were an expectation of net ecological benefit. However, the extent of ecological benefit depends on site specifics and scale of habitat alterations and adaptations.

Cost and Benefits

The cost of habitat adaptation was not estimated.

4.1.9 Setbacks for Development

Description

Use of setbacks is a technique, implemented at a local policy level, which requires new development to be located so that it can be safe from erosion and slope failure for some identified time period (Figure 23). Eventually the development can be expected to be at risk from erosion, and there will be the future question about whether the development should be removed or whether it should be protected.



Figure 23 Erosion Hazard Zones similar to those used to delimit development setbacks

General Applicability

Any coastal parcel potentially facing erosion and flood hazards being developed or redeveloped

Specific Applicability

Setback policies differ across the region, with varying methods of calculating the distance. This erosion mitigation measure is the current status quo for coastal management of erosion. Specifics of each setback

is decided by the local jurisdiction and submitted to the California Coastal Commission for approval as part of the LCP process (Table 22).

This management alternative is relevant to all areas with private property, and most relevant for application to the Subregions 1, 2, 3, 4, 6 and 7 to address possible new developments and redevelopments in these Subregions. The actual setbacks adopted in Local Coastal Programs (LCPs) are calculated differently for each of the jurisdictions in the study area and are summarized below.

State Parks in Fort Ord:

State Parks uses a 700-foot setback zone in anticipation of the 100-year erosion line.

Marina:

A setback line is determined at the time of a proposed development by a qualified geologist. It must be great enough to protect the economic life, at least 50 years, of the proposed development and east of the tsunami hazard zone.

Sand City:

A setback line is determined from the most inland extent of wave erosion and is based on at least a 50-year economic life for the project. South of Bay Avenue, in no event shall the setback be less than 200 feet from the mean high water line, as established by the City.

All new development in the coastal zone requires the preparation of geologic and soils reports to address impacts and recommended mitigation, and identify appropriate hazard setbacks or the need for protective structures. Protective structures must not reduce or restrict public access, adversely affect shore processes or increase erosion on adjacent properties (verbatim). An active recreation beach and public amenity zone, defined as between the mean high water line and the building envelope, shall be established.

The repair and expansion of a shore protective structure south of Tioga Avenue may only be permitted to protect Vista del Mar Street. Construction and maintenance of new shore protective devices, between existing ones, north of Tioga Avenue is only permitted where technically feasible based upon a geologic report. Construction of new protective structures on the old landfill site may be allowed if warranted by the geologic report and includes removal of debris.

Seaside:

A setback line for development adjacent to Roberts Lake and Laguna Grande is determined as a minimum of 50 feet from marsh or riparian vegetation (reduced to 20 feet for recreational trails and platforms). The setback line for all development proposed within an area subject to ocean storm waves and tsunamis is determined by the requirement that both the public and structural safety can be assured for a 75-year period without constructing any protective structures. The setback line determination is made by a qualified coastal engineer in a report detailing all of the required information. Public access impacts are mitigated by a requirement that all development proposed within a local coastal plan area must have at least a ten-foot wide lateral access easement as a condition of approval.

Monterey:

The California Coastal Act allows a city to create a local coastal program for specific segments within the city and to submit its proposed land use plan for certification prior to its proposed implementation plan. The City of Monterey currently has four of five land use plans certified by the California Coastal Commission, with the fifth land use plan and all implementation plans pending.

The Skyline land use plan segment was certified in 1992. It requires that new development create a drainage and erosion control plan to minimize runoff, prevent erosion, and avoid sedimentation and pollution downstream. It also requires a scenic setback of a minimum of 100 feet from Highway 68.

The Del Monte Beach land use plan segment was certified in 2003. It requires a site-specific geotechnical study and that new development not require shore protection for the life of the project. A deed restriction to waive all rights to protective devices associated with development on coastal dunes is required.

New development must be set back from the eroding coastal dunes sufficiently to protect it for the 100-year economic life of the project and is not allowed in tsunami run-up or storm wave inundation areas (excepting coastal dependent uses and public access improvements). Existing structures located within these areas may not construct additions or demolitions/rebuilds (excepting new development consistent with takings law and public utilities that cannot be feasible located elsewhere). For proposed development along the bay, the coastal erosion rate and tsunami and storm wave areas are determined by and included in the site-specific geotechnical studies. New development may not increase the erosion rate.

Future sea level rise is required to be included in the siting and design of new shore development and shore protection devices. Specifically, an increase in the historic rate of sea level rise must be reviewed and considered. Development must be setback and elevated to minimize or eliminate, to the maximum extent feasible, hazards associated with the anticipated rise in sea level over the expected 100-year economic life of the structure.

The anticipated landward migration of the sand dunes over the expected 100-year economic life of the structure must also be accounted for in proposed development occurring with the sand dunes. Sand dune migration should include anticipated sea level rise and historic dune erosion rate, among other requirements. Development must be setback from the frontal dunes and elevated to minimize or eliminate, to the maximum extent feasible, hazards from waves and inundation, as well as the anticipated rise in sea level over the expected 100-year economic life of the structure.

Where the construction of protective structures may be allowed, a geotechnical analysis must establish that the protective structure is necessary and that it is the least environmentally damaging feasible alternative. Other alternatives, such as relocating the structure or sand replenishment, are preferred. Constructed protective structures may not encroach on public land.

New development is subject to a setback line that is sufficient to prevent the need for protective structures for the life of the project. The setback may not be less than the 100-year coastal erosion line as determined using the most current methods and information.

The Harbor land use plan segment was certified in 2003. Where the construction of protective structures may be allowed, a geotechnical analysis must establish that the protective structure is necessary and that it is the least environmentally damaging feasible alternative. Other alternatives, such as relocating the structure or sand replenishment, are preferred. Protective shore structures built to protect existing legal structures and public beaches are required to include a beach maintenance program to prevent or to mitigate for loss of beach near the structure. Specific regulations for the Catellus east site apply.

New development is subject to a setback line that is sufficient to prevent the need for protective structures for the life of the project. The setback may not be less than the 100-year coastal erosion line as determined using the most current methods and information. If an existing shore protective structure needs maintenance or replacement, alternative designs and project management plans must be considered.

Proposed new development must have a site-specific geotechnical study and not require shore protection structures for the life of the project. A deed restriction to waive all rights to protective devices associated with development on coastal dunes is required.

New development is not allowed in tsunami run-up or storm wave inundation areas. Existing structures may demolish and rebuild and/or build additions only consistent with takings law and other specific exceptions. For proposed development along the bay, the coastal erosion rate and tsunami and storm wave areas are determined by and included in site-specific geotechnical studies.

Existing legal structures that do not conform to the LCP may be maintained if it does not increase the extent of nonconformity. Additions and improvements must comply with the current local coastal program.

Future sea level rise is required to be included in the siting and design of new shore development and shore protective devices. Specifically, an increase in the historical rate of sea level rise must be reviewed and considered. Development must be setback and elevated to minimize or eliminate, to the maximum extent feasible, hazards associated with the anticipated rise in sea level over the expected 100-year economic life of the structure.

The Laguna Grande/Roberts Lake land use plan segment has not yet been certified. Erosion must be minimized in new development by stabilizing and maintaining steep dunes and steep slope areas.

Table 22 Summary of Evaluation Criteria for Setbacks

Evaluation Criteria	
Reduce threat to structures	No for existing development, yes for future development, redevelopment
Maintain Beach Width	Yes
Economic Costs	Potential increase due to reduction in buildable footprint on parcels
Environmental Impacts	No. None within setback but the total depends on site specific development
Recreational	Yes. No impacts until medium/long term
Safety and Public Access	Yes. No impacts until medium/long term
Aesthetics	Yes. No impacts until medium/long term
Regulatory Viability	Yes, has been implemented, but potential opposition from landowners
Adaptability to Future Conditions	Yes until end of setback life (e.g. 50, 75 years)
Cumulative Impacts	None in short term, potentially in long term
Certainty of Success	Certain in short term, Uncertain over medium/long term

Discussion

A setback is usually established by determining where the building can be placed at present that will be located away from hazards for the expected life of the structure. Often it is determined by where other adjacent properties have been built (e.g. development line).

There are various means to determine setbacks, including a factor of safety approach, some planning horizon multiplied by the average annual recession rate, or some calculation of future recession based on specific sets of assumptions about future conditions.

Under the factor of safety (FS) approach, an acceptable factor of safety is determined against slope instability (normally taken as $FS \geq 1.5$ for static conditions and $FS \geq 1.1$ for dynamic or pseudostatic conditions) and add to that both the anticipated amount of erosion over the identified time period and a buffer.

Under the erosion rate method, some knowledge of historic changes over time must be known. This method has been implemented in the Hawaiian islands of Maui and Kauai, which is calculated using historical erosion rates times a 50 and a 75 year planning horizon, respectively. These laws are written specifically to acknowledge that it is either the above calculation or a set distance inland to provide for those locations where historic erosion rate information is either not known or invalid due to extenuating circumstances.

This siting strategy should prevent the need for armoring until the identified time period is over. However one of the largest shortcomings is that once the setback has been eroded nearly through, the structure is often protected resulting in the host of impacts associated with shore armoring.

In a review of setback lines established by various coastal states, benefits and drawbacks are identified. Perceived benefits include the ability to avoid armoring the beach during the specified time period, protecting beach width and maintaining natural coastal processes. Setbacks may also specify parameters for rebuilding after a catastrophic storm. In Maine and North Carolina, for example, repairs to existing nonconforming structures that will cost more than 50 percent of the structure's value must comply with the setback requirements. In New Jersey, setback regulations stipulate how to address issues of accretion as well. One drawback, however, is that erosion data is dynamic and requires continual updating. As an example, South Carolina updates their erosion data every eight to ten years. Another drawback may be potential takings litigation if property is deemed unbuildable due to application of a setback line. Lastly, setback lines simply defer risk and decision making to the future, when erosion has advanced and structures are once again at risk (NOAA, 2009).

Setback regulations may evolve over time, as in the case of Hawai'i. The state requires an arbitrary setback line, not based on erosion data. This setback line has proved insufficient as there has been widespread public beach loss. The island of Maui instituted additional regulations in 2003 that take into account historic erosion rates. Under the new ordinance, all development must either (a) be set back by an amount 50 times the annual erosion rate, plus 25 feet, or (b) adhere to the pre-existing statewide setback, whichever was more restrictive. Existing nonconforming structures seaward of the setback line or shore areas with protective structures were grandfathered in, likely to avoid a takings problem (NOAA, 2009).

North Carolina has established a tiered setback scheme that varies by building size and type. Most setback lines, measured from the first stable natural vegetation, are based on annual erosion rates. Structures of less than 5000 square feet must be set back by an amount equal to 30 times the average annual erosion rate. Adjustments to the setback line are made for areas that have much higher or lower erosion rates as compared to other areas. Additional requirements apply to larger structures like hotels and condos: buildings of 5,000 square feet or more must be set back by an amount equal to 60 times the average annual erosion rate or 120 feet from the vegetation line (NOAA, 2009).

Effectiveness – Maintaining beach width vs. protecting upland property

Under the use of setbacks as erosion mitigation measures, the intent is to remove the development as far back on the parcel so as to minimize future risk to the development. In practice, this only works for a certain time period which is determined by the erosion rate and time period. In Figure 24 below, the dry sand width remains the constant as the beach migrates inland, eroding the upland property during the initial time period. However, at some point in the future as the setback is eroded into, the development begins to be threatened and historically the property owner has applied for a coastal development permit to place shore armoring. In the case below we assume once erosion gets within 20' of the development then a revetment is constructed. This immediately loses a portion of the dry sand beach evidenced by the stair case drop in the beach width due to placement loss. Once the revetment is constructed, then the upland property ceases to erode, but the dry sand beach width erodes. It is also important to note that in the example below, we only calculate changes at a 5, 25, 50 and 100 years, so if the beach is still present in year 50 as in the case of Sand City, we assume that the beach width will persist until the next calculation point at 2100. In reality of the Sand City example, we expect the beach to disappear long before 2100, and in Marina we expect the beaches to disappear before 2050. As interpreted, the long term

effect of a setback policy in Southern Monterey Bay will be to lose all of our dry sand beaches by 2100, with beaches in Marina and Sand City likely disappearing in the next 50 years.

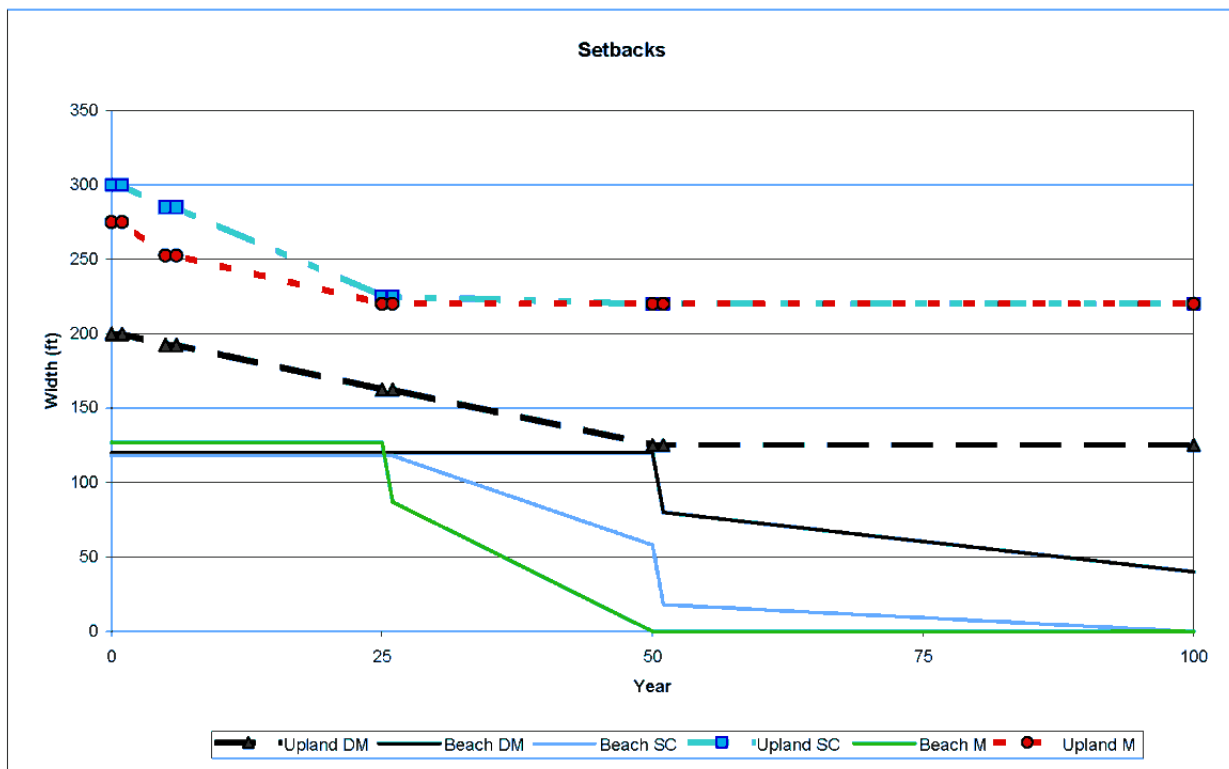


Figure 24 Effectiveness of setbacks at maintaining dry sand beach widths and upland property over time

Regulatory Viability

Yes, but if strict adherence to setbacks results in *no* development being permitted on a property, then the risk of regulatory taking liability increases dramatically.

Ecological Impacts

Generally, low for the sandy beach ecosystem, site specific impacts to upland dune habitats until setback is eroded and shore armoring is allowed at which point, ecological impacts would increase dramatically.

Cost of development setbacks (Tables 23 – 25) are relatively minor compared to some of the other land use planning tools. See Section 3.5.2 for the assumptions used in this measure. The largest cost is likely to be used for obtaining the site specific erosion rate and/or vegetation line data necessary to calculate the setback distance. Also, there may be significant administrative costs to implementing/enforcing setbacks and avoid takings claims, or fair market value compensation due to landowners with successful takings claims.

Table 23 Present Value of Benefits and Costs for Setbacks: Del Monte

Planning Horizon (Years)	0 to 5	6 to 25	26 to 50	51 to 100	0 to 100
Total Recreational Value above Baseline	\$ 2,454,388	\$ 5,209,529	\$ 5,616,133	\$ 1,013,802	\$ 14,293,851
Total Habitat Value above Baseline	\$ 770,696	\$ 1,235,423	\$ 1,465,504	\$ 131,076	\$ 3,602,699
Sum Benefits	\$ 3,225,084	\$ 6,444,952	\$ 7,081,637	\$ 1,144,878	\$ 17,896,550
Structural Adjustment Costs	0	0	0	0	0
MRWPCA	0	0	\$ 10,277,227	0	\$ 10,277,227
Cost of Private Property Compensation	\$ 142,686	\$ 1,153,592	\$ 2,321,062	\$ 1,398,504	\$ 5,015,845
Cost of Pubic Property Compensation	\$ 60,470	\$ 208,984	\$ 89,193	\$ 64,203	\$ 422,850
Construction/Nourishment Cost	\$ -	0	\$ -	\$ 4,879,666	\$ 4,879,666
Revetment Cost	\$ (43,200,000)	\$ -	\$ (12,757,080)	\$ (4,879,666)	\$ (60,836,746)
Total Cost	\$ (42,996,844)	\$ 1,362,576	\$ (69,597)	\$ 1,462,707	\$ (40,241,158)
Net Benefits	\$ 46,221,927	\$ 5,082,376	\$ 7,151,234	\$ (317,829)	\$ 58,137,709
Benefit/Cost Ratio	NA	NA	NA	NA	NA

Table 24 Present Value of Benefits and Costs for Setbacks: Sand City

Planning Horizon (Years)	0 to 5	6 to 25	26 to 50	51 to 100	0 to 100
Total Recreational Value	\$ 9,933,495	\$ 14,356,028	\$ 1,975,171	\$ -	\$ 26,264,694
Baseline	\$ 7,409,916	\$ 8,413,408	\$ -	\$ -	\$ 15,823,324
Total Habitat Value	\$ 16,933,333	\$ 25,930,217	\$ 7,276,000	\$ 2,398,093	\$ 52,537,642
Baseline	\$ 13,722,100	\$ 19,850,290	\$ 6,269,418	\$ 2,398,093	\$ 42,239,901
Sum Benefits	\$ 5,734,811	\$ 12,022,547	\$ 2,981,753	\$ (0)	\$ 20,739,111
Structural Adjustment Costs	\$ -	\$ -	\$ -	\$ 23,642,591	\$ 23,642,591
MRWPCA	\$ -	\$ 25,970,041	\$ -	\$ -	\$ 25,970,041
Cost of Private Property Compensation	\$ 208,199	\$ 745,512	\$ 378,881	\$ 1,092,315	\$ 2,424,907
Cost of Pubic Property Compensation	\$ 187,216	\$ 733,142	\$ 328,122	\$ 187,725	\$ 1,436,205
Construction/Nourishment Cost	\$ -	\$ -	\$ -	\$ 20,331,941	\$ 20,331,941
Revetment Cost	\$ (180,000,000)	\$ -	\$ (53,154,499)	\$ (20,331,941)	\$ (253,486,440)
Total Cost	\$ (179,604,584)	\$ 27,448,695	\$ (52,447,496)	\$ 24,922,631	\$ (179,680,755)
Net Benefits	\$ 185,339,396	\$ (15,426,148)	\$ 55,429,249	\$ (24,922,631)	\$ 200,419,865
Benefit/Cost Ratio	NA	NA	NA	NA	NA

Table 25 Present Value of Benefits and Costs for Setbacks: Marina

Planning Horizon (Years)	0 to 5	6 to 25	26 to 50	51 to 100	0 to 100
Total Recreational Value	\$ 10,446,180	\$ 19,139,101	\$ 8,157,800	\$ 3,120,411	\$ 40,863,493
Baseline	\$ 7,512,217	\$ 8,275,750	\$ -	\$ -	\$ 15,787,968
Total Habitat Value	\$ 21,357,208	\$ 31,537,626	\$ 10,675,252	\$ 4,083,353	\$ 67,653,439
Baseline	\$ 15,709,559	\$ 12,889,172	\$ -	\$ -	\$ 28,598,731
Net Benefits	\$ 8,581,612	\$ 29,511,804	\$ 18,833,052	\$ 7,203,765	\$ 64,130,233
Structural Adjustment Costs	0	0	0	0	0
MRWPCA	0	\$ 2,525,340	0	0	\$ 2,525,340
Cost of Private Property Compensation					
Cost of Public Property Compensation					
Construction/Nourishment Cost	\$ -	\$ -	\$ -	\$ -	\$ -
Revetment Cost	\$ (250,200,000)	\$ -	\$ (73,884,753)	\$ (28,261,398)	\$ (352,346,152)
Net Cost	\$ (250,200,000)	\$ 2,525,340	\$ (73,884,753)	\$ (28,261,398)	\$ (349,820,812)
Net Benefits	\$ 258,781,612	\$ 26,986,465	\$ 92,717,805	\$ 35,465,163	\$ 413,951,045
Benefit/Cost Ratio	NA	NA	NA	NA	NA

Benefit Cost Results

The results of the cost benefit analysis shows that Setbacks have a net positive cost benefit primarily as a result of deferring construction costs associated with the revetments until a later date (Tables 23, 24, 25). The benefits decline over time once the revetment is built and the beach narrows reducing the recreation and ecosystem benefits. The total benefits over the entire study for the 100 year planning horizon total about ~\$495 million with that made up of ~\$54 million in recreation and ecosystem benefits.

4.2 REGIONAL EROSION MITIGATION MEASURES – SOFT ENGINEERING APPROACHES

Soft Engineering Approaches refers to sand management measures primarily. This follows the practice vernacular that shore armoring are “hard” structural measures and sand placement is a “soft” non-structural measure. All the alternatives in the Coastal Regional Sediment management Plan were “soft” sand management measures (PWA et al., 2008).

4.2.1 Cessation of Sand Mining from the Beach

Description

Sand mining removed sand from the beach, backshore, nearshore, or in floodplains prevents this sand from being available for beach building. Reduction on the volume of sand extracted from the active shore area should expand the width and area of beach that is available to keep storm waves from damaging backshore development.

General Applicability

Any jurisdiction with regulatory authority over a sand mine operation.

Specific Applicability

This management alternative is most critical to for application to Subregions 6 and 7, but important to the entire southern Monterey Bay littoral cell to address critical erosion throughout (Table 26).

CEMEX INC owns two parcels 376 and 26 acres (Figure 5). The larger which has the structural improvements is assessed at \$15.1 Million while the smaller one at \$73,222, based on public records readily available but not verified. Both of these have ocean frontage with the smaller one located to the north of the larger developed parcel.

Table 26 Summary of Evaluation Criteria for Cessation of Sand Mining

Evaluation Criteria	
Reduce threat to structures	Not directly, but indirectly regional benefits to all SMB by increasing sediment supply and reducing erosion rates
Maintain Beach Width	Yes
Economic Costs	Unknown – depends on mechanism to cease, ability to acquire comparable sources of sand. No local loss of tax revenue
Environmental Impacts	No. Improves
Recreational	Yes. Improves
Safety and Public Access	Yes. Improves
Aesthetics	Yes. Improves
Regulatory Viability	Probably Feasible – likely require regulatory and/or judicial action to resolve
Adaptability to Future Conditions	Yes improves sediment supply
Cumulative Impacts	Benefit to entire region – potential increase in cost of construction grade materials
Certainty of Success	Certain to improve sediment supply, certain to reduce erosion rates, although magnitude less certain along entire study region

Background

The first sand mine in southern Monterey Bay started at Marina in 1906 by surface mining of the dunes (which does not impact beach erosion). By 1950, there were five additional sand mines that operated below MHW using drag-lines to dredge sand directly from the ocean. These mines were closed in the late 1980's when the USACE did not renew their mining permits as they determined that sand mined from the ocean caused severe coastal erosion. The mining production at Marina increased in 1965 by introducing a dredge to obtain sand from a pond created in the back beach, which captures littoral sand transport from the ocean by overwash of the berm during storms. The mine subsequently increased its production to match the total output of all previous mines combined. Therefore, even after the closure of the five drag-line mines, the total amount of mined sand derived from the ocean has remained essentially unchanged at about 200,000 cu.yd./year for the last sixty years.

Southern Monterey Bay was identified by the USGS (Hapke et al., 2008) as the most erosive shore on average in California. A comprehensive study called the Sand City Shore Erosion Study (Moffatt & Nichol, 1989) concluded that sand mining had greatly increased coastal erosion in southern Monterey Bay. A conclusion of the CRSMP for southern Monterey Bay (PWA et al., 2008) was that a primary cause of high erosion rates in SMB is the sand mine operated by CEMEX (who bought the mine in 2000) within the City of Marina.

Impact of Cessation of Mine

A quantitative measure to answer how much erosion would be mitigated by stopping sand mining requires an estimate of the change in beach erosion rates and subsequent decreases in dune erosion owing to cessation of sand mining. Erosion rates in the southern subcell of southern Monterey Bay decreased significantly after the drag-line sand mining stopped in Monterey and Sand City in the late 1980's (Table 4, Thornton et al., 2006, PWA et al., 2008). This decrease in erosion rates can provide an estimate of the impact of stopping sand mining. The sand mines were located 3.0, 3.1 and 3.5 miles from Wharf II and mined an average of 110,000 cu.yd./year between 1940 and 1988. The cumulative alongshore percent decrease in erosion rate from the time of intensive mining in Monterey and Sand City (1940-1984) compared with the time after closure of these mines and the intensified mining at the CEMEX mine in Marina (1985-2005) as a function of distance from Wharf II is shown in Figure 25. For example, the average percent decrease in erosion rate between Wharf II and mile 3.7 is 60%. A number of conclusions can be made: 1) a significant decrease in erosion rate occurred after stopping sand mining within the southern subcell ranging from 72% near Wharf II to 60% at mile 3.7; 2) the percent declines continuously to the Salinas River, indicating that the CEMEX mine impacts the entire southern Monterey Bay littoral cell; 3) the impact of continued mining is most profound within +/-2.5 miles of the CEMEX mine, which includes the entire shore of the City of Marina; and 4) beach erosion actually has increased by at least 10% when considering the entire southern Monterey Bay littoral cell (the percent decrease in erosion rate goes negative starting at mile 8.5). The results suggest that, as a first approximation, stopping sand mining would result in at least a 60-72 percent decrease in beach erosion in the southern subcell between Wharf II and mile 3.7. Since the amount of sand mined in Marina by CEMEX is approximately 200,000 cu.yd./year, which is almost twice the amount mined in Monterey and Sand City before closure, it is expected that there might be an even greater percentage decrease if it were stopped. It is estimated that the 60-70% decrease in erosion is a lower bound if the mining were stopped as the mining in Marina is assumed to have continued to cause erosion in the southern subcell owing to interruption of the littoral drift from the north and the nearly twice as much mined sand in Marina.

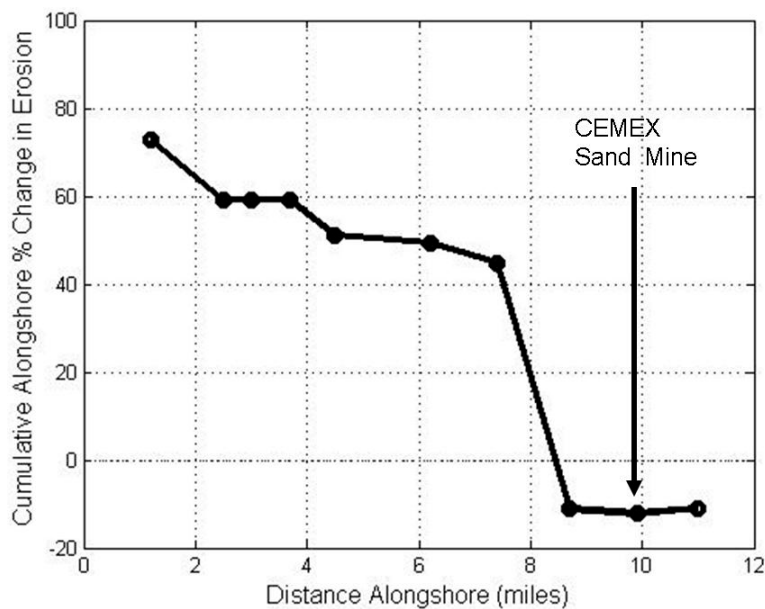


Figure 25 Cumulative alongshore percent decrease in erosion rate from time of intensive mining in Sand City and Monterey (1940-1984) compared with the time of the closure of these mines and intensified mining at the CEMEX mine in Marina (1985-2005) as a function of distance from Wharf II

Revised sediment budgets are presented in Table 27, which provide quantitative volumes of sand available to the littoral system resulting from mine closure. The sediment budget after the closure of the operations dredging sand directly from the ocean in the late 1980's is included for comparison. It is assumed that if the CEMEX sand mine is closed, beach erosion will decrease by at least 60 percent (average of southern subcell). A basic assumption is that dune recession occurs at the same rate as beach erosion (Reid, 2005). Therefore in revising the sediment budget presented in the CRSMP for southern Monterey Bay in Table 8 (PWA, 2008), the dune erosion and the beach and shoreface loss quantities are simply multiplied by a factor of $(1-0.6) = 0.4$.

A second revised sediment budget is presented in Table 27 under the scenario that CEMEX is limited to 80,000 cu.yd./year, which is the amount of sand mined at the Marina site at the time the Coastal Commission came into being. It is assumed that the beach and dune recession would be reduced by the percent of mining decrease $(120,000/200,000)$ times the 0.6 decrease assumed if the mining stopped altogether, which equals 0.36. The multiplier factor applied to the dune and beach erosion is then $(1 - 0.36) = 0.64$.

Table 27 Revised sand budget for littoral cell between Wharf II and the Salinas River for closure of CEMEX sand mine operation and a decrease in mining operation to 40%

		<u>Volume (yd³/year X 1000)</u>		
Budget Component		1984 – 2005	mine closure	mine 40%
1) Inputs	Salinas River	10	10	10
	Dune Erosion	200	80	128
	Net alongshore transport from the South	70	70	70
2) Outputs	Sand Mining	200	0	80
	Dune Accretion by wind	28	28	28
	Offshore	268-398	38-90	130-213
3) Change in Storage	Beach and Shoreface loss	-250 to -380	-100 to -152	-160 to -243
	Residual = (1) – (2) – (3)	0	0	0

The sediment budget gives an independent estimate of how much additional sand would be available to the southern Monterey Bay littoral cell if the CEMEX operation were curtailed or closed based on incorporating the rates of dune erosion from Figure 25. The differences between the beach and shoreface losses of the in sediment budget (1984-2005) and mine closure of 150 to 228,000 cu.yd./year is consistent with stopping the current mining amount of 200,000 cu.yd/year.

Jurisdiction

There presently is no permit required for the CEMEX sand mine operation. The USACE determined recently (Hicks letter, July 8, 2010) that they do not have jurisdiction based on Section 10 of the Rivers and Harbors Act of 1899 since the connection between the ocean and the pond is above MHW. Even though the mine is within City of Marina, the city has no jurisdiction and derives no direct tax revenue. Since CEMEX was plowing sand into the pond and the pond elevation is below MHW, the operation comes under Section 4 of the Clean Water Act. An injunction was placed on CEMEX in 2009 prohibiting them to bulldoze sand from the berm into their pond on this basis, but does not restrict the amount of mining. It can be argued that the Coastal Commission has jurisdiction over increases in mining since its inception in 1972. The Sierra Club requested (letter dated February 2009) that the Coastal Commission require a permit for all sand mined in excess of 80,000 yd³/year by CEMEX at Marina, which is the amount of sand mined in 1972. The request has been under jurisdictional review since.

Effectiveness – Maintaining beach width vs. protecting upland property

Under cessation of sand mining from the beach as erosion mitigation measures, the effect would be to substantially reduce erosion rates of upland property (Figure 26). This would indicate that the dry sand beach widths would remain the same while upland property is eroded. For comparison, examine Figure 26 below with Figure 17 (Land Use Planning Measures). The primary difference is that under the cessation of sand mining, upland property that would be eroded in 50 years with existing erosion rates would likely remain for nearly 100 years.

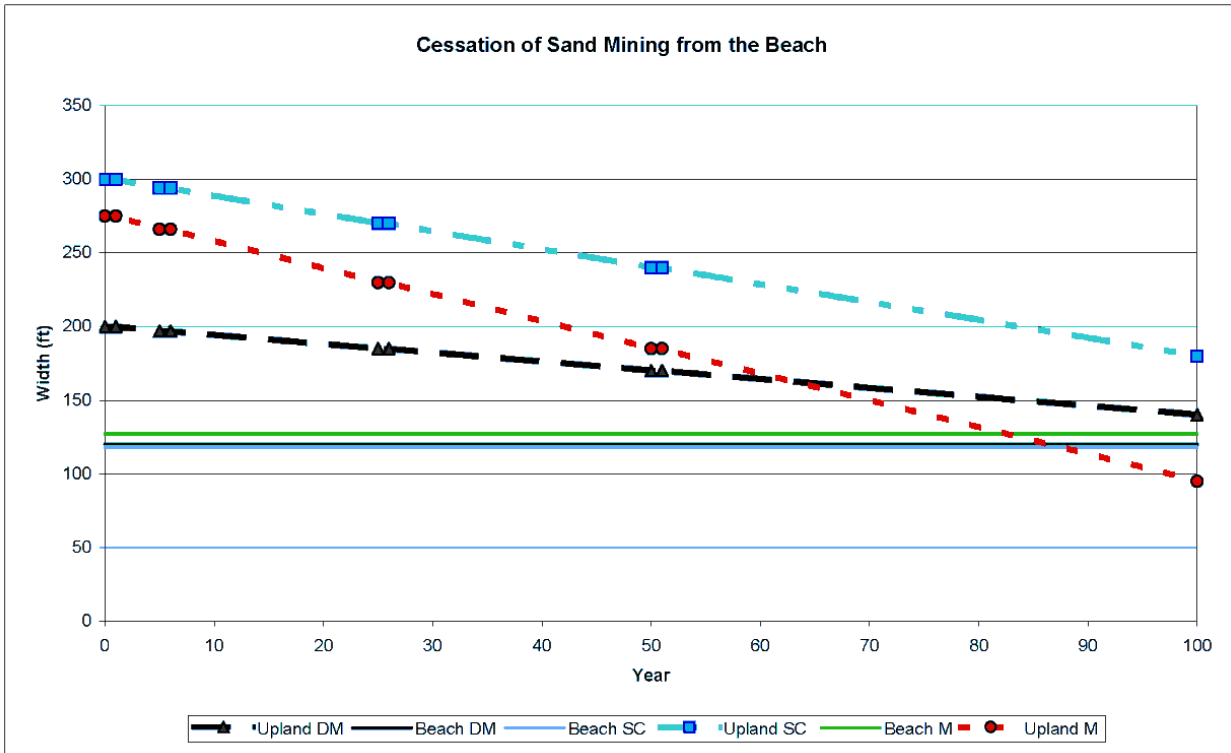


Figure 26 Effectiveness cessation of sand minding from the beach at maintaining dry sand beach widths and upland property over time

Regulatory Viability

Cessation of sand mining is considered viable since it is a man made action that can stop and was stopped at other sand mines in the area around 1990. However, the specifics of the Marina sand mining operation complicate regulatory analysis. However, a regulatory and/or judicial intervention may be required to resolve jurisdictional and regulatory compliance issues.

Ecological Impacts

The ecological impact of cessation of sand mining is expected to be strongly positive in that erosion will slow to natural levels and the adverse impacts caused by mining will not continue to accumulate. This cessation would have a positive benefit to dune habitats.

Cost and Benefits

Tables 28 through 30 present the benefit and cost analysis for ceasing sand mining. See Section 3.5.2 for the assumptions used in this measure. The baseline scenario includes the use of a revetment and the recreational and ecological benefits represent the differences between cessation of sand mining and the baseline scenario of a revetment. Our analysis did not include the losses to CEMEX from stopping the mining. The cost of closing the sand mine would avoid the expense of armoring and replacing the MRWPCA sewer infrastructure and other properties and the cost savings is greater than a present value equal to \$124.5 million in 2010 dollars.

Table 28 Present Value of Benefits and Costs for Ceasing Sand Mining: Del Monte

Planning Horizon (Years)	0 to 5	6 to 25	26 to 50	51 to 100	0 to 100
Total Recreational Value above Baseline	\$ 2,532,610	\$ 6,087,683	\$ 6,665,503	\$ 2,050,106	\$ 17,335,903
Total Habitat Value above Baseline	\$ 866,100	\$ 2,266,079	\$ 2,678,726	\$ 814,197	\$ 6,625,102
Sum Benefits	\$ 3,398,710	\$ 8,353,763	\$ 9,344,229	\$ 2,864,303	\$ 23,961,005
Structural Adjustment Costs	\$ -	\$ -	\$ -	\$ -	\$ -
MRWPCA	\$ -	\$ -	\$ -	\$ 3,186,638	\$ 3,186,638
Cost of Private Property Compensation	\$ 1,000,000	\$ -	\$ 295,000	\$ 1,044,000	\$ 2,339,000
Cost of Pubic Property Compensation	\$ 24,188	\$ 83,594	\$ 35,677	\$ 21,044	\$ 164,502
Construction/Nourishment Cost	\$ -	\$ 0	\$ -	\$ -	\$ -
Revetment Cost	\$ (43,200,000)	\$ -	\$ (12,757,080)	\$ (4,879,666)	\$ (60,836,746)
Total Cost	\$ (42,175,812)	\$ 83,594	\$ (12,426,402)	\$ (627,984)	\$ (55,146,605)
Net Benefits	\$ 45,574,522	\$ 8,270,169	\$ 21,770,632	\$ 3,492,287	\$ 79,107,610
Benefit/Cost Ratio	NA	NA	NA	NA	NA

Table 29 Present Value of Benefits and Costs for Ceasing Sand Mining: Sand City

Planning Horizon (Years)	0 to 5	6 to 25	26 to 50	51 to 100	0 to 100
Total Recreational Value	\$ 10,134,107	\$ 16,744,324	\$ 5,684,049	\$ 2,015,504	\$ 34,577,985
Baseline	\$ 7,409,916	\$ 8,413,408	\$ -	\$ -	\$ 15,823,324
Total Habitat Value	\$ 17,160,486	\$ 28,384,159	\$ 9,658,491	\$ 2,953,380	\$ 58,156,516
Baseline	\$ 13,722,100	\$ 19,850,290	\$ 6,269,418	\$ 2,398,093	\$ 42,239,901
Sum Benefits	\$ 6,162,577	\$ 16,864,785	\$ 9,073,122	\$ 2,570,791	\$ 34,671,276
Structural Adjustment Costs	\$ -	\$ -	\$ -	\$ 23,642,591	\$ 23,642,591
MRWPCA	\$ -	\$ -	\$ 11,309,061	\$ -	\$ 11,309,061
Cost of Private Property Compensation	\$ 83,280	\$ 287,815	\$ 127,074	\$ 167,554	\$ 665,723
Cost of Pubic Property Compensation	\$ 73,398	\$ 264,164	\$ 128,787	\$ 77,087	\$ 543,436
Construction/Nourishment Cost	\$ -	\$ -	\$ -	\$ -	\$ -
Revetment Cost	\$ (180,000,000)	\$ -	\$ (53,154,499)	\$ (20,331,941)	\$ (253,486,440)
Total Cost	\$ (179,843,323)	\$ 551,979	\$ (41,589,577)	\$ 3,555,291	\$ (217,325,630)
Net Benefits	\$ 186,005,900	\$ 16,312,806	\$ 50,662,699	\$ (984,500)	\$ 251,996,905
Benefit/Cost Ratio	NA	NA	NA	0.7	NA

Table 30 Present Value of Benefits and Costs for Ceasing Sand Mining: Marina

Planning Horizon (Years)	0 to 5	6 to 25	26 to 50	51 to 100	0 to 100
Total Recreational Value	\$ 10,110,428	\$ 15,338,379	\$ 4,688,750	\$ 1,779,922	\$ 31,917,479
Baseline	\$ 7,512,217	\$ 8,275,750	\$ -	\$ -	\$ 15,787,968
Total Habitat Value	\$ 21,830,823	\$ 33,018,605	\$ 10,832,113	\$ 4,143,354	\$ 69,824,894
Baseline	\$ 15,709,559	\$ 12,889,172	\$ -	\$ -	\$ 28,598,731
Net Benefits	\$ 8,719,474	\$ 27,192,061	\$ 15,520,863	\$ 5,923,276	\$ 57,355,674
Structural Adjustment Costs	0	0	0	0	0
MRWPCA	0	\$ -	0	0	\$ -
Cost of Private Property Compensation	\$ 2,173,557	\$ 1,077,184	\$ 5,134,238	\$ 1,044,000	\$ 9,428,979
Cost of Public Property Compensation	\$ 858,237	\$ 2,966,069	\$ 1,268,600	\$ 21,044	\$ 5,113,949
Construction/Nourishment Cost	\$ -	\$ -	\$ -	\$ -	\$ -
Revetment Cost	\$ (250,200,000)	\$ -	\$ (73,884,753)	\$ (28,261,398)	\$ (352,346,152)
Net Cost	\$ (247,168,205)	\$ 4,043,252	\$ (67,481,916)	\$ (27,196,355)	\$ (337,803,224)
Net Benefits	\$ 255,887,680	\$ 23,148,808	\$ 83,002,779	\$ 33,119,631	\$ 395,158,898
Benefit/Cost Ratio	NA	NA	NA	NA	NA

Benefit Cost Results

The results of the cost benefit analysis shows that Ceasing Sand Mining from the Beach have high net benefits primarily as a result of deferring construction costs associated with the revetments and reducing erosion rates which reduce private and public costs as well as costs associated with the replacement of the MRWPCA infrastructure (Tables 28, 29, 30). The total benefits over the entire study for the 100 year planning horizon total about ~\$726 million with that made up of ~\$114 million in recreation and ecosystem benefits.

As one can see in the tables above, ceasing sand mining yields substantial benefits in each reach. Indeed the present value of increased habitat and recreational value over the entire 100 year period for all three reaches is approximately \$45 million dollars. If one assumes that cessation of sand mining is an effective alternative to revetments the savings are even greater.

4.2.2 Opportunistic Sand Placement (SCOUP)

Description

Opportunistic sand is sand that is extracted from a flood channel, debris basin, navigation channel, harbor area, a by-product of construction or other source, where the main reason for extracting the sand is not to use it for beach nourishment. It is considered opportunistic sand if it can be made available for beach nourishment as a complement to the effort to remove it from its initial location (Figure 27). Opportunistic sand placement is also known as part of the Sediment Compatibility and Opportunistic Use Program (SCOUP) of the Coastal Sediment Management Workgroup (CSMW).



Figure 27 Opportunistic Sand Placement – Conceptual Schematic

General Applicability

An opportunistic placement program requires the identification of potential sources and placement sites. Typically an interim location to stockpile sediments is required to obtain enough material to have a positive benefit to beach sand volumes. As a stand-alone measure opportunistic sand placement would be unlikely to mitigate for erosion on a regional scale and is considered to have an incremental short-term benefit that would improve the effectiveness of other measures.

Specific Applicability

This management alternative is most relevant for application to Subregions 1-2 to address critical erosion areas in these Subregions. Within SMB as a whole, the regional application of opportunistic sand placement is not likely to resolve erosion issues (Table 31).

Table 31 Summary of Evaluation Criteria for Opportunistic Sand Placement

Evaluation Criteria	
Reduce threat to structures	Potential- depends on volume of material
Maintain Beach Width	Yes
Economic Costs	Potentially high transportation costs, potential loss of revenue from selling sediment for other uses
Environmental Impacts	Yes, degree depends on methods of acquisition and placement, distance from source to receiver site, scale of impacts to biologic communities, potential turbidity short term impacts
Recreational	Yes, Improves
Safety and Public Access	Yes, Improves but potential adverse change to wave breaking
Aesthetics	Depends on sediment compatibility
Regulatory Viability	Feasible but uncertain, needs regional permit to streamline stockpiling and placement; would require amendments to the MBNMS Designation Document
Adaptability to Future Conditions	Yes
Cumulative Impacts	Reduces by maintaining sediment supply to the coast
Certainty of Success	Reasonable certainty, depends on volumes of material and compatibility with existing beach sand

Discussion

Opportunistic beach nourishment (or beneficial use of sediment) was initiated in the state of California in 2001 in the Santa Barbara littoral cell, under the authority of the Beach Erosion Authority for Clean Oceans and Nourishment (BEACON), a regional joint powers agency that deals with coastal erosion and beach problems in Santa Barbara and Ventura County. The objective of this program was to obtain a five-year permit from all necessary regulatory agencies to allow the opportunistic beach-quality sediments to be placed on beach fill sites without the need for individual project permits. This program was successfully implemented and recently renewed its five-year permit in 2009.

The opportunistic sand use program (SCOUP) is a project facilitated by CSMW. CWMW developed a template for development of a program for the beneficial use of sediments generated by other activities (referred to as “opportunistic” sediment sources) for nourishment of coastal areas (SCOUP Program; Moffatt & Nichol, 2006). The SCOUP was initially designed in San Diego and developed programmatic guidance for permitting and approvals. It identified locations where the sediment should be placed (called “receiver” sites), specified sediment requirements and tests, as well as other factors that make individual, small sediment placement projects feasible. The SCOUP process and the resulting documents can help raise the awareness of regional sediment management among non-coastal entities that sediment is a resource to our coastal communities. The SCOUP is implemented regionally to account for local conditions including local sediment sources and receiver sites, as well as local constraints such as sensitive ecologic resources and seasons.

Additional documents also provide good references for beach nourishment in Southern Monterey Bay. The related *Regional General Permit 67 Discharges of Dredged or Upland-Derived Fill Materials for*

Beach Nourishment (US Army Corps of Engineers and associated certification by Regional Water quality Control Board) provides a template for possible use in Southern Monterey Bay, even though it applies only to southern California. Another pertinent template, for example, is the Initial Study and Mitigated Negative Declaration (MND) for the SCoup Oceanside Pilot Program (City of Oceanside and EDaw, 2005). Multiple other documents are listed in the southern Monterey Bay CRSMP bibliography, notably including the CSMW *Review of Biological Impacts Associated with Sediment Management and Protection of California Coastal Biota* (draft), which addresses key environmental issues associated with effects of beach nourishment. Finally, recent research and publications examining the discharge of sediment with larger fractions of finer (not sand) sediments at Santa Cruz and Tijuana Slough have produced information on impacts of turbidity that will be considered (USGS 2007; Jon Warrick, USGS personal communication).

Sand size is a factor in sand movement. If a beach is nourished with sand that is coarser than what is there through natural processes, the nourishment sand normally will remain on the beach longer than a similar volume of less coarse sand. An extreme example would be if rocks and cobbles were substituted for sand grains. The grain size change can alter the beach slope as well as the look and feel of the beach.

Back-Passing:

Back-passing takes sand that was being carried downcoast by waves and currents and relocates it farther upcoast so it can be carried past certain sections of coast more than one time. Back-passing is often considered for locations where the downcoast area is a sand sink (a canyon or a harbor) and the upcoast area is one that needs more sand. Back-passing does not add to the total volume of sand in the littoral system, but recycles sand through a portion of the transport area where it can be most beneficial. One possible example could be sand capture at the head of the Monterey submarine canyon and backpassing sediment to the southern bight (Subregions 1-4)

Effectiveness – Maintaining beach width vs. protecting upland property

Under the use of opportunistic sand placement as an erosion mitigation measure beach width remains constant, and the upland property erosion is reduced for the reaches where erosion rates are below - 1.5ft/year (Figure 28). As interpreted, this would require roughly 75,000 cy of sand to be placed every 2 to 5 years: a rate of once every 5 years was used. However, the CRSMP (PWA et al., 2008) identified this volume based on maintenance dredging of Monterey Harbor once every 25 years or so. This volume was estimated to compensate for erosion for 2 to 3 years in the low erosion area of the southern bight (Monterey area). Consequently, the effectiveness of this placement rate is limited. Also, the availability of 75,000 cubic yard every 5 years (or around 400,000 cubic yards every 25 years) is uncertain and unlikely. Still, it is expected that opportunistic sand placement would be a worthwhile over the short term where erosion rates are low and finer sands more consistent with inland sediment sources exist. For shore reaches with erosion rates greater than 1.5 feet/year, opportunistic sand placement may be incrementally worthwhile but is not likely to have much effect on mitigating upland erosion.



Figure 28 Effectiveness of opportunistic use of sand (SCOUP) at maintaining dry sand beach widths and upland property over time (about 75,000 cubic yards every 5 years)

Regulatory Viability

Uncertain, depends on the specific placement methods and impacts. The southern Monterey Bay region is relative to the southern California areas where a SCOUP has been developed and where beach nourishment has been accomplished. The Monterey Bay National Marine Sanctuary (MBNMS) is located immediately offshore and imposes more extensive environmental restrictions. Dredging and dredged material disposal are prohibited activities except where authorized through disposal site designations by the Environmental Protection Agency (USEPA). This prohibition is formalized in the Sanctuary Designation Document (Code of Federal regulations (CFR) Title 15, Section 922), and to revise this prohibition to allow for the placement of sand obtained through dredging would require environmental review under the National Environmental Protection Act (NEPA) and potentially review by the appropriate Congressional Committee.

Ecological Impacts

There is little site-specific information available for the likely ecological impacts of opportunistically placed sediments on the ecological value of the habitats of SMB. Disturbance to foraging and nesting shorebirds is one likely effect as is compaction of sediments, especially when vehicular traffic is involved in the placement. The impacts will vary based on the actual placement method and the receiver site

specifics on sensitive species and habitats. Any opportunistic sand placement program for SMB would require mitigation measures to avoid impacts to sensitive habitats and species. Our research indicates that the proposed placement rate every 5 years could have an adverse effect on beach ecology due to the frequent disturbances, indicating that site specific and project specific studies are needed in addition to a programmatic type of analysis such as the CSMW Biological Impacts Analysis presently underway.

Cost and Benefits

For opportunistic sand nourishment, the findings from the physical process analyses (Figure 28) show that the long-term effectiveness of this measure to reducing erosion is doubtful. Since it is not an effective long term erosion mitigation measure we assessed the incremental benefit of placing sand on the beach to demonstrate its benefits as an additional element of a longer term strategy (Tables 32, 33, 34). It is assumed that much of this opportunistic material is acquired at little to no cost. In many cases, there may actually be a cost savings to the entity providing the sediment source by avoiding or reducing transportation and disposal costs. For this analysis the cost increment to transport and place the sand is a project cost.

Table 32 Incremental Benefits of Opportunistic Sand Placement: Del Monte

<u>Erosion Rate: 1.5 ft/year</u>			
Subregion length: 2.4 km	per Subregion	per km	per ft
Total Benefits	\$ 1,974,062	\$ 822,256	\$ 250.70
Total Costs	\$ 192,000	\$ 80,000	\$ 24.38
B/C	10.28	10.28	10.28
Net Benefits (benefits – costs)	\$ 1,782,062	\$ 742,526	\$ 226.32

Table 33 Incremental Benefits of Opportunistic Sand Placement: Sand City

<u>Erosion Rate: 3.0 ft/year</u>			
Subregion length: 10 km	per Subregion	per km	per ft
Total Benefits	\$ 5,291,067	\$ 529,017	\$ 161.27
Total Costs	\$ 800,000	\$ 80,000	\$ 24.38
B/C	6.61	6.61	6.61
Net Benefits (benefits – costs)	\$ 4,491,067	\$ 449,107	\$ 136.89

Table 34 Incremental Benefits of Opportunistic Sand Placement: Marina

<u>Erosion Rate: 4.5 ft/year</u>			
Subregion length: 13.9 km	per Subregion	per km	per ft
Total Benefits	\$ 6,281,588	\$ 451,913	\$ 137.74
Total Costs	\$ 1,112,000	\$ 80,000	\$ 24.38
B/C	5.65	5.56	5.56
Net Benefits (benefits – costs)	\$ 5,169,588	\$ 371,913	\$ 113.36

It is apparent that in the short term, an opportunistic program would have a very high benefit cost ratio especially in the Southern Bight (Subregions 1 and 2) where erosion rates are lowest. Additional analyses could be completed, beyond the scope of this Alternatives Study, to optimize the cost benefit analysis for use in determining and prioritizing the optimal receiver and stockpile sites.

4.2.3 Beach Dewatering – Introduction

Generally, beach dewatering involves the removal of water from the beach to increase the natural accretion processes. Dewatering works on the hypothesis that a dry beachface will improve swash infiltration and thus deposit sediment on the beach. In theory, the lowering of the beach face groundwater during a falling tide promotes a small incremental enhanced accretion during each swash over the dewatered beach and integrated over many waves cycles may result in significant accretion of sand. There are three primary methods that have been tried with varying success around the world. The first is *Active Dewatering* associated with the pumping of water from the beach (Figure 29), the second is *Passive Dewatering* in which ground water in the beach is lowered passively through a tube connecting lower levels in the beach (Figure 30), and the third, methodology involves pumping of the beach groundwater from greater depths and causes a larger depression in the water table which is filled by the beach groundwater, thus lowering the beach face water table (Figure 31).

Beach dewatering systems have been promoted as a cost effective alternative to hard structures and nourishment. Field observations show that beach erosion is enhanced during ebb tide and accretion is promoted during flood tide, which is explained by observations that erosion and accretion are associated with beach face permeability (Bagnold, 1940) and variations in beach ground water dynamics (Grant, 1948; Emery and Foster, 1948). These observations led to beach dewatering as a technique to artificially lower the water table as a potential means to mitigate beach erosion. Waves swashing up and down the beach face are the mechanism for sediment transport. As waves run up and down a beach they interact with the ground water beneath the beach face. The beach water table is low during the flood tide in comparison with mean sea level, and water percolates into the beach as the waves run above the exit point of the ground water table (unsaturated region). As a consequence, the carrying capacity of the swash decreases resulting in sediment deposition. Subsequently backwash of the wave is reduced and less sediment is transported offshore. These combined effects enhance on-shore sediment transport, and hence accretion. Conversely, during ebb tide, a relative high water table exists and water exfiltrates from the beach face, which causes the opposite effects to occur with enhanced offshore sediment transport and resulting beach erosion. This simple explanation is complicated by the observation that a thinning of boundary layer occurs during infiltration, which increases shear and the sediment carrying capacity acting to oppose accretion (Nielsen et al., 2001). Conversely, Conley and Inman (1994) found that exfiltration thickens the boundary layer, reducing shear and decreasing offshore sediment transport, but at the same time causes a reduction in weight of sediments making them more mobile to be eroded. These and other complicating effects are reviewed by Masselink and Puleo (Masselink and Puleo, 2006) and they point to a lack of understanding of many of the physical processes. It is concluded that at this time the basic physical mechanisms that may contribute to the success of a beach drain concept are not fully understood.

The first qualitative field observation of beach accretion associated with pumping the ground water at the shore was to obtain purified sea water for an aquarium in 1981 (Vesterby, 2004). It was found that the

efficiency of the pump declined after a year of operation because the fronting beach had accreted 25-30m, which was associated with pumping of the ground water. The well was subsequently moved closer to the shore and the beach again accreted a similar amount. The observed correlation between lowering of the ground-water table with beach accretion led to beach dewatering projects in the early 1980's in Denmark and commercial interest. The objectives of these dewatering projects are to promote onshore sediment transport to widen and stabilize the beach by artificially lowering of the beach water table as a practical alternative to more traditional methods (Machemehl et al., 1975; Davis et al., 1992). Dewatering works on the principal that small incremental enhanced accretion occurs during each swash over the dewatered beach and integrated over many waves cycles results in significant accretion of sand.

Active Dewatering

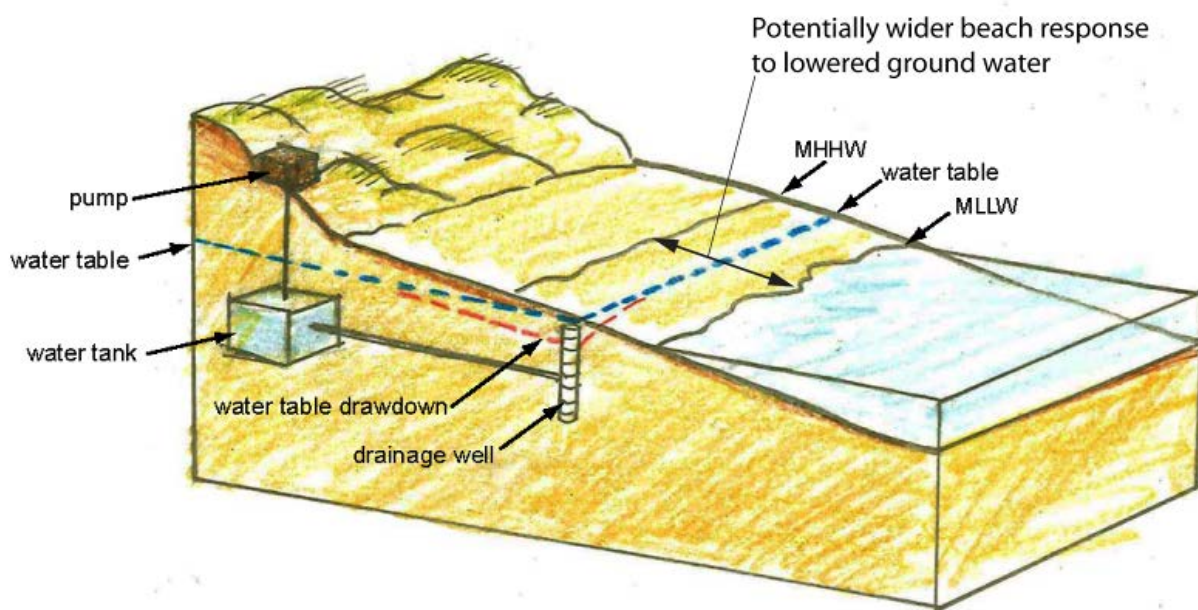


Figure 29 Schematic of Active Dewatering

General applicability

Active dewatering is potentially applicable to any sandy beach regardless of tide range, or sediment grains size or heterogeneity.

Specific Applicability

This measure is most relevant for application to Subregions 1-3 because the erosion rates and storm erosion amounts are less in these Subregions and the fixed dewatering facilities are less likely to be damaged or exposed (Table 35).

Table 35 Summary of Evaluation Criteria for Active Dewatering

Evaluation Criteria	
Reduce threat to structures	Potentially by widening beach
Maintain Beach Width	Yes, except in storm / large wave conditions
Economic Costs	Ongoing maintenance and pumping costs, reinstallation following storm impacts
Environmental Impacts	Potentially to sandy beach invertebrates
Recreational	No impacts unless pipes exposed
Safety and Public Access	No impacts unless pipes exposed
Aesthetics	No impacts unless pipes exposed
Regulatory Viability	Probably, likely requires Coastal Commission, State Lands Commission, and Sanctuary permits/approvals
Adaptability to Future Conditions	Adaptable in short term, questionable in medium to long term without relocating pumps and dewatering pipes
Cumulative Impacts	Potential impacts to sandy beach ecosystem, energy expenditure to run pumps
Certainty of Success	Relatively certain (qualitatively but not quantitative), except in storm / large wave conditions

Description

Active beach dewatering pumping techniques include pumping a closed system that pulls water from the beach and gravity flow to a well that is then pumped. A typical system is a 1000 feet horizontal drainage pipe located parallel to the shore buried 6-10 feet below MSL in the back-beach with a pumping discharge rate of 1000 gpm. The beach drainage system was patented and is commercially marketed as Beach Drain by StaBeach, or BDM. As of 2004, 35 BDM systems had been installed around the world, including the US (2), Australia (5), France (5), and Italy (7) UK (1) Germany (1).

Design parameters to be considered for installation of a beach drain system include:

1. Hydraulic conductivity (determined by sediment size, sorting and composition)
2. Wave climate (magnitude and direction)
3. Tides

The BDM systems reportedly work best where a beach is exposed to minor long-term erosion, suffering from high ground water table at the beach, and has a moderate wave climate. The BDM is not recommended as primary shore protection at severely exposed or highly protected locations and locations exposed to severe long-term erosion (Mangor, 2001). The longest installation of these systems was about 10 years. The experience has been that severe storms eventually erode back the beach to expose the drain pipes that destroys the system before the beach can recover, which is what happened to the Nantucket system after about 5 years (New York Times, July 8, 2007). Bowman et.al. points out that a sufficiently long return interval for even moderate storms is important to insure that the beach has adequate time to recover, or the system will be damaged (Bowman et.al., 2007).

Regulatory Viability

Active dewatering is probably viable in a regulatory context but may be hampered by uncertainty in performance. Likely requires Coastal Commission, State Lands Commission, and Sanctuary permits/approvals.

Ecological Impacts

There is little understanding of the ecological effects of passive dewatering on the sandy beach and dune ecosystem although it is likely to influence the tidal migrations of the sandy beach invertebrates which occurs on a daily basis.

Cost and Benefits

Owing to the uncertainty in the viability of this system, cost benefit analysis is not included.

4.2.3.1 Beach Dewatering - Passive

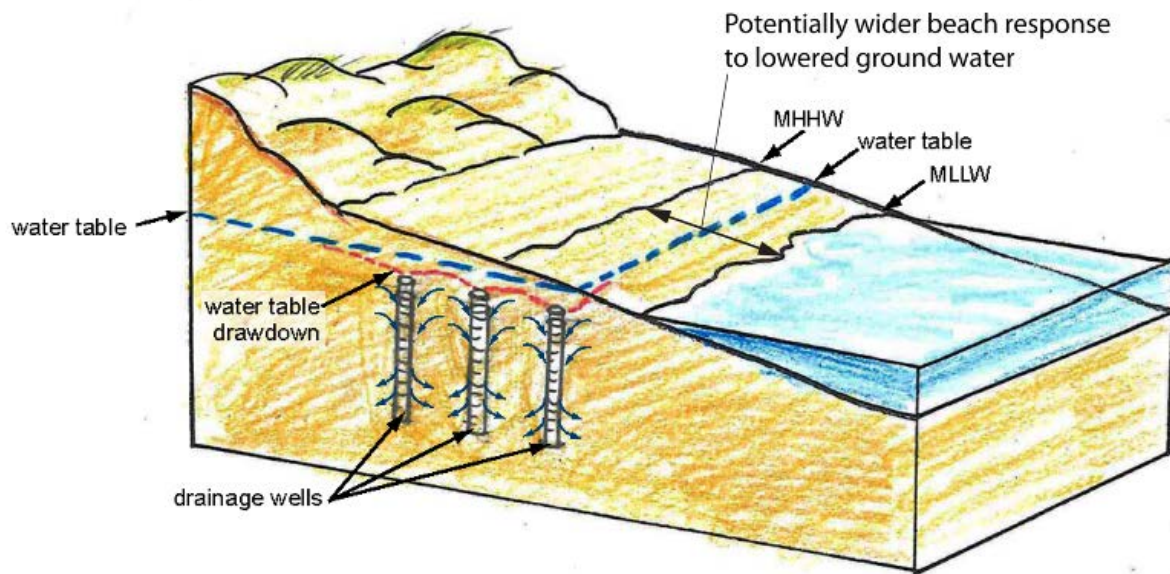


Figure 30 Schematic of Passive Dewatering

General Applicability

Passive dewatering is believed to be potentially applicable to any sandy beach with a meso to macro scale tide range, high sediment transport, and a mix of sediment grains size

Specific Applicability

This measure is most relevant for application to Subregions 1-3 because the erosion rates and storm erosion amounts are less in these Subregions and the passive dewatering facilities are less likely to be damaged or exposed (Table 36).

Table 36 Summary of Evaluation Criteria for Passive Dewatering

Evaluation Criteria	
Reduce threat to structures	Potentially yes
Maintain Beach Width	Potentially yes, except in storm / large wave conditions
Economic Costs	Ongoing maintenance and leasing costs, less than active system
Environmental Impacts	Potentially to sandy beach invertebrates
Recreational	No impacts
Safety and Public Access	No impacts
Aesthetics	No impacts
Regulatory Viability	Probably, likely requires Coastal Commission, State Lands Commission, and Sanctuary permits/approvals
Adaptability to Future Conditions	Potentially improves
Cumulative Impacts	Potential impacts to sandy beach ecosystem, energy expenditure to run pumps
Certainty of Success	Uncertain, except in storm / large wave conditions where erosion is expected

Discussion

Beach dewatering by gravity flow includes wells with a discharge pipe to the sea (Figure 29) and individual point wells (Figure 30). The point wells have been patented by Skagen Innovation Center (SIC) of Denmark and commercially marketed as Pressure Equalizing Modules, PEM's. The PEM's are vertical drain pipes approximately 6 feet in length and 2.5 inches in diameter with perforations in the bottom 3 feet. The slots allow water to flow in and out of the pipes, but exclude sand. They are typically spatially distributed in 3-5 cross-shore rows spaced 30 feet apart and separated 300 feet apart in the alongshore for one mile or more. The PEM system works during a falling tide when the sea water level in the beach intersects the perforated part of a particular PEM resulting in water flowing into the upper part of the pipe and flowing out the lower part of the pipe. The efficiency of the PEM is gained by the lack of flow resistance within the pipe. A program to assess the field performance of the PEM's was funded for one million Euros in 2004 by SIC and the Danish government and the independent results are reported by Burcharth (Burcharth, 2008). The PEM system was installed in January 2005 in two sections with test sections at the ends and in between over 11 km on the Danish coast. The foreshore and beach was composed of medium to very coarse sand with grain size diameter in the range 0.3-2.5 mm. Beach profiles were measured quarterly for three years. The beach profile analysis concluded there was no clear correlation between movements in the coastline position or changes in volume with the location of the PEM's as compared with the test sections. In addition, the PEM's were tested with pressure transducers and simulated with numerical modeling. The conclusion of the modeling was that the PEM's under certain conditions might increase the drainage in the beach, but the effect will be small. The report summarized that the PEM's will under certain conditions have a positive effect of increased drainage and perhaps accretion of sand, but the effect is marginal and almost impossible to detect in the background of the large natural morphological changes of a natural beach system. Therefore, it was concluded the effect of the PEM's is not sufficient as a coastal protection method on exposed coasts.

PEM systems have been deployed in the US (2), Denmark (5), Sweden (4), Ghana (2), Malaysia (3), and Australia (2). Two applications were reported at the 2008 ICCE to give positive results by (Jakobsen and Brogger (Jakobsen & Brogger, 2008) and Brogger and Jakobsen (Brogger & Jakobsen, 2009), but their conclusion created considerable argument from the audience on their methodology and analysis. The latest US application was in 2007 in Hillsboro, Florida. An independent review by Bob Dean found that the surveys did not show any discernable patterns that establish a positive or negative influence of the PEM installation on shore change. The study was complicated by two small nourishments placed nearby and the fact that shore data tends to be “noisy” owing to seasonal and storm induced variability. Thus, the results were found inconclusive and Dean concluded “that the PEM system is not exerting a substantial shore stabilizing influence.”

Ecological Impacts

There is little understanding of the ecological effects of passive dewatering on the sandy beach and dune ecosystem although it is likely to influence the tidal migrations of the sandy beach invertebrates which occurs on a daily basis.

Regulatory Viability

Would require Coastal Commission, State Lands Commission, and Sanctuary permits/approvals.

Cost and Benefits

The PEM system installation and monitoring costs are \$100K per mile and are leased at \$100K per year per mile which includes monitoring and maintenance as quoted by the PEM representative. After the 5 years, the system can be purchased. Currently there has not been a trial in California and the representatives may entertain a reduced rate trial. Benefits are difficult to ascertain given uncertainty about performance but given the low cost compared to some of the structural alternatives and thus an experiment to examine its performance may be warranted.

4.2.3.2 Beach Dewatering – Desalination Wells

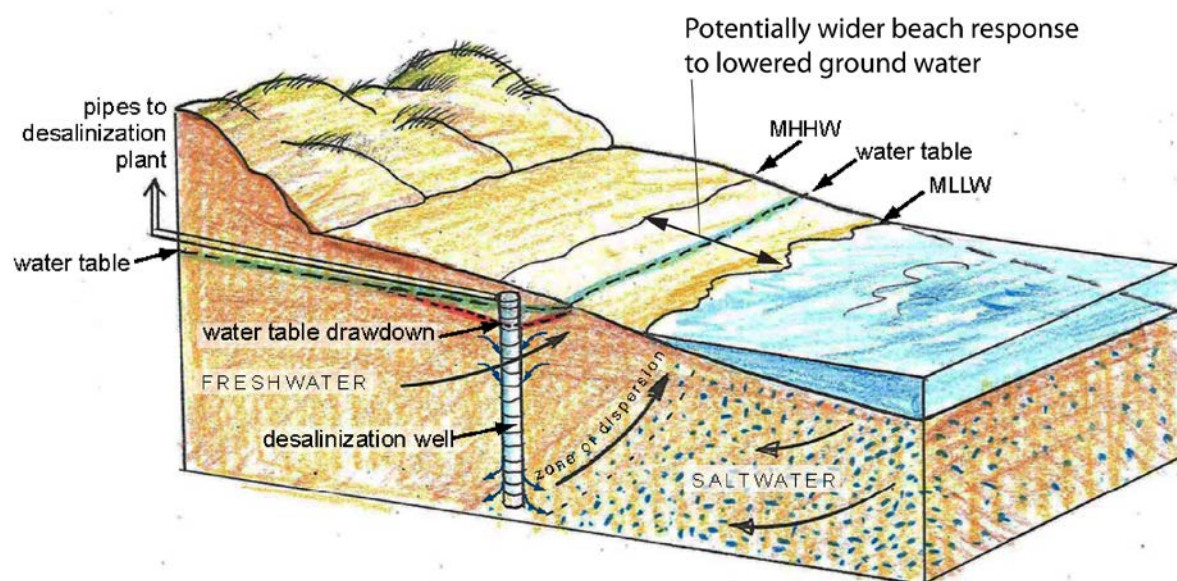


Figure 31 Example of Desalination Wells

General Applicability

Active desalination dewatering is believed to be potentially applicable to any sandy beach with some kind of groundwater basin or aquifer

Specific Applicability

This management alternative is most relevant for application to Subregions 4 and 5 where wells are either planned or have been installed. We believe this measure is most relevant for application to areas with low erosion rates and storm erosion amounts where the dewatering pipes are less likely to be damaged or exposed (Table 37).

Table 37 Summary of Evaluation Criteria for Desalination Wells

Evaluation Criteria	
Reduce threat to structures	Potentially by widening beach
Maintain Beach Width	Yes , except in storm / large wave conditions
Economic Costs	Ongoing maintenance and pumping costs, reinstallation following storm impacts
Environmental Impacts	Potentially to sandy beach invertebrates
Recreational	No impacts unless pipes exposed
Safety and Public Access	No impacts unless pipes exposed
Aesthetics	No impacts unless pipes exposed
Regulatory Viability	Uncertain, extensive state and federal permitting and environmental review processes
Adaptability to Future Conditions	Adaptable in short term, questionable in medium to long term without relocating pumps and dewatering pipes
Cumulative Impacts	Potential impacts to sandy beach ecosystem, energy expenditure to run pumps
Certainty of Success	Relatively certain (qualitatively, not quantitatively), except in storm / large wave conditions

Description

Pumping of wells located near the shore to obtain water for desalinization plants at Sand City, Marina and Fort Ord have the potential to lower the ground water-table at the beach resulting in possible erosion mitigation. The Sand City desalinization plant, which went into operation May 2010, pumps a coastal aquifer that is formed by a shallow wedge of quasi-fresh water overlying salt water from the ocean. The aquifer is composed of an approximately 50 feet deep sand layer bounded by an impermeable clay barrier that separates it from the deeper Seaside Basin aquifer. The shallow aquifer ground water system is relatively insensitive to climatic variations owing to recharge by the outflow of Robert's Lake located 1200 feet from the ocean, which is maintained at an elevation of +9.5 feet. The plant operates two vertical intake wells pumping 320 gpm each located 220 feet from the beach separated by 1635 feet alongshore at Bay Street and Tioga Avenue in Sand City. The concentrate discharge is injected into the saline wedge through a 500 foot long horizontal well, 20 feet below sea level, parallel to the shore 100 feet from the ocean between the two intake wells. The ground water elevation at the Bay Street well is naturally +2.5 feet relative to MSL and the ground water slopes seaward intersecting the beach at +2 feet MSL.

Variations in the ground water elevation at the test well were found correlated with wave height owing to set-up on the beach by waves. Thus, the ground water levels on the beach and the well are connected. Test showed that pumping at 420 gpm lowered the ground water in the test well 1-2 feet (Feeney and Williams, 2002). Assuming the water table draw-down between the well and the ocean is horizontal, the pumping has the potential to lower the beach face ground water level 1-2 feet. Field measurements of other beach drainage systems found that the lowered the ground water table extended at least 300 feet alongshore away from the location of the wells (Vesterby, 1994). Therefore, the two wells have the potential of influencing approximately 1200 feet of shore.

Regulatory Viability

Uncertain, extensive state and federal environmental review and permitting would be required (California Coastal Commission, 2004), and unlikely to occur solely for erosion mitigation.

Ecological Impacts

There is little understanding of the ecological effects of desalination on the sandy beach and dune ecosystem.

Cost and Benefits

As this is a system of opportunity, there are no costs, except for possible monitoring. Benefits are not known due to uncertainty about performance.

4.2.4 Beach Nourishment

Description

Beach Nourishment is the placement of sand to increase existing sand volumes and build beach widths (Figure 32). This strategy is widely utilized along the east coast of the United States with less frequency along the US West coast. The success of the nourishment depends on the volume of nourished material, the grain size, and the proximity or use of sand retention structures (Table 38).



Figure 32 Schematic of Beach Nourishment in Southern Bight

General Applicability

Beach nourishment is potentially applicable to any beach where either barge or vehicular access is possible and sand of appropriate quality and quantity is available.

Specific Applicability

This management alternative is most relevant for application to Subregions 1-4 to address all critical erosion areas in the southern bight (PWA et al., 2008).

Table 38 Summary of Evaluation Criteria for Beach Nourishment

Evaluation Criteria	
Reduce threat to structures	Yes – depends on volume and duration that material remains in place
Maintain Beach Width	Widens
Economic Costs	Potentially high, depends on sediment sources, transportation costs, and placement methods
Environmental Impacts	Short term impacts with the severity depending on placement mechanisms and preexisting conditions
Recreational	Improves – after placement
Safety and Public Access	Depends on sediment characteristics, likely improves but potential short term impact to safety caused by alterations in breaking wave characteristics
Aesthetics	Depends on sediment characteristics
Regulatory Viability	Uncertain, may require Congressional modification of MBNMS Designation Document
Adaptability to Future Conditions	Yes, but periodic nourishments likely to be required
Cumulative Impacts	Depends on volumes, number and mechanisms of placements
Certainty of Success	Certain in immediate term, uncertain in short to long term without sand retention structures

Discussion

Subaerial Placement:

Subaerial placement of sand is the placement of sand on the dry beach (Sub-aerial is “under the air” as opposed to submarine or “under the water”.) This method of placement results in an immediately wider beach, but as the waves sort the sand material and work the beach face to relocate sand through the entire beach profile and especially the offshore part of the profile, the beach may rapidly lose width to accommodate this profile adjustment. Normally when sand is placed directly on the beach, there needs to be some local education so the public knows that this rapid loss of beach is a normal process and that it is not an indication that the nourishment project has been a failure.

Nearshore Placement:

Nearshore placement puts sand into the submarine nearshore. The intent is that this sand will buffer offshore waves and at the same time, that onshore wave movement will carry some of this sand inland to create a wider beach. Nearshore placement of sand should result in a wider dry beach, but at a much more gradual rate than if the same volume of sand were placed directly into the dry beach. The option of placement often depends upon the original source of sand and the equipment that is available to move the sand from its source location to the receiver site.

Dredge Sand from Deep or Offshore Deposits:

There are many areas of the offshore that have sand deposits; however, this sand is too far removed from the shore and regular coastal processes to be carried onto the beach by normal processes. This sand can be dredged and placed either on the beach or in the nearshore, where it can become part of the littoral sand

supply and nourish beach areas. Dredging sand from deep or offshore deposits is a way to add new sand material to the littoral supply.

Effectiveness – Maintaining beach width vs. protecting upland property

Under the large beach nourishment option as described in the CRSMP, beach nourishment appears to be a moderately successful tool at balancing maintaining beach widths with upland property protection. In general, the beach widths fluctuate dramatically, enlarging after a fill project and then eroding in the following years at an accelerated rate, however as long as the beach width remains wider than the initial beach widths, then it can be assumed that the upland property is not affected by erosion (Figure 33)). For reaches of southern Monterey Bay with erosion rates less than 1.5 ft/year, a 25 year nourishment cycle seems able to limit upland erosion, although the analysis in the CRSMP recommended renourishment very 20 years or more frequently depending on storms. However, for reaches north of Sand city with higher erosion rates, there is indication that upland erosion occurs between nourishments. One solution would be to reduce the time period between nourishments, but that was not analyzed in detail in this report.

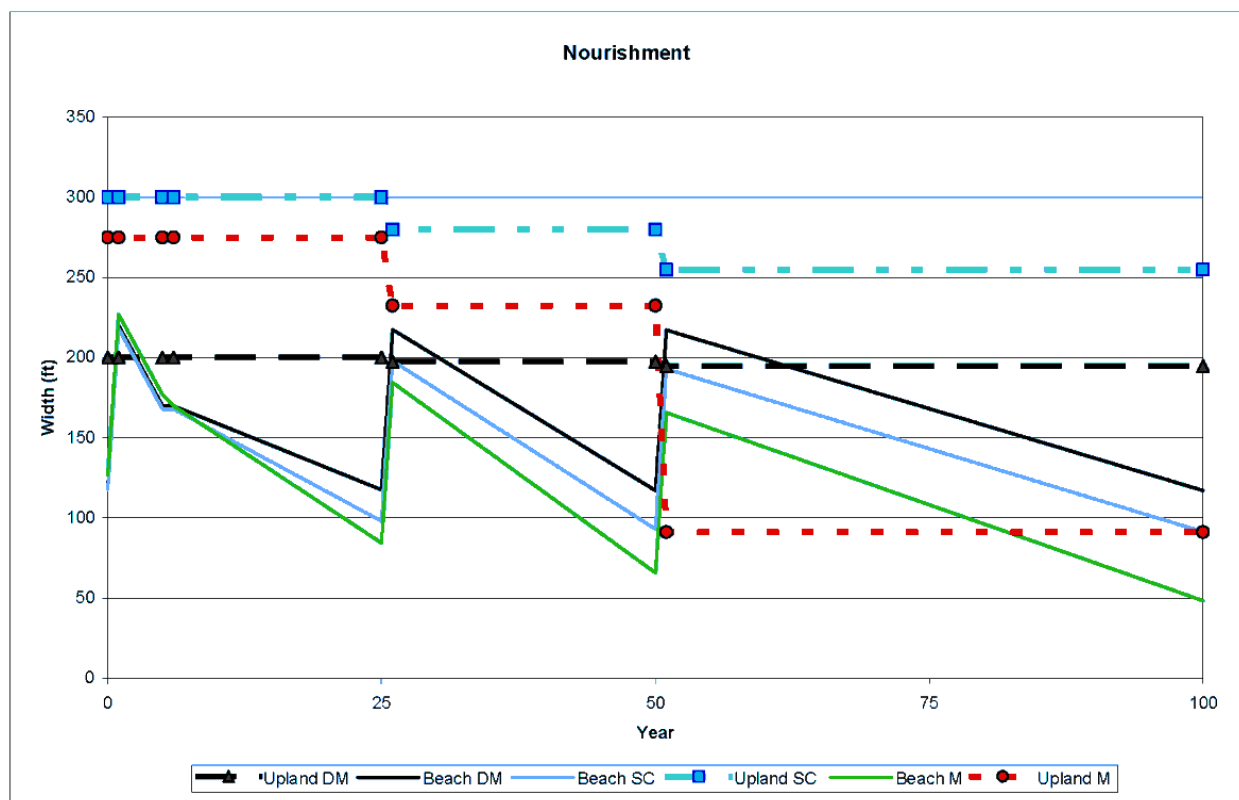


Figure 33 Effectiveness of beach nourishment at maintaining dry sand beach widths and upland property over time assuming 2million cubic yards placed every 25 years

Regulatory Viability

The regulatory viability of beach nourishment is uncertain. At present, this is not likely to be a viable option under existing MBNMS Regulations.

Ecological Impacts

Beach nourishment, as currently practiced, can create significant and lasting impacts to beach ecosystems, although comprehensive studies are limited (National Research Council, 1995; CSMW, 2008). The project size, timing, amount, zone, fill method and sediment match are all important to determining the level of impacts. Immediate impacts occur to both the “borrow” and “receiver” sites. For example, near complete mortality of species living in the intertidal zone, significant declines in shorebird use and physical alterations to the habitat (such as rocky reef or eelgrass beds) may cause lasting impacts to the distribution and abundance of impacted species living within receiver sites (Peterson et al., 2006; Speybroeck et al., 2006). Recovery may be delayed, especially if repeated nourishment occurs in the same area (Dolan et al., 2006). Nourishment impacts to the beach ecosystem can propagate up the beach food web from invertebrates to shorebirds and fish, including endangered species such as snowy plovers. In SANDAG where the beach had been reduced to cobble substrate the sand nourishment did restore some of the shorebird habitat although extensive ecological monitoring of the sandy beach ecosystem was not conducted.

The extent of impacts may be mitigated if timed appropriately. For example, sand crab recruitment occurs primarily in the late winter and spring. If nourishment activities avoid this time frame, potential recovery of at least some young of the year individuals could occur. However for longer-lived species with irregular recruitment, such as Pismo clams, impacts to existing populations could last for many years. Other invertebrates, such as amphipods, isopods and flightless insects, depend on the growth, reproduction and survival of resident populations, including their survival through winter bottlenecks, to recover and to produce any subsequent generations. Impacts to these taxa from beach replenishment projects implemented at any time of year could last for years as well.

Cost and Benefits

Tables 39, 40 and 41 present the benefit and cost analysis for nourishment. See section 3.5.2 for the assumptions used in this measure.

Table 39 Present Value of Benefits and Costs for Nourishment: Del Monte

Planning Horizon (Years)	0 to 5	6 to 25	26 to 50	51 to 100	0 to 100
Total Recreational Value above Baseline	\$ 6,264,058	\$ 8,683,684	\$ 6,467,992	\$ 3,336,364	\$ 24,752,098
Total Habitat Value above Baseline	\$ 2,379,420	\$ 3,343,773	\$ 3,770,172	\$ 1,456,984	\$ 10,950,350
Sum Benefits	\$ 8,643,478	\$ 12,027,458	\$ 10,238,163	\$ 4,793,348	\$ 35,702,448
Structural Adjustment Costs	\$ -	\$ -	\$ -	\$ -	\$ -
MRWPCA	\$ -	\$ -	\$ -	\$ -	\$ -
Cost of Private Property Compensation	\$ -	\$ 864,000	\$ -	\$ -	\$ 864,000
Cost of Pubic Property Compensation	\$ -	\$ 17,415	\$ 6,689	\$ 2,004	\$ 26,108
Construction/Nourishment Cost	\$ 12,000,000	\$ -	\$ 3,543,633	\$ 1,355,463	\$ 16,899,096
Revetment Cost	\$ (43,200,000)	\$ -	\$ (12,757,080)	\$ (4,879,666)	\$ (60,836,746)
Total Cost	\$ (31,200,000)	\$ 881,415	\$ (9,206,757)	\$ (3,522,199)	\$ (43,047,541)
Net Benefits	\$ 39,843,478	\$ 11,146,043	\$ 19,444,920	\$ 8,315,547	\$ 78,749,989
Benefit/Cost Ratio	-0.3	NA	-1.1	-1.4	-0.8

Table 40 Present Value of Benefits and Costs for Nourishment: Sand City

Planning Horizon (Years)	0 to 5	6 to 25	26 to 50	51 to 100	0 to 100
Total Recreational Value	\$ 13,992,272	\$ 19,837,540	\$ 8,551,893	\$ 3,080,322	\$ 45,462,026
Baseline	\$ 7,409,916	\$ 8,413,408	\$ -	\$ -	\$ 15,823,324
Total Habitat Value	\$ 23,636,352	\$ 33,071,961	\$ 13,382,444	\$ 4,498,989	\$ 74,589,747
Baseline	\$ 13,722,100	\$ 19,850,290	\$ 6,269,418	\$ 2,398,093	\$ 42,239,901
Net Benefits	\$ 16,496,608	\$ 24,645,803	\$ 15,664,919	\$ 5,181,217	\$ 61,988,547
Structural Adjustment Costs	\$ -	\$ -	\$ -	\$ -	\$ -
MRWPCA	\$ -	\$ -	\$ -	\$ -	\$ -
Cost of Private Property Compensation	\$ -	\$ 239,846	\$ 102,365	\$ 34,378	\$ 376,589
Cost of Pubic Property Compensation	\$ -	\$ 216,963	\$ 101,199	\$ 34,047	\$ 352,209
Construction/Nourishment Cost	\$ 50,000,000	\$ -	\$ 14,765,139	\$ 5,647,761	\$ 70,412,900
Revetment Cost	\$ (180,000,000)	\$ -	\$ (53,154,499)	\$ (20,331,941)	\$ (253,486,440)
Net Cost	\$ (130,000,000)	\$ 456,809	\$ (38,185,797)	\$ (14,615,755)	\$ (182,344,742)
Net Benefits	\$ 146,496,608	\$ 24,188,995	\$ 53,850,715	\$ 19,796,972	\$ 244,333,290
Benefit/Cost Ratio	NA	NA	NA	NA	NA

Table 41 Present Value of Benefits and Costs for Nourishment: Marina

Planning Horizon (Years)	0 to 5	6 to 25	26 to 50	51 to 100	0 to 100
Total Recreational Value	\$ 13,910,851	\$ 19,337,757	\$ 7,783,927	\$ 2,569,539	\$ 43,602,075
Baseline	\$ 7,512,217	\$ 8,275,750	\$ -	\$ -	\$ 15,787,968
Total Habitat Value	\$ 31,069,085	\$ 39,460,633	\$ 13,310,839	\$ 3,995,526	\$ 87,836,083
Baseline	\$ 15,709,559	\$ 12,889,172	\$ -	\$ -	\$ 28,598,731
Net Benefits	\$ 21,758,160	\$ 37,633,468	\$ 21,094,766	\$ 6,565,065	\$ 87,051,459
Structural Adjustment Costs	0	0	0	0	0
MRWPCA	0	0	0	0	0
Cost of Private Property Compensation	\$ -	\$ 2,891,074	\$ 13,421,057	\$ -	\$ 16,312,131
Cost of Public Property Compensation	\$ -	\$ 3,501,609	\$ 4,121,033	\$ 2,004	\$ 7,624,645
Construction/Nourishment Cost	\$ 69,500,000	\$ -	\$ 19,546,231	\$ 7,850,388	\$ 96,896,620
Revetment Cost	\$ (250,200,000)	\$ -	\$ (73,884,753)	\$ (28,261,398)	\$ (352,346,152)
Net Cost	\$ (180,700,000)	\$ 6,392,683	\$ (36,796,432)	\$ (20,409,006)	\$ (231,512,756)
Net Benefits	\$ 202,458,160	\$ 31,240,785	\$ 57,891,199	\$ 26,974,071	\$ 318,564,214
Benefit/Cost Ratio	NA	NA	NA	NA	NA

Benefit Cost Results

The results of the cost benefit analysis shows that Nourishment has a net positive cost benefit primarily as a result of avoidance of revetment construction cost, a reduction in private and public costs as well as avoidance of costs associated with the replacement of the MRWPCA infrastructure. The total benefits over the entire study for the 100 year planning horizon total about ~\$631 million with that made up of ~\$185 million in recreation and ecosystem benefits. Construction costs associated with 100 years of nourishment are estimated at ~\$184 million for the entire study area

Nourishment provides substantial benefits over the use of revetments. However, beach nourishment does not protect development and upland property as well as revetments. This means that a more frequent sand placement rate is required than the 25 years assumed based on CSBAT calculations in the CRSMP.

The nourishment benefits are likely overstated, because the degradation of beach ecology associated with nourishment construction was not considered in this analysis. This would mean that the habitat benefits are overstated relative to land use planning measures. . The analysis could be improved by reducing habitat value until re-population could occur. However there have been no long term systematic sandy beach ecological studies on the impacts and recovery time of nourishment in California that could inform this habitat degradation value. Conceptually, though if it took 10 years for the beach ecology to recover, for example, then the ecological value would be reduced significantly since the ecology would be degraded about half of the time.

4.3 REGIONAL EROSION MITIGATION ALTERNATIVES – HARD ENGINEERING APPROACHES

Hard Engineering Approaches refers to structural measures. This follows the coastal engineering and management practice vernacular that shoreline armoring are “hard” structural measures and sand placement is a “soft” non-structural measure. Structural measures include rock revetments (aka rip rap, rock slope protection), seawalls, artificial reefs, groins and breakwaters.

4.3.1 Artificial Reefs/ Submerged Breakwaters/ Low Crested Structures

Description

The artificial reef (submerged breakwater or low crested structure) is a variant of the common shore-parallel emergent breakwater in which the structure crest height is below the still water level (i.e., non-surface piercing) (Figure 34). Artificial reefs installed to act as submerged breakwaters have received increased attention in recent years as a means of shore stabilization and erosion control, primarily due to their low aesthetic impact and enhanced water exchange relative to traditional emergent breakwaters (Vicinanza et al., 2009) and the potential to enhance local surfing conditions (Ranasinghe & Turner, 2006). These structures are designed to be overtopped and to provide partial wave attenuation through greater wave reflection, breaking, and turbulent energy dissipation than a natural beach (Dean & Dalrymple, 2002). Artificial reefs can reduce the amount of wave energy reaching the shore that cause erosion, and can also create an area of relatively calm conditions shoreward of the reef, allowing suspended sand to be deposited and often a salient to build out.

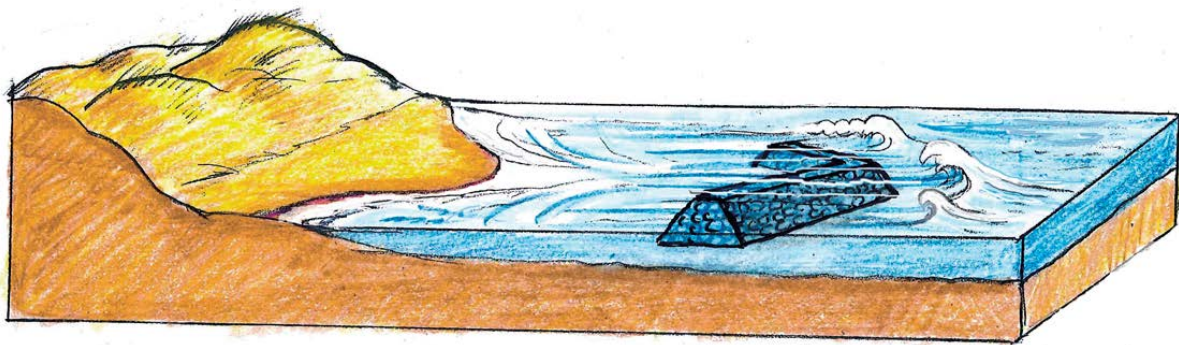


Figure 34 Schematic of an Artificial Reef

Three general types of artificial reefs are recognized in the literature: (1) rubble-mound with trapezoidal cross section, (2) prefabricated modular units, and (3) flexible-membrane units (Harris 1996). Laboratory tests were conducted starting in the mid-1980s to determine the degree of wave attenuation possible with these structures. Ahrens and Fulford showed that properly designed structures could initiate premature wave breaking and greater wave height dissipation than a natural sloping beach, with as much as 17-56% reduction in wave height (Ahrens & Fulford, 1988). Armono and Hall investigated in a laboratory study the effects of different configurations of hollow hemispherical shaped artificial reefs on wave transmission, and found that on average, there was about a 60% reduction in wave energy associated with the structures (Armono & Hall, 2003). Field installations of pre-fabricated reef units began in the 1970s

and 1980s along the Atlantic, Great Lakes, Gulf of Mexico, and Hawaii coasts (Goldsmith et al., 1992), although detailed field experiments and monitoring projects did not begin until the late 1980s (summarized in Stauble & Tabar, 2003).

Artificial reefs must be designed to endure the forces of heavy waves and are typically constructed of durable materials such as concrete, rock, or sand-filled geotextile containers. Structures built using geotextile containers have the advantage of improved safety as well as being easily modified or removed. Certain commercially designed components such as the Prefabricated Erosion Prevention (“P.E.P.”) reef and Beachsaver breakwater units are manufactured (i.e., pre-fabricated) and sold for this purpose, and some are designed to provide habitat for marine organisms (e.g. ReefBall). The pre-fabricated units are typically modular and fitted together in the field to create a continuous structure. For the modular units above, typical unit dimensions are 5 ft high, 10-25 ft long, and 15 ft wide at the base, with a crest width of 1-2 ft. Units are typically installed using a barge-mounted crane in the nearshore region at a depth shallow enough to influence incoming waves.

The effectiveness of a submerged structure in dissipating wave energy is controlled by the structure dimensions, water depth and distance offshore, local wave conditions, and nearshore bathymetry (Dean et al., 1994; Wamsley et al., 2002). Dattatri et al. identified the relative submerged depth and relative crest width of the structure as being significant factors associated with wave transmission (Dattatri et al., 1978), and Ahrens developed relationships of wave transmission and reflection as a function of relative crest height and relative water depth (Ahrens, 1987). Other design parameters such as structure material and weight, surface area and habitat value, wave and current interaction with the structure, and scour, deposition, and settlement should also be considered (Table 42).

General Applicability

Artificial reefs and low crested breakwaters are potentially applicable to any location with a relatively stable sea bed. Given their function, they are typically constructed in an environment with wave energy.

Specific Applicability

This management alternative is most relevant for application to Subregions 1-4 to address critical erosion areas throughout.

An offshore reef was one of the alternatives considered for the Ocean Harbor House seawall project (Del Monte Beach, CA), however was abandoned due to regulatory considerations, even though it was concluded that this option would “provide long-term protection of the sand dune bluff feature that protects the shallow spread footings of the buildings, the common area, and the sewer system and other utilities”.

Table 42 Summary of Evaluation Criteria for Artificial Reefs

Evaluation Criteria	
Reduce threat to structures	Yes
Maintain Beach Width	Yes – potentially widen behind structure
Economic Costs	High – depends on type and source of material, transportation, and placement costs. Ongoing monitoring and maintenance
Environmental Impacts	Potential impacts to offshore bottom species, promotion of non-native species, alters habitat types from sand to rock
Recreational	Potentially improves surfing and fishing
Safety and Public Access	Improves
Aesthetics	Minimal impacts if any below sea surface
Regulatory Viability	Uncertain
Adaptability to Future Conditions	Potentially – depends on rate of climate changes, ability to add material to increase crest of structure elevation
Cumulative Impacts	Conversion of sand bottom habitat to rock reef, increase in non-native species diversity and abundance
Certainty of Success	Mixed results, more certain in short term, uncertain in short to long term without placement of additional material or raising crest elevation

Discussion

The increased popularity of submerged structures is due, in part, to the growing recognition that the structures can be optimized to enhance local surfing conditions. Engineering design and implementation of artificial surfing reefs is still in its infancy, and only six structures have been constructed worldwide in California, UK, Australia, and New Zealand (Scarfe, 2008). Little is known about the shore response to these structures because the concept of multi-functional (i.e., wave dissipation, habitat, and recreation) artificial reefs is relatively new.

The shore response to submerged structures is not well understood and is an area of active research. While the theoretical concept of using a submerged structure to dissipate wave energy (i.e., reduce wave height) is sound (Ahrens, 1987; Ahrens & Fulford, 1988; Armono & Hall, 2003), the implementation of these structures to promote *shore stability* is yet to be proven (Scarfe, 2008). Relatively little is known about the shore response to submerged structures in general, and key environmental and structural parameters governing shore response are yet to be fully resolved (Ranasinghe & Turner, 2006). In a review of shore response to submerged structures, Ranasinghe et al. reported mixed results, and concluded that 70% of documented cases actually resulted in net shore erosion in the lee of the structure (Ranasinghe et al., 2006).

The well-established methods currently used to predict shore response to emergent structures cannot be directly applied to submerged breakwaters because of the fundamentally different interaction of the structure with the nearshore wave and current field (Ranasinghe & Turner, 2006). Dean et al. proposed that the normal seaward return flow of water pumped over the structure by waves is impeded by the presence of the breakwater, resulting in increased currents and scour at the ends of the breakwater (Dean et al., 1994). In a modeling study of the morphologic impacts of submerged breakwaters, Lesser et al.

observed scour holes at the breakwater ends and between breakwater sections for various breakwater-gap configurations (Lesser et al., 2003). Bathymetric monitoring of the artificial surfing reef at Mount Maunganui, NZ documented a scour hole 3 times the size of the structure itself (in the lee of the structure) (Scarfe, 2008).

In addition to modifying local hydrodynamics, localized scour can also act to destabilize the structure. Stauble and Tabar discuss the performance of six installations of modular narrow-crested submerged breakwaters in Florida and New Jersey, all of which experienced scour landward of the breakwater that undermined the base of the structures and contributed to settlement and slumping of the units by 1.5 to 5.0 ft. Since settlement acts to increase the submerged depth of the structure and reduce effectiveness, controlling scour and settlement is a key design issue (Stauble & Tabar, 2003). Recent installations have employed a geotextile fabric base with concrete anchor to minimize scour and settlement (Stauble & Giovannozzi, 2003).

Structure resilience to storms and sea level rise is another important design consideration. Both storm surge and sea level rise act to increase the depth of submergence of the structure, and reduce effectiveness. Over time, settlement of the Vero Beach, FL pre-fabricated modular breakwater units rendered the structures ineffective in terms of wave dissipation due to the increased submergence of the structure (Priest & Harris, 2009). This highlights the major disadvantage of the submerged breakwater – that they become less effective during storms due to storm surge (Dean & Dalrymple, 2002), and over time with sea level rise. Designs which anticipate the gradual increase in submergence with sea level rise and allow for structure modification (e.g., stackable geotextile tubes) in the future will be more resilient to climate change.

While artificial reefs are typically associated as having fewer environmental impacts (e.g., aesthetic and water quality) than other alternatives, they do involve activities that can significantly impact the seafloor environment. However if properly designed and sited, these structures can have the advantage of potential environmental enhancement by providing habitat for marine life as well as recreational enhancement and shore protection. Another important consideration with any submerged offshore structure is the impacts it can cause to recreational and commercial activities that occur in the vicinity, as it can represent a significant hazard.

Effectiveness – Maintaining beach width vs. protecting upland property

Under the artificial reefs that are used in conjunction with a large nourishment project as a retention device, the effect on effectiveness at maintaining beach widths and upland property is shown below (Figure 35). In this case, the beach widths oscillate based on the fill interval with upland property only eroded along reaches of SMB where erosion rates exceed 3 ft/year.

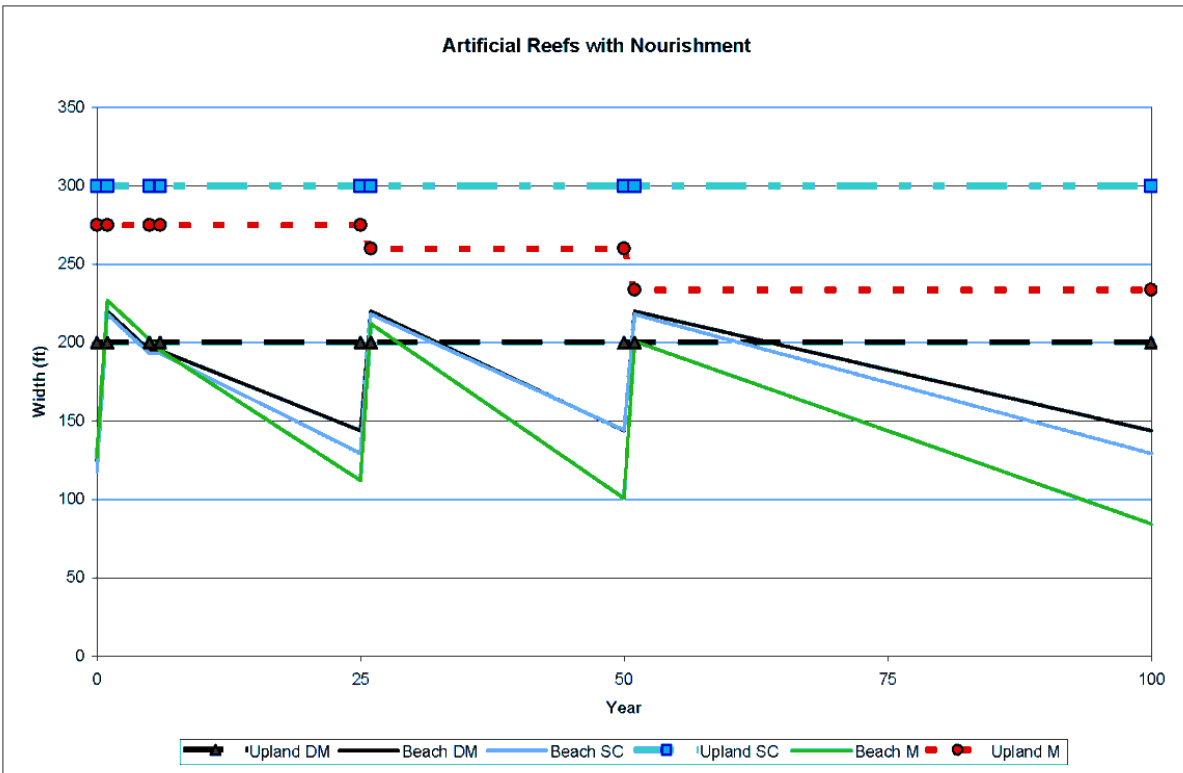


Figure 35 Effectiveness of artificial reefs as a sand retention device used in conjunction with a large beach nourishment at maintaining dry sand beach widths and upland property over time

Regulatory Viability

The regulatory viability of offshore structures is uncertain. Constructing offshore structures in the marine environment within a National Marine Sanctuary would require MBNMS NEPA review and authorization for seabed alteration.

Ecological Impacts

Ecological Impacts are unknown in SMB but expected to be site-specific. The conversion of sandy substrate to rocky reef would be one unavoidable impact. In Narrowneck, Australia, the reef became a favorite spot for recreational fishing since it was the only hard substrate within a large sandy bay. Some initial ecological evaluation results of Low Crested structures in Italy suggest that the hard structures preferentially favor generalist species with high recruitment rates as opposed to more soft substrate dwelling species (Airolidi et al., 2005). The conversion of such of artificial hard substrata in predominately soft sediment ecosystems can provide habitat and stepping stones for sessile species, many of which are invasive or weedy forms.

Costs and Benefits

Tables 43 - 45 present the benefit and cost analysis for artificial reefs. See section 3.5.2 for the assumptions used in this measure.

Table 43 Present Value of Benefits and Costs for Reefs: Del Monte

Planning Horizon (Years)	0 to 5	6 to 25	26 to 50	51 to 100	0 to 100
Total Recreational Value above Baseline	\$ 6,263,912	\$ 10,455,313	\$ 9,735,916	\$ 3,661,289	\$ 30,116,431
Total Habitat Value above Baseline	\$ 2,606,574	\$ 4,387,256	\$ 4,062,990	\$ 1,554,120	\$ 12,610,940
Sum Benefits	\$ 8,870,486	\$ 14,842,569	\$ 13,798,906	\$ 5,215,409	\$ 42,727,371
Structural Adjustment Costs	\$ -	\$ -	\$ -	\$ -	\$ -
MRWPCA	\$ -	\$ -	\$ -	\$ -	\$ -
Cost of Private Property Compensation	\$ -	\$ -	\$ -	\$ -	\$ -
Cost of Pubic Property Compensation	\$ -	\$ -	\$ -	\$ -	\$ -
Construction/Nourishment Cost	\$ 93,600,000	\$ -	\$ 27,640,339	\$ 8,162,269	\$ 129,402,608
Revetment Cost	\$ (43,200,000)	\$ -	\$ (12,757,080)	\$ (4,879,666)	\$ (60,836,746)
Total Cost	\$ 50,400,000	\$ -	\$ 14,883,260	\$ 3,282,603	\$ 68,565,863
Net Benefits	\$ (41,529,514)	\$ 14,842,569	\$ (1,084,354)	\$ 1,932,807	\$ (25,838,492)
Benefit/Cost Ratio	0.18	NA	0.93	1.59	0.62

Table 44 Present Value of Benefits and Costs for Reefs: Sand City

Planning Horizon (Years)	0 to 5	6 to 25	26 to 50	51 to 100	0 to 100
Total Recreational Value	\$ 14,581,846	\$ 22,753,697	\$ 10,014,746	\$ 3,734,999	\$ 51,085,287
Baseline	\$ 7,409,916	\$ 8,413,408	\$ -	\$ -	\$ 15,823,324
Total Habitat Value	\$ 24,582,824	\$ 38,696,898	\$ 17,322,610	\$ 6,626,011	\$ 87,228,343
Baseline	\$ 13,722,100	\$ 19,850,290	\$ 6,269,418	\$ 2,398,093	\$ 42,239,901
Sum Benefits	\$ 18,032,654	\$ 33,186,897	\$ 21,067,938	\$ 7,962,916	\$ 80,250,404
Structural Adjustment Costs	\$ -	\$ -	\$ -	\$ -	\$ -
MRWPCA	\$ -	\$ -	\$ -	\$ -	\$ -
Cost of Private Property Compensation	\$ -	\$ -	\$ -	\$ -	\$ -
Cost of Pubic Property Compensation	\$ -	\$ -	\$ -	\$ -	\$ -
Construction/Nourishment Cost	\$ 390,000,000	\$ -	\$ 115,168,081	\$ 44,052,539	\$ 549,220,620
Revetment Cost	\$ (180,000,000)	\$ -	\$ (53,154,499)	\$ (20,331,941)	\$ (253,486,440)
Total Cost	\$ 210,000,000	\$ -	\$ 62,013,582	\$ 23,720,598	\$ 295,734,180
Net Benefits	\$ (191,967,346)	\$ 33,186,897	\$ (40,945,644)	\$ (15,757,682)	\$ (215,483,776)
Benefit/Cost Ratio	0.09	NA	0.34	0.34	0.27

Table 45 Present Value of Benefits and Costs for Reefs: Marina

Planning Horizon (Years)	0 to 5	6 to 25	26 to 50	51 to 100	0 to 100
Total Recreational Value	\$ 14,468,120	\$ 21,837,871	\$ 9,195,297	\$ 3,216,681	\$ 48,717,969
Baseline	\$ 7,512,217	\$ 8,275,750	\$ -	\$ -	\$ 15,787,968
Total Habitat Value	\$ 32,384,681	\$ 47,230,252	\$ 18,859,604	\$ 5,972,042	\$ 104,446,579
Baseline	\$ 15,709,559	\$ 12,889,172	\$ -	\$ -	\$ 28,598,731
Net Benefits	\$ 23,631,024	\$ 47,903,200	\$ 28,054,901	\$ 9,188,723	\$ 108,777,848
Structural Adjustment Costs	0	0	0	0	0
MRWPCA	0	0	0	0	0
Cost of Private Property Compensation	\$ -	\$ 2,186,381	\$ 4,949,671	\$ -	\$ 7,136,051
Cost of Public Property Compensation	\$ -	\$ 2,677,181	\$ 2,513,731	\$ -	\$ 5,190,912
Construction/Nourishment Cost	\$ 542,100,000	\$ -	\$ 152,460,602	\$ 61,233,030	\$ 755,793,632
Revetment Cost	\$ (250,200,000)	\$ -	\$ (73,884,753)	\$ (28,261,398)	\$ (352,346,152)
Net Cost	\$ 291,900,000	\$ 4,863,562	\$ 86,039,250	\$ 32,971,631	\$ 415,774,444
Net Benefits	\$ (268,268,976)	\$ 43,039,637	\$ (57,984,349)	\$ (23,782,908)	\$ (306,996,595)
Benefit/Cost Ratio	NA	NA	NA	NA	NA

Benefit Cost Results

The results of the cost benefit analysis shows that the Artificial Reefs with Nourishment measure show a net negative cost benefit primarily as a result of high construction cost. Construction costs associated with 100 years of reefs with nourishment are estimated at ~\$1.18 billion. Some positives are the benefits from reduction in private and public costs as well as avoidance of costs associated with the replacement of the MRWPCA infrastructure. The total costs (negative net benefits) over the entire study for the 100 year planning horizon total about ~\$547 million with that made up of ~\$232 million in recreation and ecosystem benefits.

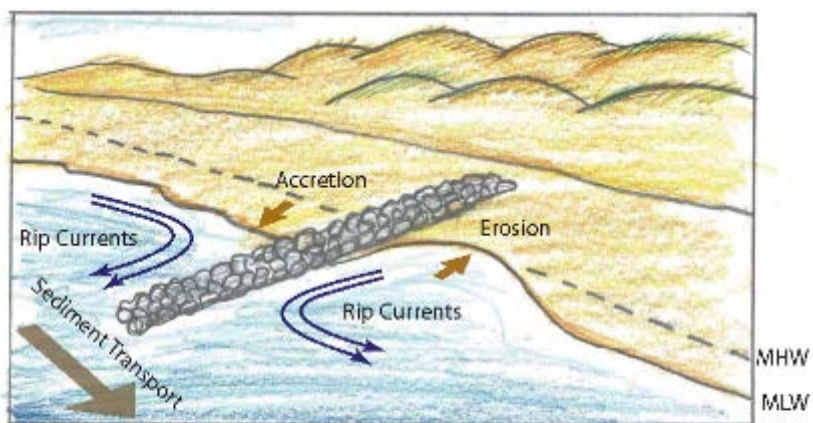
In all three reaches the benefits of using reefs as a policy alternative do not outweigh the costs. Indeed, in many cases the net benefits are negative, implying that reefs, even though they cost more than the baseline strategy of revetment, actually lower overall benefits. The most striking differences are in the 0-5 year planning horizon, where the costs are ten to twenty times the benefits in Del Monte and Sand City respectively. Net benefits are only positive for the 6-25 year planning horizon. However that is misleading because our model assumes that reefs are replaced every 25 years and the 5-25 year horizon does not include those costs. As the 100-year planning horizon indicates, the overall benefit cost ratio is far less than one in all instances, indicating that artificial reefs are not likely to be cost-effective. However, they do maintain a beach, protect inland property and could potentially mitigate some of the adverse effects of beach nourishment (less frequent sand placement, new subtidal habitat) and recreational effects (surfing and fishing benefits).

4.3.2 Groins

Description

Groins are structures built to extend out from the beach with the objective of capturing or retaining sand. Sand capture occurs as sand is transported alongshore by the waves and alongshore current (Figure 36). When the sediment being transported alongshore encounter the groin, the currents and sediment are diverted offshore into deeper water where the currents slow down depositing much of their sediment load. Alternative groin designs include weir groins and partially transparent groins that slow down the alongshore current transport the sediment so that the sediments are deposited at the groin. Groins work best where there is a dominant wave direction that drives currents and sediment alongshore. Groins are also used to retain a nourished beach at its end, again in a location where there is a dominant transport towards the groin (Table 46).

Traditionally groins have been built out of rock, concrete or sheetpile. There are some innovative designs that use geotextile bags or tubes, filled with gravel, stone, sand, or other material, instead of the more traditional materials. The geotextile groins can be built entirely of filled geotextile bags or tubes, or could be filled with more traditional rock as an outer armor layer. Any groin project would need to be designed for the local wave and current regime and the local forces may limit the use of various materials



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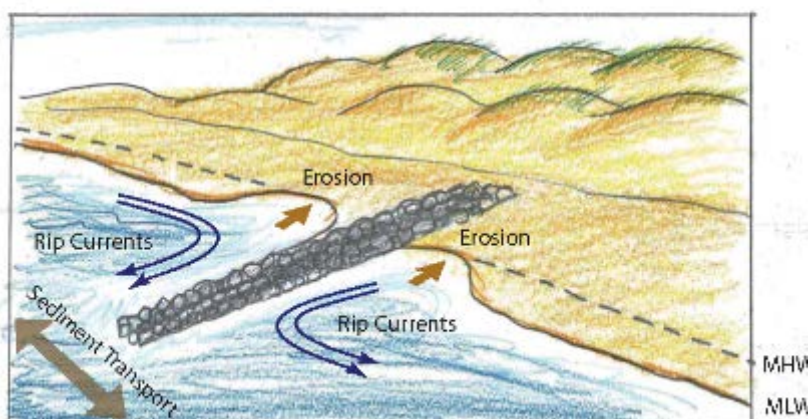


Figure 36 Examples of Groins

General Applicability

Groins are generally considered along stretches of coast with high net longshore sediment transport. The authors posit that the most applicable location for groins is in an area of increased longshore transport rate between slower transport rate areas: This situation would allow for a finite length of groin field and limited downstream erosion effects. These conditions do not exist along the sandy shores in southern Monterey Bay.

Specific Applicability

This mitigation measure is most relevant for application to Subregions 1-4 to be used possibly for sand retention in conjunction with beach nourishment.

Table 46 Summary of Evaluation Criteria for Groins

Evaluation Criteria	
Reduce threat to structures	Yes generally in areas updrift of structure
Maintain Beach Width	Potentially improves updrift narrows downdrift
Economic Costs	High
Environmental Impacts	Yes
Recreational	Potential benefits to beach width and surfing
Safety and Public Access	Impacts from rip current generation, and lateral access
Aesthetics	Impacts
Regulatory Viability	Uncertain
Adaptability to Future Conditions	Depends on rates of climate change, likely not in medium/long term
Cumulative Impacts	Likely downcoast erosion impacts. One groin usually leads to fields of groins, a reasonable expectation of long term buildout of groin field
Certainty of Success	For areas with mainly uni-directional transport, and with pre-filling of the accretion fillet: Certain in short term, less certain in medium/long term

Discussion

Well-defined rip channels and associated rip currents are the dominant morphologic feature in southern Monterey Bay owing to the near-normal wave incidence year-round (Reniers et al., 2007). The near-normal wave incidence results in weak alongshore currents. Placing a groin in a rip field acts as a perturbation on the morphology that will result in a rip current at the groin. The strong off-going current will most likely create a scour hole off the end of the groin. Instead of capturing sand, the groin may act to enhance erosion locally.

Effectiveness – Maintaining beach width vs. protecting upland property

Under this mitigation measure groins would be used in conjunction with a large nourishment project as a retention device, the affect on effectiveness at maintaining beach widths and upland property is shown below (Figure 37). In this case, the beach widths oscillate based on the fill interval with upland property only eroded along reaches of SMB where erosion rates near 4.5 ft/year.

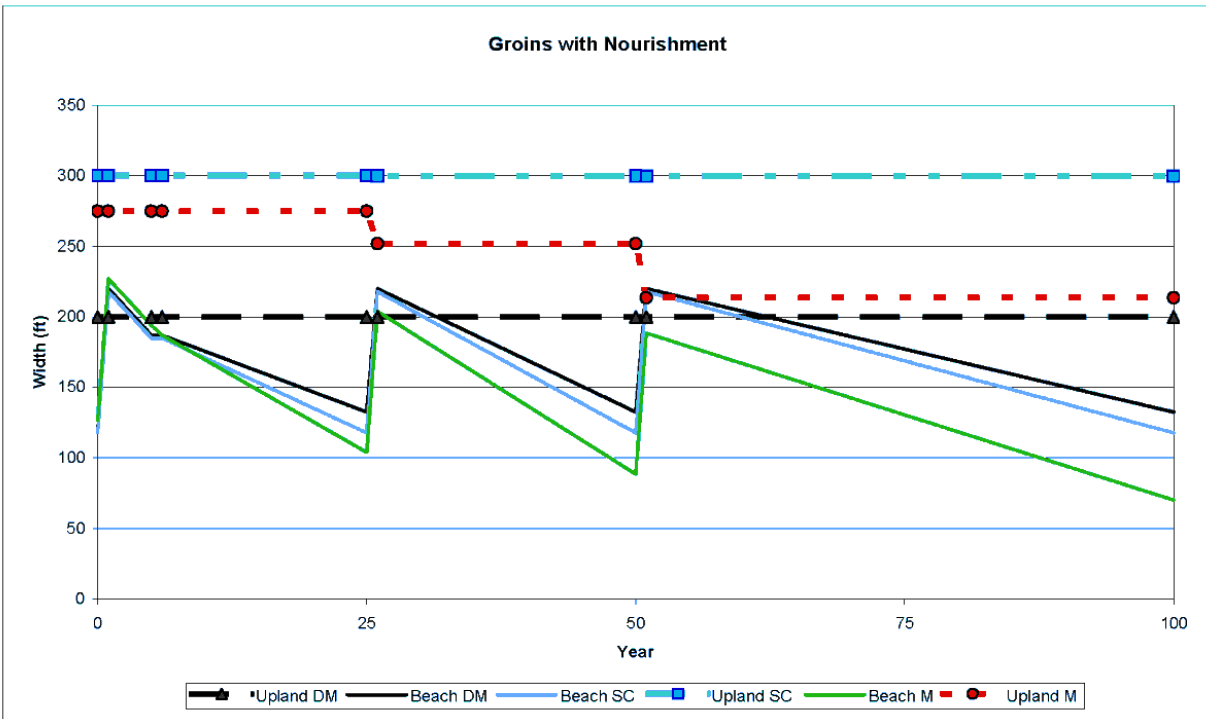


Figure 37 Effectiveness of groins as retention structures plus beach nourishment at maintaining dry sand beach widths and upland property over time

Regulatory Viability

Uncertain, constructing offshore structures in the marine environment within a National Marine Sanctuary would require MBNMS NEPA review and authorization for seabed alteration.

Ecological Impacts

Unknown in SMB. Likely to be site specific, although the conversion of sandy substrate to rocky reef would be one unavoidable impact. The conversion of such artificial hard substrata in predominately soft sediment ecosystems can provide habitat and stepping stones for generalist sessile species, many of which are invasive or weedy forms.

Costs and Benefits

Tables 47 through 49 present the benefit and cost analysis for groins. See Section 3.5.2 for the assumptions used in the cost benefit analysis for this measure.

Table 47 Present Value of Benefits and Costs for Groins plus Nourishment: Del Monte

Planning Horizon (Years)	0 to 5	6 to 25	26 to 50	51 to 100	0 to 100
Total Recreational Value above Baseline	\$ 6,661,144	\$ 10,345,791	\$ 7,164,437	\$ 14,467	\$ 24,185,838
Total Habitat Value above Baseline	\$ 2,533,885	\$ 3,997,035	\$ 3,839,422	\$ 1,503,315	\$ 11,873,657
Sum Benefits	\$ 9,195,028	\$ 14,342,825	\$ 11,003,859	\$ 1,517,782	\$ 36,059,495
Structural Adjustment Costs	\$ -	\$ -	\$ -	\$ -	\$ -
MRWPCA	\$ -	\$ -	\$ -	\$ -	\$ -
Cost of Private Property Compensation	\$ -	\$ -	\$ -	\$ -	\$ -
Cost of Pubic Property Compensation	\$ -	\$ -	\$ -	\$ -	\$ -
Construction/Nourishment Cost	\$ 62,400,000	\$ -	\$ 18,426,893	\$ 7,048,406	\$ 87,875,299
Revetment Cost	\$ (43,200,000)	\$ -	\$ (12,757,080)	\$ (4,879,666)	\$ (60,836,746)
Total Cost	\$ 19,200,000	\$ -	\$ 5,669,813	\$ 2,168,740	\$ 27,038,554
Net Benefits	\$ (10,004,972)	\$ 14,342,825	\$ 5,334,046	\$ (650,958)	\$ 9,020,942
Benefit/Cost Ratio	0.48	NA	1.94	0.70	1.33

Table 48 Present Value of Benefits and Costs for Groins plus Nourishment: Sand City

Planning Horizon (Years)	0 to 5	6 to 25	26 to 50	51 to 100	0 to 100
Total Recreational Value	\$ 14,394,505	\$ 21,724,339	\$ 9,599,581	\$ 3,545,590	\$ 49,264,015
Baseline	\$ 7,409,916	\$ 8,413,408	\$ -	\$ -	\$ 15,823,324
Total Habitat Value	\$ 24,279,953	\$ 37,098,009	\$ 16,773,088	\$ 6,415,042	\$ 84,566,092
Baseline	\$ 13,722,100	\$ 19,850,290	\$ 6,269,418	\$ 2,398,093	\$ 42,239,901
Sum Benefits	\$ 17,542,442	\$ 30,558,650	\$ 20,103,251	\$ 7,562,538	\$ 75,766,881
Structural Adjustment Costs	\$ -	\$ -	\$ -	\$ -	\$ -
MRWPCA	\$ -	\$ -	\$ -	\$ -	\$ -
Cost of Private Property Compensation	\$ -	\$ 1,319	\$ 653	\$ 231	\$ 2,203
Cost of Pubic Property Compensation	\$ -	\$ 1,163	\$ 575	\$ 204	\$ 1,942
Construction/Nourishment Cost	\$ 260,000,000	\$ -	\$ 76,778,721	\$ 29,368,360	\$ 366,147,080
Revetment Cost	\$ (180,000,000)	\$ -	\$ (53,154,499)	\$ (20,331,941)	\$ (253,486,440)
Total Cost	\$ 80,000,000	\$ 2,482	\$ 23,625,449	\$ 9,036,853	\$ 112,664,785
Net Benefits	\$ (62,457,558)	\$ 30,556,168	\$ (3,522,198)	\$ (1,474,315)	\$ (36,897,903)
Benefit/Cost Ratio	0.22	NA	0.85	0.84	0.67

Table 49 Present Value of Benefits and Costs for Groins plus Nourishment: Marina

Planning Horizon (Years)	0 to 5	6 to 25	26 to 50	51 to 100	0 to 100
Total Recreational Value	\$ 14,291,003	\$ 21,113,157	\$ 8,733,001	\$ 2,984,682	\$ 47,121,843
Baseline	\$ 7,512,217	\$ 8,275,750	\$ -	\$ -	\$ 15,787,968
Total Habitat Value	\$ 31,963,690	\$ 44,948,329	\$ 16,757,471	\$ 5,044,221	\$ 98,713,711
Baseline	\$ 15,709,559	\$ 12,889,172	\$ -	\$ -	\$ 28,598,731
Net Benefits	\$ 23,032,917	\$ 44,896,563	\$ 25,490,472	\$ 8,028,903	\$ 101,448,855
Structural Adjustment Costs	0	0	0	0	0
MRWPCA	0	0	0	0	0
Cost of Private Property Compensation	\$ -	\$ 2,391,383	\$ 5,056,063	\$ -	\$ 7,447,445
Cost of Pubic Property Compensation	\$ -	\$ 1,894,988	\$ 1,080,516	\$ -	\$ 2,975,504
Construction/Nourishment Cost	\$ 361,400,000	\$ -	\$ 101,640,402	\$ 40,822,020	\$ 503,862,421
Revetment Cost	\$ (250,200,000)	\$ -	\$ (73,884,753)	\$ (28,261,398)	\$ (352,346,152)
Net Cost	\$ 111,200,000	\$ 4,286,371	\$ 33,892,227	\$ 12,560,621	\$ 161,939,219
Net Benefits	\$ (88,167,083)	\$ 40,610,192	\$ (8,401,755)	\$ (4,531,718)	\$ (60,490,364)
Benefit/Cost Ratio	NA	NA	NA	NA	NA

Benefit Cost Results

The results of the cost benefit analysis shows that the Groins with Nourishment measure has a net negative cost benefit primarily as a result of high construction cost. Construction costs associated with 100 years of groins with nourishment for the entire study area are estimated at ~\$957 million. Some positives are the benefits from reduction in private and public costs as well as avoidance of costs associated with the replacement of the MRWPCA infrastructure. The total costs (negative net benefits) over the entire study including cost savings from not building a revetment (baseline scenario) for the 100 year planning horizon total about ~\$89 million with that made up of ~\$213 million in recreation and ecosystem benefits. It should be noted that in the Del Monte Reach groins with nourishment have a net positive of \$9 million over the 100-year time horizon

4.3.3 Emergent – Offshore Breakwaters

Description

Breakwaters are structures constructed offshore with the intended purpose of reducing the wave energy inland of the structure (Figure 38). Emergent or surface penetrating breakwaters are relatively common in California and have been constructed in Venice (for beach retention), Santa Monica (to create an anchorage, but has mainly been for beach retention), Ventura (as part of the harbor), and other locations.

Breakwaters hold sand by reducing the wave energy inland of the structure. As the wave energy decreases, there is less energy for sand transport and sand is deposited inland of the structure. In some situations, the salient of sand inland of the structure can become large enough to act itself as a barrier to sand transport; this has happened in Santa Monica where the upcoast sand retention is a factor of both the breakwater and the salient (Table 50).

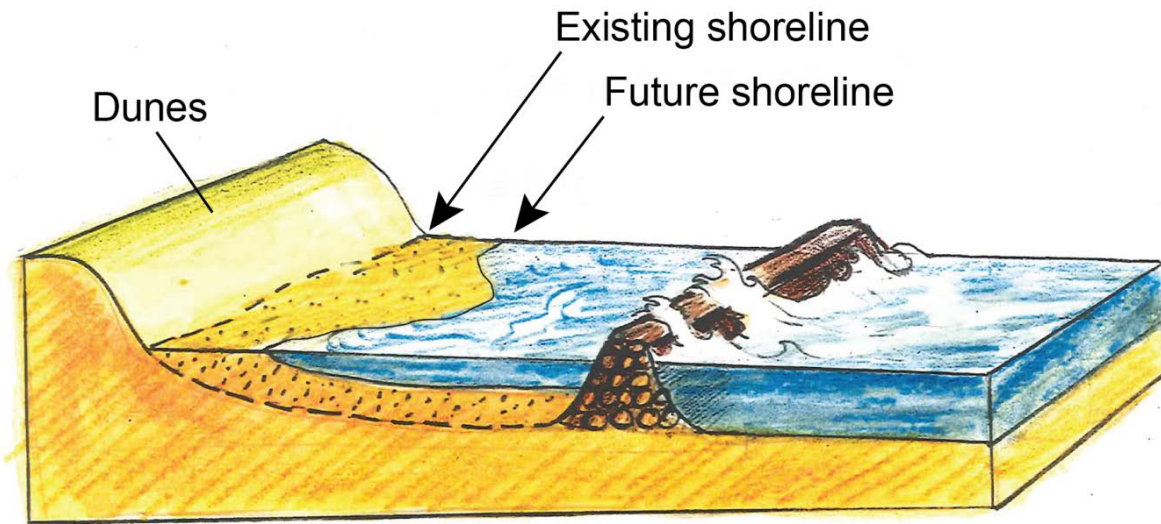


Figure 38 Schematic of Emergent Offshore Breakwaters with Beach Nourishment

General Applicability

Offshore breakwaters and beach nourishment are generally applicable where there is a firm seabed and the need to create a calm area free from wave energy.

Specific Applicability

This management measure is potentially applicable to all Subregions but is most likely to be appropriate in Subregions 1-4 where the conditions are calmer and there is more coastal development.

Table 50 Summary of Evaluation Criteria for Breakwaters

Evaluation Criteria	
Reduce threat to structures	Yes
Maintain Beach Width	Yes to improves
Economic Costs	High
Environmental Impacts	Yes – sand to rock habitat, potential to become a sink of sediment until equilibrium is reached
Recreational	Benefits to beach recreation and potentially swimming and fishing, impacts to surfing and boating
Safety and Public Access	Reduces wave energy, promotes calmer waters
Aesthetics	Impacts
Regulatory Viability	Uncertain
Adaptability to Future Conditions	Eventually become submerged breakwater
Cumulative Impacts	Depends on scale of breakwater, a breakwater may also lead to additional structures
Certainty of Success	Certain

Discussion

Offshore breakwaters have been constructed in California at Long Beach, Santa Monica, Oxnard-Ventura and Half Moon Bay.

At Long Beach, there are studies to remove a portion of the offshore breakwater to improve water quality and beach quality, and to restore surfing. Of interest, the Long Beach is very wide and stable, but is not considered to be adequate by those that want the breakwater removed. This is an important consideration before embarking on extensive coastal engineering works – part of the allure of a beach is apparently its natural character.

At Santa Monica, the beach widening has been relatively successful and seems to serve the human-centric design objectives.

At Oxnard – Ventura, offshore breakwaters are mostly associated with harbors and sand trapping / bypassing operations. These projects indicate the need to consider carefully the operational costs of coastal engineering works and the potential need to mechanically move sand to maintain the engineered shore in a configuration well removed from its natural condition.

At Pillar Point Harbor, the offshore breakwater provides a more sheltered area for boat mooring. Of interest, there have been ongoing erosion problems within this harbor area (Griggs et al. 2005). There is also increased erosion just south of the harbor breakwaters, with the erosion attributed to the breakwaters focusing wave energy. This indicates that a reduction of wave climate alone does not prevent erosion: It is the resulting gradient of wave energy and sand transport that affects erosion and accretion.

We are not aware of any offshore breakwaters constructed on California's Pacific coast since the 1980s and most are much older. Offshore breakwaters proposed for Imperial Beach (San Diego County) have been strongly opposed for years, and may never be constructed despite continuing studies.

Effectiveness – Maintaining beach width vs. protecting upland property

Under the offshore or emergent breakwater mitigation measure used in conjunction with a large nourishment project as a retention device, the effectiveness at maintaining beach widths and upland property is shown below (Figure 39). This erosion mitigation measure is the most effective at balancing beach widths with upland erosion protection. In this case, the beach widths oscillate based on the fill interval with upland property only eroded along reaches of SMB where erosion rates exceed 4.5 ft/year for 25 years or greater. This finding however, does not identify the high costs, ecological impacts and changes to recreational and aesthetic values.

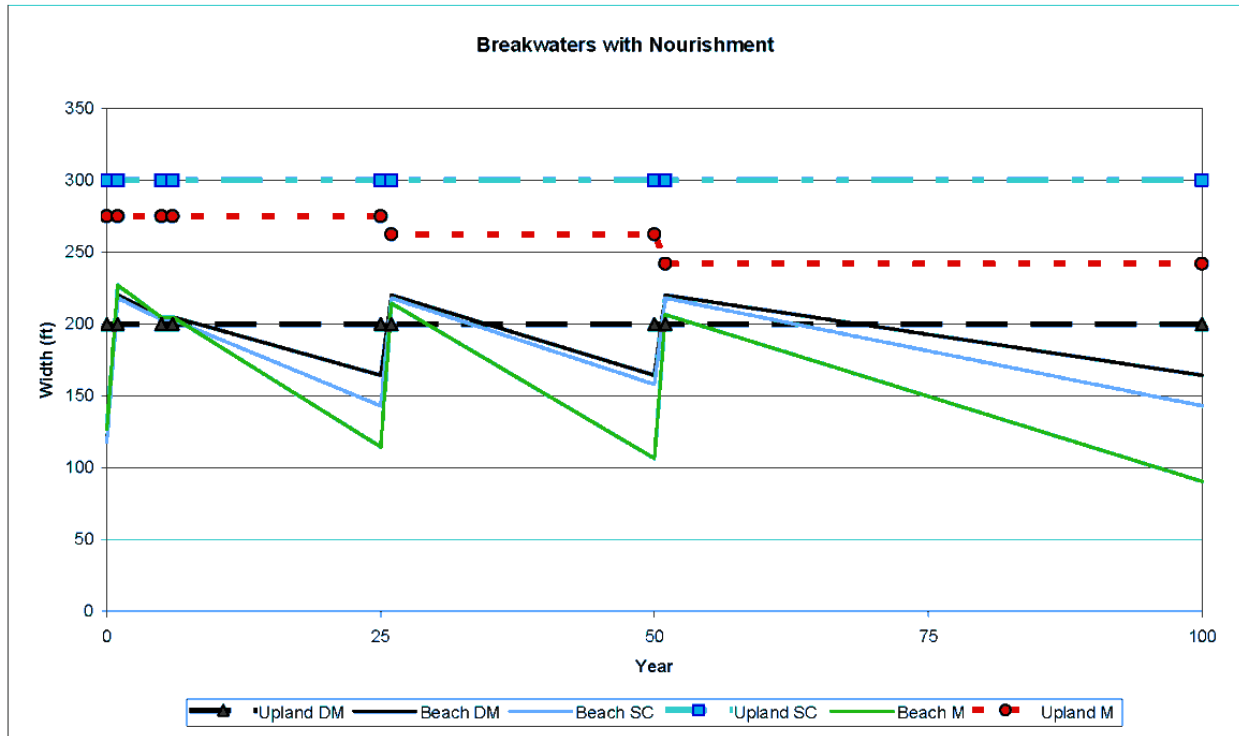


Figure 39 Effectiveness of offshore breakwaters as a sand retention device used in conjunction with a large beach nourishment at maintaining dry sand beach widths and upland property over time

Regulatory Viability

Regulatory viability is dubious at best. Constructing offshore structures in the marine environment within a National Marine Sanctuary would require MBNMS NEPA review and authorization for seabed alteration.

Ecological Impacts

The ecological impacts in SMB are not known but are likely to be potentially significant. The conversion of sandy substrate to rocky reef would be one unavoidable impact. The conversion of such artificial hard substrata in predominately soft sediment ecosystems can provide habitat and stepping stones for generalist sessile species, many of which are invasive or weedy forms.

Costs and Benefits

Tables 51 through 53 present the benefit and cost analysis for offshore breakwaters plus nourishment. See Section 3.5.2 for the assumptions used in the cost benefit analysis for this measure.

Table 51 Present Value of Benefits and Costs for Breakwater plus Nourishment: Del Monte

Planning Horizon (Years)	0 to 5	6 to 25	26 to 50	51 to 100	0 to 100
Total Recreational Value above Baseline	\$ 6,484,360	\$ 7,722,888	\$ 7,722,888	\$ 3,909,409	\$ 25,839,546
Total Habitat Value above Baseline	\$ 2,697,435	\$ 4,996,483	\$ 4,174,134	\$ 1,579,931	\$ 13,447,984
Sum Benefits	\$ 9,181,795	\$ 12,719,372	\$ 11,897,022	\$ 5,489,341	\$ 39,287,530
Structural Adjustment Costs	\$ -	\$ -	\$ -	\$ -	\$ -
MRWPCA	\$ -	\$ -	\$ -	\$ -	\$ -
Cost of Private Property Compensation	\$ -	\$ -	\$ -	\$ -	\$ -
Cost of Public Property Compensation	\$ -	\$ -	\$ -	\$ -	\$ -
Construction/Nourishment Cost	\$ 93,600,000	0	\$ 27,640,339	\$ 10,572,609	\$ 131,812,949
Revetment Cost	\$ (43,200,000)	\$ -	\$ (12,757,080)	\$ (4,879,666)	\$ (60,836,746)
Total Cost	\$ 50,400,000	\$ -	\$ 14,883,260	\$ 5,692,944	\$ 70,976,203
Net Benefits	\$ (41,218,205)	\$ 12,719,372	\$ (2,986,237)	\$ (203,603)	\$ (31,688,674)
Benefit/Cost Ratio	0.18	NA	0.80	0.96	0.55

Table 52 Present Value of Benefits and Costs for Breakwater plus Nourishment: Sand City

Planning Horizon (Years)	0 to 5	6 to 25	26 to 50	51 to 100	0 to 100
Total Recreational Value	\$ 14,814,425	\$ 23,984,649	\$ 10,496,953	\$ 3,949,235	\$ 53,245,263
Baseline	\$ 7,409,916	\$ 8,413,408	\$ -	\$ -	\$ 15,823,324
Total Habitat Value	\$ 24,961,413	\$ 40,638,966	\$ 17,987,709	\$ 6,880,415	\$ 90,468,503
Baseline	\$ 13,722,100	\$ 19,850,290	\$ 6,269,418	\$ 2,398,093	\$ 42,239,901
Sum Benefits	\$ 18,643,822	\$ 36,359,917	\$ 22,215,244	\$ 8,431,557	\$ 85,650,541
Structural Adjustment Costs	\$ -	\$ -	\$ -	\$ -	\$ -
MRWPCA	\$ -	\$ -	\$ -	\$ -	\$ -
Cost of Private Property Compensation	\$ -	\$ -	\$ -	\$ -	\$ -
Cost of Public Property Compensation	\$ -	\$ -	\$ -	\$ -	\$ -
Construction/Nourishment Cost	\$ 390,000,000	\$ -	\$ 115,168,081	\$ 44,052,539	\$ 549,220,620
Revetment Cost	\$ (180,000,000)	\$ -	\$ (53,154,499)	\$ (20,331,941)	\$ (253,486,440)
Total Cost	\$ 210,000,000	\$ -	\$ 62,013,582	\$ 23,720,598	\$ 295,734,180
Net Benefits	\$ (191,356,178)	\$ 36,359,917	\$ (39,798,338)	\$ (15,289,041)	\$ (210,083,639)
Benefit/Cost Ratio	0.09	NA	0.36	0.36	0.29

Table 53 Present Value of Benefits and Costs for Breakwater plus Nourishment: Marina

Planning Horizon (Years)	0 to 5	6 to 25	26 to 50	51 to 100	0 to 100
Total Recreational Value	\$ 14,523,252	\$ 22,062,550	\$ 9,399,010	\$ 3,315,971	\$ 49,300,782
Baseline	\$ 7,512,217	\$ 8,275,750	\$ -	\$ -	\$ 15,787,968
Total Habitat Value	\$ 32,516,240	\$ 47,943,352	\$ 19,723,817	\$ 6,423,572	\$ 106,606,981
Baseline	\$ 15,709,559	\$ 12,889,172	\$ -	\$ -	\$ 28,598,731
Net Benefits	\$ 23,817,716	\$ 48,840,979	\$ 29,122,827	\$ 9,739,542	\$ 111,521,064
Structural Adjustment Costs	0	0	0	0	0
MRWPCA	0	0	0	0	0
Cost of Private Property Compensation	\$ -	\$ 2,122,318	\$ 4,899,362	\$ -	\$ 7,021,679
Cost of Public Property Compensation	\$ -	\$ 1,029,885	\$ 576,688	\$ -	\$ 1,606,573
Construction/Nourishment Cost	\$ 542,100,000	\$ -	\$ 152,460,602	\$ 61,233,030	\$ 755,793,632
Revetment Cost	\$ (250,200,000)	\$ -	\$ (73,884,753)	\$ (28,261,398)	\$ (352,346,152)
Net Cost	\$ 291,900,000	\$ 3,152,203	\$ 84,051,899	\$ 32,971,631	\$ 412,075,733
Net Benefits	\$ (268,082,284)	\$ 45,688,777	\$ (54,929,072)	\$ (23,232,089)	\$ (300,554,668)
Benefit/Cost Ratio	NA	NA	NA	NA	NA

Benefit Cost Results

The results of the cost benefit analysis shows that the Offshore Breakwaters with Nourishment measure has a net negative cost benefit primarily as a result of high construction cost. Construction costs associated with 100 years of offshore breakwaters with nourishment for the entire study area are estimated at ~\$1.44 billion. Some positives are the benefits from reduction in private and public costs as well as avoidance of costs associated with the replacement of the MRWPCA infrastructure. The total costs over the entire study including cost savings from not building a revetment (baseline scenario) for the 100 year planning horizon total about ~\$541 million with that made up of ~\$236 million in recreation and ecosystem benefits.

In all three reaches the benefits of using breakwaters as an erosion mitigation measure do not outweigh the costs. Indeed, in most cases the net benefits are negative, implying that groins/nourishment, even though they cost more than the baseline strategy of revetment, actually lower overall benefits. As the 100-year planning horizon indicates, the overall benefit cost ratio is less than one in all instances, indicating that breakwaters/nourishment is not a viable or cost-effective option.

4.3.4 Perched Beaches

Description

Perched beaches are formed by constructing a sill at the seaward edge of the proposed beach and either allowing sand to collect landward of the sill or intentionally placing sand landward of the sill to build a beach (Figure 40). The perched beach is a special case of the submerged breakwater in which the sill's primary function is to retain sand in a perched (i.e., elevated) profile as opposed to reducing incident

wave energy (Moreno, 2003). The sill acts to raise the natural beach profile, resulting in a wider beach at the shore. The width of shore advance can be predicted using equilibrium profile theory (Gonzalez, 1999). The dry beach area inland of the sill will provide the access and recreation functions of a naturally wide beach, as well as many of the same storm protection functions (Table 54).

Along armored shores, an extreme example of a perched beach would be to terrace the structure and import some sand so that there would be a flat terrace above impacts of the waves that could provide some recreational utility.

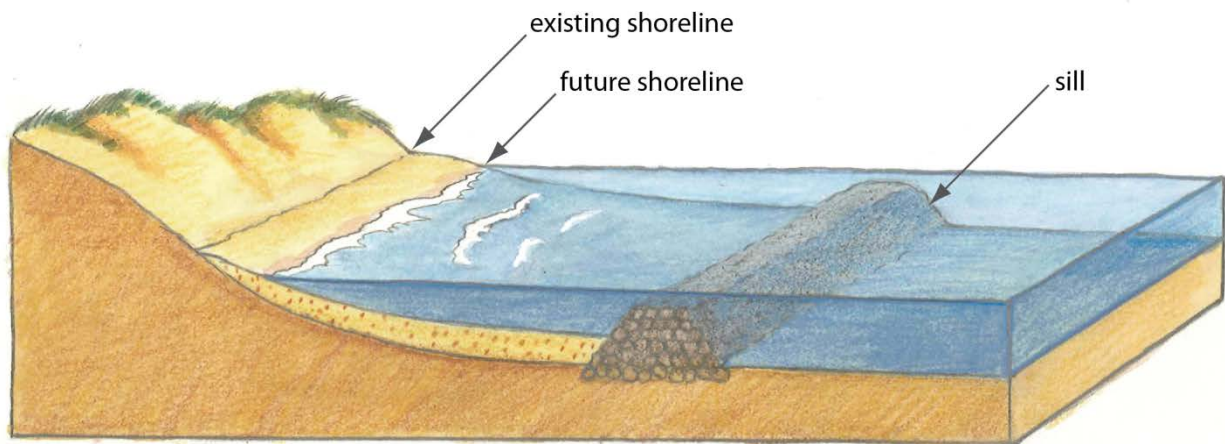


Figure 40 Schematic of a Perched Beach using a submerge sill

The perched beach method is typically proposed in conjunction with beach nourishment behind a constructed sill. A perched beach requires less sand than would be needed to nourish the full offshore portion of a natural beach because the sill effectively truncates the length of the active profile and limits offshore movement of sand (Dean & Dalrymple, 2002). Therefore, an offshore sill along a segment of the coast may be more economical than full profile nourishment. This is especially true for steep eroded profiles in which establishment of the full equilibrium profile through nourishment would not be economically feasible (Raudkivi & Dette, 2002), or where sand is readily lost offshore.

A variety of construction methods can be employed to construct the offshore sill, many of which are similar to the submerged breakwater. Rubble mound structures constructed of quarystone are traditionally the most common type of coastal structure used worldwide (USACE 1992). Armor size is selected based on design wave conditions and water depth. Offshore sills for perched beaches could also be constructed using geotextile sand bags, grout-filled bags, sheet-piles, or bulkheads, although the sill need not be a “structure” at all, and could be constructed by placing a rock ridge or gravel/cobble mound to retain sand (Raudkivi & Dette, 2002). Stauble and Giovannozzi describe installation of a linear, prefabricated concrete sill at Cape May, NJ using modular units typically used for parking garage decks (Double-T structures) (Stauble & Giovannozzi, 2003). The units were placed end-to-end in an inverted position with vertical legs extending approximately 2.5 ft above the bed. Modular units are typically placed using a barge-mounted crane.

As with many structures in the nearshore, wave and current velocities are often increased in the vicinity of the structure, which can lead to scour and undermining of the foundation (Sumer et al., 2001). The stability of the perched beach will depend upon the stability of the sill and its ability to withstand scour and wave forces. The sill foundation is often the critical design feature for these structures, and may require installation of filter cloth to prevent winnowing of fine sediment and undermining of the structure. In addition, some regular nourishment may be needed for the beach itself if there are not sufficient onshore transport mechanisms to keep the entire beach area filled.

Perched beaches are not likely to be stable during high swell and large storm events. Under these conditions, the large volumes of water transported onto the shore and returning seaward will likely overwhelm the sill structure and scour the beach. By perching the profile landward of the sill, an abrupt drop off on the seaward side of the structure may exist that can alter some of the available aquatic recreational opportunities for the area and create potentially difficult water access. Safety may be compromised if beach goers are pulled seaward past the sill. For these reasons, perched beaches are considered primarily for sheltered areas.

General Applicability

Perched beaches are conceptually applicable to any parcel threatened with erosion with relatively low wave energy. The California ocean shore is exposed to long period swell which tends to have large dynamic setup pulses. The authors posit that such conditions are likely to scour sand from behind sills and therefore question the applicability to southern Monterey Bay. Examples of application in California have not been found.

Specific Applicability

Perched beaches would be mostly likely viable in the Southern Bight where wave exposure is typically limited. Therefore, we concluded that this management alternative is most relevant for application to Subregions 1 and 2 to address critical all erosion areas in these Subregions.

Table 54 Summary of Evaluation Criteria for Perched Beaches

Evaluation Criteria	
Reduce threat to structures	Yes behind toe structure, potential flanking erosion on adjacent parcels
Maintain Beach Width	Yes potentially widens
Economic Costs	High initial cost, ongoing maintenance
Environmental Impacts	Conversion of sand bottom to rocky reef
Recreational	Improves to maintains
Safety and Public Access	Improves lateral access, potential safety issue by alterations of breaking wave characteristics and deepwater offshore of toe structure
Aesthetics	Minimal impacts if any below sea surface
Regulatory Viability	Uncertain
Adaptability to Future Conditions	Adaptable until depth over sill increases and stops dissipating wave energy
Cumulative Impacts	Conversion of sand bottom habitats to rock reef
Certainty of Success	Low Wave Exposure: Somewhat certain in short term, less certain in medium/long term without improvement/repairs to sill structure High Wave Exposure: Uncertain.

Discussion

The theory of perched beaches is often presented in the literature as an alternative to traditional shore armoring approaches (Dean & Dalrymple, 2002; USACE, 1992), but few documented cases of implementation exist. In general, there is little engineering guidance available as to the morphodynamic response of a beach to a sill structure, which has likely reduced the number of successful applications. For example, construction of a perched beach was considered for beach protection at Adelaide, Australia, but was eliminated due to uncertainties associated with their performance (South Australia EPA, 1999).

The concept of a perched beach is based on several assumptions that require careful consideration when implementing the method: (1) no loss of material over sill, (2) no alongshore losses, and (3) equilibrium beach profile applies. Laboratory tests conducted by various researchers show contradictory evidence of onshore/offshore transport from a perched beach (Sorenson & Beil, 1988; Dette et al., 1997), and a specific submerged sill may have either a beneficial or undesirable shore response depending on the incident wave conditions and structure geometry (Moreno, 2003; Raudkivi & Dette, 2002).

Numerical modeling studies for a proposed perched beach at the Port of Rotterdam found that the magnitude of offshore losses was dependent on structure distance offshore, with greater losses for structures closer to shore (Eversdijk, 2005). Since greater offshore losses result in increased frequency of nourishment, the cross-shore location of the sill is a cost optimization problem (i.e., placing the structure close to shore saves initial nourishment costs but may result in increased cumulative offshore losses over time). This is especially pertinent to perched beaches because, unlike a natural beach where offshore transport is a reversible process (e.g., onshore transport during long-period swell events), offshore movement of sand from a perched beach is permanent.

In areas of significant wave energy, alongshore transport out of the project area will be an important design consideration, especially as it relates to frequency of re-nourishment. The problem of coast-wise continuity of a project can be solved using solid or permeable groins to limit alongshore transport (Raudkivi & Dette, 2002). Some installations tie in to existing structures or headlands at lateral boundaries. An installation near Venice used solid groins with the seaward half submerged to allow some alongshore transport. Physical model tests of that installation showed negligible loss of sediment from the perched beach compartment bounded by the groins (Raudkivi & Dette, 2002).

Much of the engineering literature on beach nourishment and beach profile evolution relies on the “equilibrium profile” concept, which suggests that under constant wave and water levels, the shoreface will attain an equilibrium form that dissipates wave energy without significant change in shape or net sand transport (Larson and Kraus 1989). There is a well-documented debate on the validity of the equilibrium profile in the literature (e.g., Dean, 1977; Dean, 1991; Pilkey et al., 1993); nonetheless, its application to coastal engineering problems is widespread. Gonzalez (1999) provides a theoretical description of the equilibrium profile for a perched beach that predicts shore advance and profile shape. Results compared well with laboratory data. Gonzalez concluded that the most important factor in determining the shape of the profile (and the resulting shore advance) is the degree of wave reflection at the submerged sill, which depends on the sill geometry, location, and incident wave conditions. Not surprisingly, maximum shore advance is predicted to occur as the crest of the sill approaches the water surface; however, the equilibrium profile concept does not account for the effect of the sill on nearshore hydrodynamics which may act to modify the profile through transport and scour of sediment. As a result, conceptual models of equilibrium profiles for perched beaches may have limited applicability to actual projects in the field.

Regulatory Viability

The regulatory viability of perched beaches is uncertain. Constructing offshore structures in the marine environment within a National Marine Sanctuary would require MBNMS NEPA review and authorization for seabed alteration.

Ecological Impacts

The ecological affects of perched beaches is unknown in SMB. Effects are likely to be potentially significant but site specific. The conversion of sandy substrate to rocky reef would be one unavoidable impact. The conversion of such artificial hard substrata in predominately soft sediment ecosystems can provide habitat and stepping stones for generalist sessile species, many of which are invasive or weedy forms.

4.3.5 Seawalls/Revetments

Description

Seawalls are vertical structures along a beach or bluff, used to protect structures from wave action as a course of last resort (Figure 41). A seawall works by absorbing or dissipating wave energy. They may be either gravity- or pile-supported structures. Seawalls can have a variety of face shapes. Seawalls and bulkheads are normally constructed of stone or concrete, however other materials can be used. Current seawall projects usually require design elements that allow the structure to resemble the natural

environment in that area, in order to blend in with the existing geologic conditions. Currently in the Southern Monterey Bay Region seawall projects have been built for the Ocean Harbor House and the Monterey Beach Resort.

Revetments provide protection to existing slopes affronting a threatened structure, and are constructed of a sturdy material such as stone. Similar in purpose to a seawall, revetments work by absorbing or dissipating wave energy. They are made up of: an *armor layer*--either stone or concrete rubble piled up or a carefully placed assortment of interlocking material which forms a geometric pattern, a *filter layer* -- which provides for drainage, and retains the soil that lies beneath, and a *toe*--which adds stability at the bottom of the structure. Revetments are the most common coastal protection structure along the shore of the southern Monterey Bay, currently protecting several structures such as the Del Monte Lake storm drain outfall. In comparison to seawalls, revetments tend to have greater visual impacts and require a larger footprint, which leads to a larger placement loss and impacts to public access (Table 55).



Figure 41 Example of a seawall, Ocean Harbor House, Monterey, CA (Photo Gary Griggs)

Geotextile revetment constructed of geotextile bags or tubes have most of the same constraints as any other revetment; however, the geotextile option allows the use of smaller aggregate for construction, where normally the design conditions would require larger material. In theory, the geotextiles, while not as stable as rock, have the advantage of relative easy removal.

General Applicability

Seawalls are potentially applicable to any oceanfront parcel that can be established as existing development under the Coastal Act.

Specific Applicability

This management alternative is most relevant for application to Subregions 1-4 and 6 to address critical erosion problems where there are existing structures on the coast.

Table 55 Summary of Evaluation Criteria for Seawalls / Revetments

Evaluation Criteria	
Reduce threat to structures	Yes in short to medium term
Maintain Beach Width	No – loss due to structure footprint and narrowing due to passive erosion
Economic Costs	High (\$3,500-\$10,000 per lineal foot of shore)
Environmental Impacts	Impacts to sandy beach habitats, shorebirds, potential flanking erosion to adjacent unprotected parcels
Recreational	Reduces beach widths over time
Safety and Public Access	Reduces
Aesthetics	Impact but partially mitigable with concrete contouring, texturing
Regulatory Viability	Probably, case-by-case analysis required
Adaptability to Future Conditions	No
Cumulative Impacts	Large cumulative impacts to recreation, and beach habitats
Certainty of Success	Certain in short term, less certain in medium/long term

Discussion

There are a number of environmental impacts associated with seawalls including short-term construction impacts as well as long-term cumulative impacts. The most commonly recognized impacts include: visual and aesthetic effects, encroachment onto beach due to placement loss, restriction of vertical and lateral public access, prevention of historic sand supply from hardening of eroding cliffs, passive and active erosion, and potential biological impacts. These impacts vary significantly depending on the design of the structure, the magnitude of the project, and the specific geologic, biologic, and oceanographic conditions in the area, and must be evaluated on a case-by-case basis.

The southern Monterey Bay shore is a highly erosive shore and seawalls contribute to passive erosion. Passive erosion occurs on erosive shores where the shore erodes landward of a hardened structure such as a seawall that then projects into the ocean. This peninsula effect blocks lateral access of the shore. Examples in southern Monterey Bay of where lateral access is blocked are the rip-rap seawall fronting Stillwell Hall in Fort Ord (since removed) and the rip-rap at the end of Tioga Avenue in Sand City. In addition, the shore access is presently blocked at high tide at the Monterey Beach Hotel and the Ocean Harbor House Condominiums seawalls during the winter when the beach is cut back. This situation is expected to become worse with time until the seawalls project into the ocean completely blocking shore lateral access, unless other mitigation measures such as beach nourishment are instituted.

Effectiveness – Maintaining beach width vs. protecting upland property

Seawalls and Revetments protect upland property by fixing the backshore in place which leads to a loss of beach width (Figure 8). The primary difference between the revetment and seawall is the footprint of the structure that occupies the beach (placement loss). On the eroding shores of Southern Monterey Bay, both the seawall and the revetment options lead to a loss of beaches between 25 and 50 years into the future (Figure 42 and 43).



Figure 42 Effectiveness of seawalls at maintaining dry sand beach widths and upland property over time

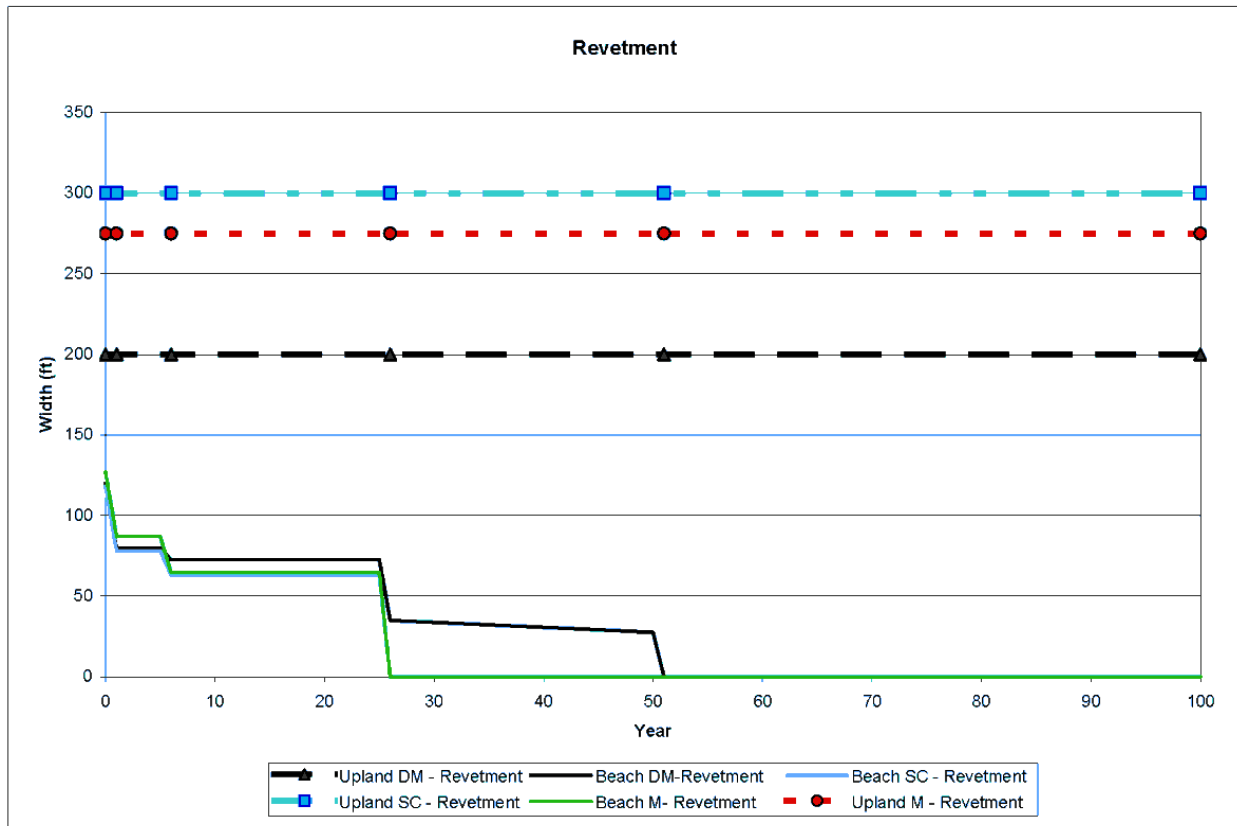


Figure 43 Effectiveness of revetments at maintaining dry sand beach widths and upland property over time

Regulatory Viability

Seawalls and revetments are controversial due to adverse effects on shores but are generally approved by the Coastal Commission and other regulatory agencies with significant conditions to help mitigate for recreation and sand supply. Probably, case-by-case analysis is required.

Ecological Impacts

Despite widespread use of coastal armoring on coastlines around the world for thousands of years, numerous studies of their physical effects, costs and efficacy and a very active debate on the geomorphic impacts of these structures on both open and sheltered coasts, the ecological impacts of these structures have only just begun to be addressed or considered (NRC 2007, Dugan et al 2010). Results of recent studies suggest that coastal armoring, including seawalls and revetments, causes a number of significant ecological impacts to open coast beach ecosystems (Dugan and Hubbard 2006, Dugan et al 2008, Dugan et al in press). Many of these impacts are associated with the loss of beach habitat with strongest effects evident on the upper shore. Shore-parallel armoring also disrupts vital connections between the marine and terrestrial realms, eliminating key exchanges (detritus, sediments, nutrients, prey, propagules) and functions (nutrient remineralization and cycling, water filtration) for coastal ecosystems (Dugan et al. 2011, in press).

The placement of and subsequent beach erosion and narrowing associated with an armoring structure cause the reduction and eventual loss of upper to middle habitat zones of the beach, including the vegetated coastal strand, the dry sand and the driftline zones. In California, these higher shore zones support unique biodiversity (~40% of intertidal invertebrate species, Dugan et al., 2003) and ecological functions (Dugan and Hubbard 2010, Dugan et al 2011, in press), which are not replicated in the lower damp and saturated sand zones that may persist. As the upper intertidal zone, including the driftline, shifts from the beach to the armoring structure, strong ecological consequences including reduced biodiversity, invertebrate abundance and prey resources for shorebirds and fish are realized. Rich, three-dimensional infaunal beds of the driftline are eliminated and replaced by the steep artificial habitat of the armoring which may support a low diversity of some rocky shore species (e.g. Chapman, 2003; Chapman & Bulleri, 2003) but has little or no resource value for shorebirds. This reduction and alteration of beach habitat from coastal armoring was associated with significant 2 to 36-fold impacts to beach zone widths, driftwood and wrack accumulation, upper shore macroinvertebrates, abundance and diversity of foraging shorebirds and of roosting gulls and seabirds for intertidal seawalls on open coast beaches in California (Dugan et al., 2008; Dugan & Hubbard, 2006). In those studies, the reductions in abundance of shorebirds and of gulls, seabirds and other birds associated with coastal armoring (>3-fold and >4-fold respectively) exceeded that predicted by the overall loss of beach habitat area from armoring (2-fold) suggesting that avifauna are responding to other impacts of armoring, including prey abundance and the availability of high tide feeding and roosting habitat and refuges. The greatly reduced retention and accumulation of macrophyte wrack seaward of armoring structures strongly affects beach food webs via impacts to intertidal biodiversity and abundance that are key prey resources for shorebirds, including snowy plovers (see Dugan et al., 2003). Furthermore, preliminary studies suggest that the distribution, abundance, and survival of important macroinvertebrates of the mid to lower shore (e.g. bivalves, isopods and hippid crabs) are reduced by the loss of habitat, changes in habitat quality, and restrictions on tidal migration, as well as by the decreased availability of alternative sandy habitats or refuges during high surf conditions imposed by armoring (Jaramillo et al., unpublished). The uppermost zones of the beach ecosystem most affected by armoring structures also provide critical wildlife support, which includes habitat for nesting snowy plovers and grunion spawning (Dugan et al., in press).

Along with the physical effects as predicted by Weigel (Weigel, 2002a; Weigel 2002b; Weigel, 2002c), the ecological impacts of any armoring structure are expected to increase as the amount of interaction between the structure and waves and tides increases, whether this is due to initial placement or subsequent erosion of the beach. Hence, the lower a structure is located on the beach profile, the stronger ecological impacts are expected to be.

Costs and Benefits

Tables 56 through 58 present the benefits and costs analysis for revetments. See Section 3.5.2 for assumptions used in this measure. Since the baseline scenario includes the use of a revetment we present the net benefits and costs.

Table 56 Present Value of Benefits and Costs for Revetment: Del Monte

Planning Horizon (Years)	0 to 5	6 to 25	26 to 50	51 to 100	0 to 100
Total Recreational Value Above Baseline	\$ -	\$ -	\$ -	\$ -	\$ -
Total Habitat Value Above Baseline	\$ -	\$ -	\$ -	\$ -	\$ -
Sum Benefits	\$ -	\$ -	\$ -	\$ -	\$ -
Structural Adjustment Costs	\$ -	\$ -	\$ -	\$ -	\$ -
MRWPCA	\$ -	\$ -	\$ -	\$ -	\$ -
Cost of Private Property Compensation	\$ -	\$ -	\$ -	\$ -	\$ -
Cost of Pubic Property Compensation	\$ -	\$ -	\$ -	\$ -	\$ -
Construction/Nourishment Cost	\$ 43,200,000	\$ -	\$ 12,757,080	\$ 4,879,666	\$ 60,836,746
Total Cost	\$ 43,200,000	\$ -	\$ 12,757,080	\$ 4,879,666	\$ 60,836,746
Net Benefits	\$ (43,200,000)	0	\$ (12,757,080)	\$ (4,879,666)	\$ (60,836,746)
Benefit/Cost Ratio	NA	NA	NA	NA	NA

Table 57 Present Value of Benefits and Costs for Revetment: Sand City

Planning Horizon (Years)	0 to 5	6 to 25	26 to 50	51 to 100	0 to 100
Total Recreational Value	\$ 7,409,916	\$ 8,413,408	\$ -	\$ -	\$ 15,823,324
Total Habitat Value	\$ 13,722,100	\$ 19,850,290	\$ 6,269,418	\$ 2,398,093	\$ 42,239,901
Sum Benefits	\$ 21,132,016	\$ 28,263,698	\$ 6,269,418	\$ 2,398,093	\$ 58,063,225
Structural Adjustment Costs	\$ -	\$ -	\$ -	\$ -	\$ -
MRWPCA	\$ -	\$ -	\$ -	\$ -	\$ -
Cost of Private Property Compensation	\$ -	\$ -	\$ -	\$ 112,670	\$ 112,670
Cost of Pubic Property Compensation	\$ -	\$ -	\$ -	\$ 109,517	\$ 109,517
Construction/Nourishment Cost	\$ 180,000,000	0	\$ 53,154,499	\$ 20,331,941	\$ 253,486,440
Total Cost	\$ 180,000,000	\$ -	\$ 53,154,499	\$ 20,554,128	\$ 253,708,627
Net Benefits	\$ (158,867,984)	\$ 28,263,698	\$ (46,885,081)	\$ (18,156,034)	\$ (195,645,401)
Benefit/Cost Ratio	NA	NA	NA	NA	NA

Table 58 Present Value of Benefits and Costs for Revetment: Marina

Planning Horizon (Years)	0 to 5	6 to 25	26 to 50	51 to 100	0 to 100
Total Recreational Value	\$ 7,512,217	\$ 8,275,750	\$ -	\$ -	\$ 15,787,968
Total Habitat Value	\$ 15,709,559	\$ 12,889,172	\$ -	\$ -	\$ 28,598,731
Sum Benefits	\$ 23,221,776	\$ 21,164,923	\$ -	\$ -	\$ 44,386,699
Structural Adjustment Costs	\$ -	\$ -	\$ -	\$ -	\$ -
MRWPCA	\$ -	\$ -	\$ -	\$ -	\$ -
Cost of Private Property Compensation	\$ -	\$ -	\$ -	\$ -	\$ -
Cost of Pubic Property Compensation	\$ -	\$ -	\$ -	\$ -	\$ -
Construction/Nourishment Cost	\$ 250,200,000	0	\$ 73,884,753	\$ 28,261,398	\$ 352,346,152
Total Cost	\$ 250,200,000	\$ -	\$ 73,884,753	\$ 28,261,398	\$ 352,346,152
Net Benefits	\$ (226,978,224)	\$ 21,164,923	\$ (73,884,753)	\$ (28,261,398)	\$ (307,959,453)
Benefit/Cost Ratio	NA	NA	NA	NA	NA

Benefit Cost Results

The results of the cost benefit analysis shows that the Revetment and Seawall measures have a negative net benefit primarily as a result of high construction cost. Construction costs associated with 100 years of revetment for the entire study area are estimated at ~\$ 667 million. Seawall construction is estimated at ~\$1.22 billion for the entire study area. Some positives are the benefits from reduction in private and public cost associated with erosion damages as well as avoidance of costs associated with the replacement of the MRWPCA infrastructure. The net cost over the entire study for a revetment (baseline scenario) for the 100 year planning horizon total about ~\$667 million with no additional recreation and ecosystem benefits (because the revetment is the baseline). The net cost over the entire study for a seawall for the 100 year planning horizon total about ~\$461 million with that made up of ~\$94 million in recreation and ecosystem benefits.

In every case the B/C ratio is less than one indicating that the costs exceed the benefits. In other words, the loss in recreational and habitat value is greater than the costs of building a revetment (and the net benefits are negative).

Tables 59 through 61 present essentially the same tables for a seawall. The only difference is that a seawall is about twice as expensive as a revetment and yields similar benefits, thus the B/C ratio is even lower.

Table 59 Present Value of Benefits and Costs for Seawall: Del Monte

Planning Horizon (Years)	0 to 5	6 to 25	26 to 50	51 to 100	0 to 100
Total Recreational Value above Baseline	\$ 1,891,463	\$ 3,751,875	\$ 2,078,659	\$ 973,121	\$ 8,695,117
Total Habitat Value above Baseline	\$ 578,022	\$ -	\$ -	\$ -	\$ 578,022
Sum Benefits	\$ 2,469,485	\$ 3,751,875	\$ 2,078,659	\$ 973,121	\$ 9,273,139
Structural Adjustment Costs	\$ -	\$ -	\$ -	\$ -	\$ -
MRWPCA	\$ -	\$ -	\$ -	\$ -	\$ -
Cost of Private Property Compensation	\$ -	\$ -	\$ -	\$ -	\$ -
Cost of Pubic Property Compensation	\$ -	\$ -	\$ -	\$ -	\$ -
Construction/Nourishment Cost	\$ 79,200,000	0	\$ 23,387,980	\$ 8,946,054	\$ 111,534,034
Revetment Cost	\$ (43,200,000)	\$ -	\$ (12,757,080)	\$ (4,879,666)	\$ (60,836,746)
Total Cost	\$ 36,000,000	\$ -	\$ 10,630,900	\$ 4,066,388	\$ 50,697,288
Net Benefits	\$ (33,530,515)	\$ 3,751,875	\$ (8,552,240)	\$ (3,093,268)	\$ (41,424,149)
Benefit/Cost Ratio	0.07	NA	0.20	0.24	0.18

Table 60 Present Value of Benefits and Costs for Seawall: Sand City

Planning Horizon (Years)	0 to 5	6 to 25	26 to 50	51 to 100	0 to 100
Total Recreational Value	\$ 9,356,974	\$ 12,204,183	\$ 1,748,297	\$ -	\$ 23,309,454
Baseline	\$ 7,409,916	\$ 8,413,408	\$ -	\$ -	\$ 15,823,324
Total Habitat Value	\$ 16,130,525	\$ 23,477,205	\$ 6,922,872	\$ 2,398,093	\$ 48,928,696
Baseline	\$ 13,722,100	\$ 19,850,290	\$ 6,269,418	\$ 2,398,093	\$ 42,239,901
Sum Benefits	\$ 4,355,482	\$ 7,417,691	\$ 2,401,751	\$ -	\$ 14,174,925
Structural Adjustment Costs	\$ -	\$ -	\$ -	\$ -	\$ -
MRWPCA	\$ -	\$ -	\$ -	\$ -	\$ -
Cost of Private Property Compensation	\$0	\$0	\$0	\$112,670	\$112,670
Cost of Pubic Property Compensation	\$0	\$0	\$0	\$109,517	\$109,517
Construction/Nourishment Cost	\$ 330,000,000	\$ -	\$ 97,449,915	\$ 37,275,226	\$ 464,725,140
Revetment Cost	\$ (180,000,000)	\$ -	\$ (53,154,499)	\$ (20,331,941)	\$ (253,486,440)
Total Cost	\$ 150,000,000	\$ -	\$ 44,295,416	\$ 17,165,471	\$ 211,460,887
Net Benefits	\$ (145,644,518)	\$ 7,417,691	\$ (41,893,664)	\$ (17,165,471)	\$ (197,285,962)
Benefit/Cost Ratio	NA	NA	NA	NA	NA

Table 61 Present Value of Benefits and Costs for Seawall: Marina

Planning Horizon (Years)	0 to 5	6 to 25	26 to 50	51 to 100	0 to 100
Total Recreational Value	\$ 9,336,491	\$ 10,575,941	\$ 6,937	\$ 2,654	\$ 19,922,022
Baseline	\$ 7,512,217	\$ 8,275,750	\$ -	\$ -	\$ 15,787,968
Total Habitat Value	\$ 19,057,268	\$ 16,292,382	\$ -	\$ -	\$ 35,349,651
Baseline	\$ 15,709,559	\$ 12,889,172	\$ -	\$ -	\$ 28,598,731
Net Benefits	\$ 5,171,983	\$ 5,703,400	\$ 6,937	\$ 2,654	\$ 10,884,974
Structural Adjustment Costs	0	0	0	0	0
MRWPCA	0	0	0	0	0
Cost of Private Property Compensation	\$ -	\$ -	\$ -	\$ -	\$ -
Cost of Public Property Compensation	\$ -	\$ -	\$ -	\$ -	\$ -
Construction/Nourishment Cost	\$ 458,700,000	\$ -	\$ 135,455,381	\$ 51,812,564	\$ 645,967,945
Revetment Cost	\$ (250,200,000)	\$ -	\$ (73,884,753)	\$ (28,261,398)	\$ (352,346,152)
Net Cost	\$ 208,500,000	\$ -	\$ 61,570,628	\$ 23,551,165	\$ 293,621,793
Net Benefits	\$ (203,328,017)	\$ 5,703,400	\$ (61,563,690)	\$ (23,548,512)	\$ (282,736,819)
Benefit/Cost Ratio	NA	NA	NA	NA	NA

The results indicate that shore armoring is not cost effective in terms of multiple objectives including recreation and ecology (ecosystem services). However, we believe the extensive construction of shore armoring indicates that there is at least a perception of a favorable net benefit. We speculate that this apparent dichotomy is logically derived from a different accounting of costs and benefits, as follows:

- Shore armoring projects do not consider ecosystem services except as forced in the regulatory process. On eroding shores, beaches are lost over time in front of shore armoring with most of the costs borne by others than those that armor.
- Property owners and infrastructure managers have great incentive to protect their property and infrastructure, but are not directly accountable for the consequences of their decisions at the future time when concerns of loss of beach may arise.

5. DISCUSSION OF REGULATORY RISK

5.1 INTRODUCTION

The purpose of this section of the report is to estimate the regulatory risk associated with four different land use planning tools as applied to hypothetical categories of development in southern Monterey Bay¹²(Figure 44).

This study considers several land use alternatives for coping with coastal erosion. One perception of local governments who may implement some of these land use planning measures is that they may face takings challenges from private property owners. Under the so-called “Takings Clause” of the Fifth Amendment to the U.S. Constitution, the federal or a state government may not “take” private property for public use without providing the landowner with just compensation.

When agencies act to impair recognized property rights without providing compensation, they may encounter Fifth Amendment challenges from property owners. Such challenges are analyzed under one of four legal frameworks, depending on the sort of regulation at issue:

1. A regulation that leads to an involuntary, permanent, and physical occupation of property, no matter how small, is an automatic (or “per se”) taking that must be compensated.¹³
2. A regulation that deprives the property owner of all economically beneficial use of the property is a taking that must be compensated, unless the agency can show that the regulation merely codifies an already existing limitation on the owner’s use of her property.¹⁴
3. A regulation that results in a partial diminution in property value is analyzed under a loose, three-factor test that balances: (a) the economic impact of the regulation, (b) the reasonable investment-backed expectations of the owner, and (c) the character of the regulation (e.g., whether the regulation restricts harmful activity across the community versus targeting specific property owners).¹⁵
4. Exactions or dedications (e.g., conditions imposed by an agency for approval of a coastal development permit) may constitute an unlawful taking unless they are both logically related to and roughly proportional to the impact of the individual project.¹⁶

¹² Note: nothing in this document should be construed as conveying legal advice. This document provides INFORMATION ABOUT THE LAW as it relates to hypothetical fact situations, and is solely for academic and informational purposes. Legal information is not the same as legal advice, which applies the law to specific circumstances. Nothing in this document purports to apply law to specific situations or to provide a comprehensive picture of the law. We make no claims, assurances, or guarantees as to the accuracy or completeness of the information in this document. One should consult a lawyer for up-to-date information about the law or legal advice.

¹³ *Loretto v. Teleprompter Manhattan CATV Corp.*, 458 U.S. 419 (1982).

¹⁴ *Lucas v. South Carolina Coastal Council*, 505 U.S. 1003, 1022-23.

¹⁵ *Penn Central Transp. Co. v. New York City*, 438 U.S. 104 (1978).

¹⁶ *Nollan v. California Coastal Comm’n*, 483 U.S. 825 (1987); *Dolan v. City of Tigard*, 512 U.S. 374 (1994).

5.2 POTENTIAL TAKINGS ANALYSIS USING HYPOTHETICAL SITUATIONS

KEY: ■ = Possible High Risk ■ = Likely Medium Risk ■ = Likely Low Risk

		HYPOTHETICAL PROPERTY TYPE		
		Undeveloped property with proposed development	Developed property with “no future armoring” permit condition in place	Residential development predating the Coastal Act
HYPOTHETICAL LAND USE TOOL	Transfer of development rights (TDR) credits	No Development Allowed; Partial Diminution in Property Value—1	N/A, although TDRs can be used in combination with easements and setbacks to reduce regulatory risk.	N/A, although TDRs can be used in combination with easements and setbacks to reduce regulatory risk.
	Lateral conservation easement condition to CDP	Exactions or Dedications—2	Exactions or Dedications—3	Exactions or Dedications—4
	Rolling easement (“no future armoring”) condition to CDP	Exactions or Dedication—5	N/A, although TDRs can be used in combination with easements and setbacks to reduce regulatory risk.	Exactions or Dedication—6
	Rolling easement regulation	Partial Diminution in Property Value—7	Partial Diminution in Property Value—8	Partial Diminution in Property Value—9
	Setback condition to CDP	Exactions or Dedications—10	Exactions or Dedications—11	Exactions or Dedications—12
	Setback regulation	Denial of All Economically Beneficial Use; Partial Diminution in Property Value—13	Denial of All Economically Beneficial Use; Partial Diminution in Property Value—14	Denial of All Economically Beneficial Use; Partial Diminution in Property Value—15

Figure 44 Comparison matrix of hypothetical land use tools and property types

5.2.1 Transfer of Development Rights (TDR) Credits

1. **Undeveloped property with proposed development:** If no development is allowed and compensation is not provided, a court might find a regulatory taking because the regulation may deny the owner all economically beneficial use of her property.¹⁷ However, with a well-designed TDR program, a court is more likely to find that the transfer of development rights credits amounts to sufficient compensation for the taking. In particular, a court would be more likely to rule in favor of the local government if the local government guaranteed a ready market for TDR credits, ensuring that the property owner could sell credits at a predictable and fair price.¹⁸

¹⁷ See *Suitum v. Tahoe Reg'l Planning Agency*, 520 U.S. 725, 747-50 (1997) (Scalia, J., concurring).

¹⁸ See *Suitum*, 520 U.S. 725.

If some minimal amount of development is allowed, and so long as some economic value remains, a court applying the partial diminution in value analysis may not find a taking.¹⁹ Under the first prong of analysis, the economic impact of the regulation is offset by the TDR credits, and under the third prong, the character of the regulation is to protect public resources.

5.2.2 Lateral Conservation Easement Condition to CDP

1. **Undeveloped property with proposed development:** As a condition to a Coastal Development Permit, a court may find that a lateral conservation easement is logically related to and roughly proportional to the impact of developing the property, because the development will be subject to sea-level rise and inevitable future interference with public tidelands.
2. **Developed property with “no new seawalls” condition:** As a condition to a Coastal Development Permit for redevelopment of the property, a court may find that a lateral easement is logically related to and roughly proportional to the impact of redevelopment if the remodeling extends the life of the property, thereby subjecting it to sea-level rise and inevitable future interference with public tidelands. However, an argument incorporating sea-level rise and the public trust doctrine has not yet been tested in court. Additionally, in the past, the U.S. Supreme Court has not looked favorably upon lateral conservation easements as conditions to redevelopment permits where adequate nexus findings were not made.²⁰
3. **Residential development predating the Coastal Act:** As a condition to a Coastal Development Permit for *coastal armoring*, a court may find that a lateral conservation easement is logically related to and roughly proportional to the impact of the shoreline armoring, if, for example, the regulator can demonstrate with quantified studies that seawalls accelerate beach erosion and hinder public access to tidelands.²¹

As a condition to a Coastal Development Permit for *redevelopment of the property*, a court may find that a lateral easement is logically related to and roughly proportional to the impact of redevelopment if the remodeling extends the life of the property, thereby subjecting it to sea-level rise and the inevitable need for future coastal armoring or future interference with public tidelands. However, an argument incorporating sea-level rise and the public trust doctrine has not yet been tested in court. Additionally, in the past, the U.S. Supreme Court has not looked favorably upon lateral conservation easements as conditions to redevelopment permits where adequate nexus findings were not made.²²

5.2.3 Rolling easement condition to CDP

1. **Undeveloped property with proposed development:** As a condition to a Coastal Development Permit for development of a property, a court may find a “no future armoring” condition to be logically related and roughly proportional to the impact of developing the property because the

¹⁹ *Penn Central*, 438 U.S. 104.

²⁰ *See Nollan*, 483 U.S. 825.

²¹ *See Dolan*, 512 U.S. 374.

²² *See Nollan*, 483 U.S. 825.

development would be subject to sea-level rise and inevitable future interference with public tidelands. Of course, proper findings must be made. Such a condition operationalizes Coastal Act provisions that prevent the Coastal Commission from approving new development (a) contributing to erosion,²³ (b) requiring the construction of armoring devices,²⁴ or (c) interfering with the public's right of access to the shore.²⁵

2. **Residential development predating the Coastal Act:** The Coastal Act is generally interpreted to grant owners of structures predating the Act the privilege to armor if specified conditions are met.²⁶ In cases of redevelopment where the pre-Coastal Act structure is removed, the court should treat the property as undeveloped property with proposed development.

5.2.4 Rolling easement regulation

1. **Undeveloped property with proposed development:** A rolling easement should not result in a partial diminution in property value. It is difficult to predict with certainty how a court will apply the subjective three-part balancing test; but, under the first prong, the rolling easement would reduce the value of the property so slowly that a court is unlikely to find a "taking." Under the second prong, it is possible a court will find that the owners can have no investment-backed expectation of interfering with the "public trust," the land seaward of the mean high tide line that is held in trust for the public by the state. Indeed, a rolling easement regulation would merely codify preexisting limits on development that are found in the public trust doctrine. Finally, the third prong of the balancing test should be persuasive to the court, as the character of the regulation is to prevent private property owners from interfering with the public trust.
2. **Developed property with "no new seawalls" condition:** A rolling easement is easiest to defend against a takings claim in this case because, under the second prong of the subjective balancing test applied by the court, the owner has no reasonable expectation of armoring the property. A court should also be persuaded by the third prong of the test that the character of the regulation is to protect private property owners from interfering with the public trust doctrine, which holds that the land below the mean high tide line is held in trust for the public by the state.
3. **Residential development predating the Coastal Act:** In this case, a rolling easement may result in a partial diminution in property value. It is difficult to predict with certainty how a court will apply the subjective three-part balancing test; but, under the second prong, it is possible a court will find that the owners have already enjoyed beneficial use of the residential structure(s) and should have no continued expectation to armor the property. The third prong should be most persuasive to the court, as the character of the regulation is to protect private property owners from interfering with the public trust resources and tidelands. The public trust doctrine holds that land below the mean high tide line is held in trust for the public by the state.

²³ CAL. PUB. RES. CODE § 30253(b).

²⁴ *Id.*

²⁵ CAL. PUB. RES. CODE §§ 30211, 30252.

²⁶ *See* CAL. PUB. RES. CODE § 30235.

Furthermore, even if the rolling easement, at the time it is asserted, would result in a loss of all economically beneficial use of the property, a court could find that the denial is not a “taking” because it merely codifies preexisting limits on development grounded in the public trust doctrine.

5.2.5 Setback condition to CDP

1. **Undeveloped property with proposed development:** As a condition of a coastal development permit for developing the property, a court may find that a setback is logically related to and roughly proportional to the impact of developing the property because the development would be subject to sea-level rise.
2. **Developed property with “no new seawalls” condition:** As a condition to a Coastal Development Permit for redevelopment of the property, a court may find that a setback requirement is logically related to and roughly proportional to the impact of redevelopment if the remodeling extends the life of the property, thereby subjecting it to sea-level rise and the inevitable future interference with public tidelands.
3. **Residential development predating the Coastal Act:** As a condition to a Coastal Development Permit for redevelopment of the property, a court likely should find that a setback requirement is logically related to and roughly proportional to the impact of redevelopment if the remodeling extends the life of the property, thereby subjecting it to sea-level rise and the inevitable need for future coastal armoring or future interference with public tidelands.

5.2.6 Setback Regulation

1. **Undeveloped property with proposed development:** A court may find regulatory setbacks to be a regulatory taking²⁷ if the use of a meaningful erosion rate over an appropriate time period will result in a setback that denies the property owner any economically beneficial use of her property. Such could be the case if there were not enough space left on the property to reconstruct the development behind the setback line. In practice, however, the local government could exercise its authority to grant a variance from the setback regulation in extreme situations, thus avoiding a takings claim.

If there is still room to construct development behind the setback line, a court applying the partial diminution in value balancing test is less likely to rule against an owner who purchased the property under a different understanding of land use restrictions. However, if the property owner purchased the property with knowledge of the regulation, a court applying the subjective balancing test might be persuaded by the fact that the character of the regulation is to protect the public trust, and the owner had no reasonable investment-backed expectations of developing the property in interference with public trust lands.

²⁷ See *Lucas*, 505 U.S. at 1022-23.

2. **Developed property with “no new seawalls” condition:** A court could find regulated setbacks to be a regulatory taking²⁸ if the use of any meaningful erosion rate over an appropriate time period would result in a setback that denied the property owner any economically beneficial use of her property. Such might be the case if there were not enough space left on the property to reconstruct development behind the setback line. In practice, however, the local government could exercise its authority to grant a variance from the setback regulation in situations where the regulated setback would deny the property owner any economically beneficial use of her property, thus avoiding a takings claim.

Even if there still is room to reconstruct development behind the setback line, a court applying the partial diminution in value balancing test may be unlikely to rule against an owner who developed the property under a different understanding of land use restrictions.

3. **Residential development predating the Coastal Act:** A court may find regulated setbacks to be a regulatory taking²⁹ if the use of a meaningful erosion rate over an appropriate time period results in a setback that denies the property owner any economically beneficial use of her property. Such would be the case if there were not enough space left on the property to reconstruct development behind the setback line. In practice, however, the local government could exercise its authority to grant a variance from the setback regulation in extreme situations, thus avoiding a takings claim.

Even if there still is room to reconstruct the development behind the setback line, a court applying the partial diminution in value balancing test may be unlikely to rule against an owner who developed the property under a different understanding of land use restrictions.

²⁸ *See id.*

²⁹ *See id.*

6. RESULTS

6.1 COST /BENEFITS RESULTS

The value of the properties located within the coastal erosion hazard zones is shown in Table 62. This shows that there are substantial properties at risk (>\$400 million) within the coastal hazard zones for the entire region (identified as the planning horizon multiplied by the historic erosion rates).

Table 62 Existing Fair Market Value of Properties within Hazard Zones

Planning Region	Assessor Value	Estimated Market Value
Del Monte	\$20	\$45
0-5	\$	\$1
6-25	\$2	\$3
26-50	\$6	\$13
51-100	\$11	\$28
Marina	\$121	\$236
0-5	\$38	\$38
6-25	\$6	\$6
26-50	\$36	\$85
51-100	\$40	\$107
Sand City	\$84	\$125
0-5	\$33	\$32
6-25	\$15	\$24
26-50	\$15	\$30
51-100	\$21	\$39
Grand Total	\$225	\$406

\$ Damages Rounded in Millions

Table 62 shows existing value if the damages to the property occurred today. However, the modeling considered when in the future the damages would occur. The damages were discounted to present value using a 5% discount rate and are shown in Table 63. This demonstrates the importance of the timing of the damages when compared to implementing the erosion mitigation measures. There were not any adjustments to account for changes in perceived market value (e.g. due to threat of erosion or high protection costs) at future dates.

Table 63 Net Present Value of Properties within Hazard Zones Discounted at 5%

Planning Region	Assessor Value	Estimated Market Value
Del Monte	\$5	\$10
0-5	\$	\$1
6-25	\$2	\$3
26-50	\$2	\$4
51-100	\$1	\$2
Marina	\$58	\$78
0-5	\$38	\$38
6-25	\$5	\$5
26-50	\$11	\$25
51-100	\$3	\$9
Sand City	\$52	\$65
0-5	\$33	\$32
6-25	\$13	\$21
26-50	\$4	\$9
51-100	\$2	\$3
Grand Total	\$115	\$153

\$ Damages Rounded in Millions

In order to summarize the benefit/cost analysis, the tables below (Tables 64 - 66) present a comparative examination between each of the erosion mitigation measures. To simplify, we only look at the complete planning horizon of 0-100 years. However, since we have discounted future costs and benefits it is appropriate to sum all of these planning horizons. Indeed, this is how a typical benefit/costs analysis would be performed (e.g. for the USACE).

To aid in the analysis, we also present the summarized benefit/cost analysis where the baseline scenario is construction of a revetment. All benefits and costs were discounted by 5% during the relevant time period over the 100-year time horizon. We assumed that all benefits and costs are in real 2010 dollars and the figures should be interpreted accordingly. As discussed in section 3.5, all benefits and costs presented in Section 4 were measured relative to the baseline of shore armoring with a revetment. For example, if adding 50 feet of beach width increases recreational value, the incremental (or marginal) increase in recreational value from this increased beach width was measured (not the total value of the recreation). Similarly, losses in land, infrastructure or residences were measured compared to the losses that would incur in the baseline scenario construction of a revetment. In some cases the biggest benefit of the measure is the savings associated with not building the revetment.

6.1.1 Del Monte Reach

Table 64 below summarizes all of the data presented previously in this paper over the 100 years.

Table 64 Summary of Benefits and Costs for all Alternatives: Del Monte

	Baseline:Rock Revetment	Nourishment	Nourishment with Groins	Nourishment with Reefs	Nourishment with Breakwaters	Seawall	Cease Sand Mining	Setbacks	Conservation Easement	Fee Simple	Rolling Easements
Total Recreational Value Above Baseline	\$0	\$24,752,098	\$24,185,838	\$30,116,431	\$25,839,546	\$ 8,695,117	\$ 17,335,903	\$ 14,293,851	\$ 18,613,794	\$ 18,613,794	\$ 18,613,794
Total Habitat Value Above Baseline	\$0	\$10,950,350	\$11,873,657	\$12,610,940	\$13,447,984	\$ 578,022	\$ 6,625,102	\$ 3,602,699	\$ 5,734,853	\$ 5,734,853	\$ 5,734,853
Total Government Property Value (PV) above Baseline	\$ 534,259	-\$31,317	\$0	\$0	\$0	\$0	\$ (211,916)	\$ (534,259)	\$ (534,259)	\$ (534,259)	\$ (534,259)
Total Private Property Value (PV) above Baseline	\$ 191,636	\$0	\$0	\$0	\$0	\$0	\$ -	\$ (191,636)	\$ (191,636)	\$ (191,636)	\$ (191,636)
Total Property Value (PV) above Baseline	\$ 725,894	\$694,577	\$725,894	\$725,894	\$725,894	\$ 725,894	\$ 513,979	\$ 77,398			
MRWPCA above baseline	\$ 10,277,227	\$0	\$0	\$0	\$0	\$0	-\$3,186,638	-\$10,277,227	-\$10,277,227	-\$10,277,227	-\$10,277,227
Structural Adjustment Benefits above Baseline	\$ -	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0
Sum Benefits	\$0	\$35,702,448	\$36,059,495	\$42,727,371	\$39,287,530	\$9,273,139	\$23,961,005	\$17,896,550	\$24,348,648	\$24,348,648	\$24,348,648
Structural Adjustment Costs	\$ -	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0
MRWPCA	\$ -	\$0	\$0	\$0	\$0	\$0	\$3,186,638	\$10,277,227	\$10,277,227	\$10,277,227	\$10,277,227
Cost of Private Property Compensation	\$ -	\$864,000	\$0	\$0	\$0	\$0	\$ 2,339,000	\$ 5,015,845	\$ 4,627,000	\$ 9,254,000	
Cost of Pubic Property Compensation	\$ -	\$26,108	\$0	\$0	\$0	\$0	\$164,502	\$ 191,636	\$ 211,425	\$ 422,850	
Construction/Nourishme nt Cost	\$ 60,836,746	\$16,899,096	\$87,875,299	\$129,402,608	\$131,812,949	\$111,534,034	\$0	\$ 4,879,666	\$ -	\$ -	\$ -
Revetment Cost	\$ 60,836,746	\$60,836,746	\$60,836,746	\$60,836,746	\$60,836,746	\$60,836,746	\$60,836,746	\$60,836,746	\$60,836,746	\$60,836,746	\$60,836,746
Cost over Baseline	\$ -	\$ (43,047,541)	\$ 27,038,554	\$ 68,565,863	\$ 70,976,203	\$ 50,697,288	\$ (55,146,605)	\$ (40,472,372)	\$ (45,721,094)	\$ (40,882,669)	\$ (50,559,519)
Net Benefits over Baseline	\$0	\$ 78,749,989	\$ 9,020,942	\$ (25,838,492)	\$ (31,688,674)	\$ (41,424,149)	\$ 79,107,610	\$ 58,368,923	\$ 70,069,742	\$ 65,231,317	\$ 74,908,166
Benefit/Cost Ratio		NA	1.3	0.6	0.6	0.2	NA	NA	NA	NA	NA

Cessation of sand mining and beach nourishment measures provide the highest long term net benefits. The two measures reduce the risk of erosion impacts to infrastructure but do not completely prevent damages. In addition, several of the land use planning measures including Rolling Easements, Conservation Easements, and Fee Simple Acquisition provide similar levels of net benefits. However, it is important to note that these measures do not prevent damages to property and infrastructure but rather purchase or regulate the ability of the coast to erode and simply provides more benefits than the cost. It is our interpretation that the costs of all these measures may be under estimated as described in Section 4. Also, the benefits of beach nourishment to beach ecology are probably overstated relative to a natural beach without construction impacts. Hence, we expect the actual net benefits and benefit cost ratio of the nourishment measure to be less than presented herein. All of the land use planning measures (e.g. managed shore retreat and realignment) yielded over \$70 million in benefits which is slightly lower than nourishment or ceasing sand mining, but still substantially higher than armoring the coast or setbacks which is the current policy practice. As described above, it is likely that a better accounting of construction costs and ecological benefits would increase the viability of the land use planning measures above beach nourishment. Moreover, had the habitat analysis properly accounted for loss in habitat value, the nourishment option would likely have a lower value, though ceasing sand mining would then be the superior alternative. Also noteworthy is that the groin with nourishment option remains a net positive long-term benefit in the Del Monte Reach, although the high construction costs and difficult regulatory viability make this measure questionable.

Table 65 shows the ranking (1 = best to 11= worst) of each of the erosion mitigation measures for the various time horizons for Del Monte.

Table 65 Ranking of Erosion Mitigation Strategies For Each Time Horizon: Del Monte

Ranking	Immediate	Short	Medium	Long
1	Rolling Easements	Rolling Easements	Sand Mining	Sand Mining
2	Setbacks	Cons. Easements	Nourishment	Nourishment
3	Cons. Easements	Sand Mining	Rolling Easements	Rolling Easements
4	Fee Simple	Fee Simple	Cons. Easements	Cons. Easements
5	Sand Mining	Setbacks	Fee Simple	Fee Simple
6	Nourishment	Nourishment	Setbacks	Setbacks
7	Revetment	Groins	Groins	Groins
8	Groins	Revetment	Revetment	Revetment
9	Seawalls	Reefs	Seawalls	Reefs
10	Breakwaters	Breakwaters	Breakwaters	Breakwaters
11	Reefs	Seawalls	Seawalls	Seawalls

From the table above it appears that ceasing sand mining has the highest net benefits of all of the other measures. While nourishment comes ranked #2 in the long term it seems unwise to consider a costly large scale nourishment while sand mining continues in SMB. The high ranking of the land use planning tools especially in the shorter time frames provides support that they should be implemented immediately to provide the longest and highest net benefits. This supports taking short-term action to enact appropriate

policies and regulations. It is also apparent that structural alternatives make little sense in the long term although groins do have positive net benefits and appear to make the most sense of the structural alternatives in the long term. The low ranking of seawalls and revetments result from the lack of benefits and relatively high cost associated with these measures. Seawalls as modeled show higher benefits as a result of less placement loss initially.

6.1.2 Sand City Reach

Table 66 presents the same analysis for the Sand City reach. The results are similar to those for Del Monte with the land use planning within 10% of the nourishment and cease sand mining alternative. With the higher erosion rates, however the groins cease to be net positive in the long term but still remain as the highest net benefits of any of the structural measures.

Table 66 Summary of Benefits and Costs for all Alternatives: Sand City

	Baseline:Rock Revetment	Nourishment	Nourishment with Groins	Nourishment with Reefs	Nourishment with Breakwaters	Seawall	Cease Sand Mining	Setbacks	Conservation Easement	Fee Simple	Rolling Easement
Total Recreational Value Above Baseline	\$ -	\$29,638,702	\$33,440,691	\$35,261,963	\$37,421,939	\$ 7,486,130.27	\$ 18,754,661	\$ 10,441,369.80	\$ 24,592,108.45	\$ 24,592,108.45	\$ 24,592,108.45
Total Habitat Value Above Baseline	\$ -	\$32,349,846	\$42,326,191	\$44,988,441	\$48,228,602	\$ 6,688,794.32	\$ 15,916,615	\$ 10,297,740.90	\$ 11,203,976.59	\$ 11,203,976.59	\$ 11,203,976.59
Sum Benefits	\$ -	\$ 61,988,547	\$ 75,766,881	\$ 80,250,404	\$ 85,650,541	\$ 14,174,925	\$ 34,671,276	\$ 20,739,111	\$ 35,796,085	\$ 35,796,085	\$ 35,796,085
Structural Adjustment Costs	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 23,642,591	\$ 23,642,591	\$ 23,642,591	\$ 23,642,591	\$ 23,642,591
MRWPCA	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 11,309,061	\$ 25,970,041	\$ 25,970,041	\$ 25,970,041	\$ 25,970,041
Cost of Private Property Compensation		\$ 376,589	\$ 2,203	\$ -	\$ -	\$ 112,670	\$ 665,723	\$ 2,424,907	\$ 1,747,023	\$ 3,494,046	
Cost of Pubic Property Compensation		\$ 352,209	\$ 1,942	\$ -	\$ -	\$ 109,517	\$ 543,436	\$ 1,436,205	\$ 718,103	\$ 1,436,205	
Construction/Nourishment Cost	\$ (253,486,440)	\$ 70,412,900	\$ 366,147,080	\$ 549,220,620	\$ 549,220,620	\$ 464,725,140	\$ -	\$ 20,331,941	\$ -	\$ -	\$ -
Revetment Cost	\$ (253,486,440)	\$ (253,486,440)	\$ (253,486,440)	\$ (253,486,440)	\$ (253,486,440)	\$ (253,486,440)	\$ (253,486,440)	\$ (253,486,440)	\$ (253,486,440)	\$ (253,486,440)	\$ (253,486,440)
Cost over Baseline	0	\$ (182,344,742)	\$ 112,664,785	\$ 295,734,180	\$ 295,734,180	\$ 211,460,887	\$ (217,325,630)	\$ (179,680,755)	\$ (201,408,682)	\$ (198,943,557)	\$ (203,873,808)
Net Benefits	\$0	\$ 244,333,290	\$ (36,897,903)	\$ (215,483,776)	\$ (210,083,639)	\$ (197,285,962)	\$ 251,996,905	\$ 200,419,865	\$ 237,204,767	\$ 234,739,642	\$ 239,669,893
Benefit/Cost Ratio		NA	0.67	0.27	0.29	NA	NA	NA	NA	NA	NA

Table 67 shows the ranking (1 = best to 11= worst) of each of the erosion mitigation measures for the various time horizons for Sand City.

Table 67 Ranking of Erosion Mitigation Strategies For Each Time Horizon: Sand City

Ranking	Immediate	Short	Medium	Long
1	Rolling Easements	Rolling Easements	Sand Mining	Sand Mining
2	Sand Mining	Sand Mining	Rolling Easements	Nourishment
3	Cons. Easements	Fee Simple	Cons. Easements	Rolling Easements
4	Fee Simple	Cons. Easements	Fee Simple	Cons. Easements
5	Setbacks	Nourishment	Setbacks	Fee Simple
6	Nourishment	Setbacks	Nourishment	Setbacks
7	Groins	Groins	Revetment	Revetment
8	Seawalls	Revetment	Groins	Groins
9	Revetment	Seawalls	Seawalls	Seawalls
10	Breakwaters	Breakwaters	Breakwaters	Breakwaters
11	Reefs	Reefs	Reefs	Reefs

The table above for Sand City is similar to the findings for the Del Monte reach and it appears that ceasing sand mining has the highest net benefits of all of the other measures. While nourishment comes ranked #2 in the long term it seems unwise to consider large scale nourishment while sand mining continues in SMB. The high ranking of the land use planning tools especially in the shorter time frames provides support that they should be implemented immediately to provide the longest and highest net benefits. This supports taking short-term action to enact appropriate policies and regulations. It is also apparent that structural alternatives make little sense in the long-term although groins do seem to be the most beneficial over the long-term. The low ranking of the breakwaters and reefs result from the extremely high costs associated with construction dwarfing the recreational and ecological benefits.

6.1.3 Marina Reach

Table 68 summarizes the results for the Marina reach which differ from the other two reaches. In this reach, the land use planning options of Rolling Easements and Conservation Easements have the highest long-term net benefits followed by Ceasing of Sand Mining and Fee Simple Acquisition (all within ~10%) All of these options maintain the sand supply caused by Dune erosion and are critical to supporting the sediment budget in the rest of the littoral cell. We assume that these results reflect on the lack of development in this reach and relative lack of critical infrastructure costs. Even with the generous assumptions used in the Nourishment alternative it begins to become clearer that nourishment while still beneficial does not have as many long-term benefits. Of all of the hard structural alternatives groins still seems to make the most sense, but the potential to exacerbate or stabilize erosion hotspots (see Section 4.3.2) may negate this relative benefit compared to other alternatives.

Table 68 Summary of Benefits and Costs for all Alternatives: Marina

	Baseline:Rock Revetment	Nourishment	Nourishment with Groins	Nourishment with Reefs	Nourishment with Breakwaters	Seawall	Cease Sand Mining	Setbacks	Conservation Easement	Fee Simple	Rolling Easements
Total Recreational Value Above Baseline	\$ -	\$ 27,814,107	\$ 31,333,875	\$ 32,930,001	\$ 33,512,815	\$ 4,134,055	\$ 16,129,511	\$ 6,599,710	\$ 25,075,525	\$ 25,075,525	\$ 25,075,525
Total Habitat Value Above Baseline	\$ -	\$ 59,237,351	\$ 70,114,980	\$ 75,847,847	\$ 78,008,250	\$ 6,750,920	\$ 41,226,163	\$ 10,320,890	\$ 39,054,708	\$ 39,054,708	\$ 39,054,708
Sum Benefits	\$0	\$ 87,051,459	\$ 101,448,855	\$ 108,777,848	\$ 111,521,064	\$ 10,884,974	\$ 57,355,674	\$ 16,920,600	\$ 64,130,233	\$ 64,130,233	\$ 64,130,233
Structural Adjustment Costs	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
MRWPCA	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ 2,525,340	\$ 2,525,340	\$ 2,525,340	\$ 2,525,340
Cost of Private Property Compensation	\$ -	\$ 16,312,131	\$ 7,447,445	\$ 7,136,051	\$ 7,021,679	\$ -	\$ 9,428,979	\$ 14,429,497	\$ 18,846,962	\$ 37,693,923	
Cost of Pubic Property Compensation	\$ -	\$ 7,624,645	\$ 2,975,504	\$ 5,190,912	\$ -	\$ -	\$ 5,113,949	\$ 13,007,229	\$ 6,522,145	\$ 13,044,289	
Construction/Nourishmen t Cost	\$ 352,346,152	\$ 96,896,620	\$ 503,862,421	\$ 755,793,632	\$ 755,793,632	\$ 645,967,945	\$ -	\$ 102,146,152	\$ -	\$ -	\$ -
Total Cost (PV)	\$ 352,346,152	\$ 120,833,396	\$ 514,285,371	\$ 768,120,596	\$ 762,815,312	\$ 645,967,945	\$ 14,542,928	\$ 132,108,218	\$ 27,894,446	\$ 53,263,553	\$ 2,525,340
Revetment Cost	\$ 352,346,152	\$ 352,346,152	\$ 352,346,152	\$ 352,346,152	\$ 352,346,152	\$ 352,346,152	\$ 352,346,152	\$ 352,346,152	\$ 352,346,152	\$ 352,346,152	\$ 352,346,152
Cost over Baseline	\$ -	\$ (231,512,756)	\$ 161,939,219	\$ 415,774,444	\$ 410,469,160	\$ 293,621,793	\$ (337,803,224)	\$ (220,237,934)	\$ (324,451,706)	\$ (299,082,599)	\$ (349,820,812)
Net Benefits	\$0	\$ 318,564,214	\$ (60,490,364)	\$ (306,996,595)	\$ (298,948,096)	\$ (282,736,819)	\$ 395,158,898	\$ 237,158,534	\$ 388,581,939	\$ 363,212,833	\$ 413,951,045
Benefit/Cost Ratio	NA	NA	0.63	0.26	0.27	0.04	NA	NA	NA	NA	NA

Table 69 shows the ranking (1 = best to 11= worst) of each of the erosion mitigation measures for the various time horizons for Sand City.

Table 69 Ranking of Erosion Mitigation Strategies for Each Time Horizon: Marina

Ranking	Immediate	Short	Medium	Long
1	Rolling Easements	Rolling Easements	Rolling Easements	Rolling Easements
2	Cons. Easements	Sand Mining	Sand Mining	Sand Mining
3	Sand Mining	Cons. Easements	Cons. Easements	Cons. Easements
4	Setbacks	Fee Simple	Fee Simple	Fee Simple
5	Fee Simple	Setbacks	Nourishment	Nourishment
6	Nourishment	Nourishment	Setbacks	Setbacks
7	Groins	Groins	Revetment	Revetment
8	Seawalls	Seawalls	Groins	Groins
9	Revetment	Revetment	Seawalls	Seawalls
10	Breakwaters	Breakwaters	Breakwaters	Breakwaters
11	Reefs	Reefs	Reefs	Reefs

The table above for Marina shows the high ranking of the land use planning tools throughout the 100 year long-term time frame. This analysis provides support that they should be implemented immediately to provide the longest and highest net benefits. This supports taking short-term action to enact appropriate policies and regulations. It is also interesting to note that nourishment, the #2 ranking alternative in Del Monte and Sand City drops below Fee Simple Acquisition by nearly \$45M over the long time period. This is associated with the low levels of development and extremely high erosion rates in this reach of the study area.

6.1.4 Economic Impacts

Policy makers typically like to know the economic and fiscal (revenue) impacts of these programs in addition to looking at the benefits and costs associated with them. The analysis below only includes options which enhance beach width, leading to increased recreation (in particular attendance) and thus more economic impact and taxes. As part of the analysis, we looked at spending related to beach and other forms of coastal recreation that would be (negatively) impacted by coastal erosion. A more detailed analysis of the methodology we used is contained in Section 3.5. Briefly, we estimated spending per visitor and lower attendance implies lower spending. Similarly, we estimated taxes generated by coastal recreation spending applying figures from the California Statistical Abstract. Our analysis does not include losses in property tax revenues due to property erosion losses or storm damage losses. In the case of the Marina stretch, our analysis indicates that these losses would be substantial (in the millions of dollars); in the other two reaches they would be very small (in the thousands of dollars). Local spending impacts are lower because not all spending related to recreation occurs locally (e.g., someone buys gas at home and drives to the region).

As one can see in the tables below (Tables 70 – 72) present the economic impacts of these policies (above the baseline) are quite substantial generating tens of millions in spending and millions in State taxes. Tax revenues at the local level would rise also, but less substantially, on the order of several hundred thousand dollars per reach.

Table 70 Economic Impacts of Management Options: Del Monte

	Baseline:Rock Revetment	Nourishment	Nourishment with Groins	Nourishment with Reefs	Nourishment with Breakwaters	Seawall	Cease Sand Mining	Setbacks	Conservation Easement	Fee Simple	Rolling Easements
Direct Local Spending Above Baseline	\$ 85,040,537	\$106,723,526	\$116,293,991	\$113,518,524	\$121,187,939	\$ 56,865,659	\$ 79,306,581	\$ 67,894,917	\$ 67,894,917	\$ 67,894,917	\$ 67,894,917
Direct State Spending Above Baseline	\$ 106,300,671	\$133,404,408	\$145,367,488	\$141,898,156	\$151,484,924	\$ 71,082,074	\$ 99,133,227	\$ 84,868,646	\$ 84,868,646	\$ 84,868,646	\$ 84,868,646
	\$ -										
Direct Local Taxes Above Baseline	\$ 2,126,013	\$2,668,088	\$2,907,350	\$2,837,963	\$3,029,698	\$ 1,421,641	\$ 1,982,665	\$ 1,697,373	\$ 1,697,373	\$ 1,697,373	\$ 1,697,373
Direct State Taxes Above Baseline	\$ 9,236,299	\$5,594,886	\$6,182,569	\$5,875,115	\$6,309,209	\$ 2,383,329	\$ 3,456,048	\$ 3,101,952	\$ 3,101,952	\$ 3,101,952	\$ 3,101,952

Table 71 Economic Impacts of Management Options: Sand City

	Baseline:Rock Revetment	Nourishment	Nourishment with Groins	Nourishment with Reefs	Nourishment with Breakwaters	Seawall	Cease Sand Mining	Setbacks	Conservation Easement	Fee Simple	Rolling Easement
Direct Local Spending Above Baseline	\$ 77,644,208	\$ 110,366,004	\$ 122,201,650	\$ 127,895,078	\$ 134,440,139	\$ 34,627,675	\$ 79,601,951	\$ 45,580,194	\$ 45,580,194	\$ 45,580,194	\$ 45,580,194
Direct State Spending Above Baseline	\$ 97,055,260	\$ 137,957,505	\$ 152,752,063	\$ 159,868,848	\$ 168,050,174	\$ 43,284,594	\$ 99,502,439	\$ 56,975,242	\$ 56,975,242	\$ 56,975,242	\$ 56,975,242
Direct Local Taxes Above Baseline	\$ 1,389,920	\$ 1,171,621	\$ 1,287,267	\$ 1,344,145	\$ 1,410,749	\$ 416,936	\$ 758,121	\$ 568,330	\$ 568,330	\$ 568,330	\$ 568,330
Direct State Taxes Above Baseline	\$ 7,992,041	\$ 6,736,821	\$ 7,401,785	\$ 7,728,831	\$ 8,111,806	\$ 2,397,380	\$ 4,359,196	\$ 3,267,897	\$ 3,267,897	\$ 3,267,897	\$ 3,267,897

Table 72 Economic Impacts of Management Options: Marina

	Baseline:Rock Revetment	Nourishment	Nourishment with Groins	Nourishment with Reefs	Nourishment with Breakwaters	Seawall	Cease Sand Mining	Setbacks	Conservation Easement	Fee Simple	Rolling Easements
Change to Direct Local Spending (PV)		\$95,980,918	\$276,505,716	\$112,201,976	\$283,210,098	\$ 17,774,773	\$ 61,463,990	\$ 20,246,776	\$ 20,246,776	\$ 20,246,776	\$ 20,246,776
Change to Direct State Spending (PV)		\$119,976,148	\$345,632,145	\$140,252,470	\$354,012,622	\$ 22,218,466	\$ 76,829,988	\$ 25,308,470	\$ 25,308,470	\$ 25,308,470	\$ 25,308,470
		\$0	\$0	\$0	\$0	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Change to Direct Local Taxes (PV)		\$397,144	\$4,737,367	\$552,439	\$4,798,237	\$ 444,369	\$ 1,536,600	\$ 506,169	\$ 506,169	\$ 506,169	\$ 506,169
Change to Direct State Taxes (PV)		\$6,335,331	\$23,188,111	\$7,228,274	\$23,538,113	\$ 1,664,029	\$ 3,682,951	\$ 2,244,713	\$ 2,244,713	\$ 2,244,713	\$ 2,244,713

6.1.5 Sensitivity Analysis and Robustness

In addition to the analysis above, we checked to see how sensitive our results are to the various cost and benefit assumptions used. In particular, we ran a high cost and low cost scenario for nourishment and armoring measures. Under the low cost scenario, the B/C ratio for nourishment is somewhat higher, indicating that it is even more desirable as an alternative. The B/C ratios for the hard engineering mitigation measures are also somewhat higher but still well below one. In sum, the high cost and low cost scenarios yield slightly different estimates but the policy conclusions are exactly the same, which lends credence to our conclusions.

The habitat valuation estimate used is also subject to some uncertainty. To check for robustness, we also examined how varying the estimate of habitat valuation effected our conclusions. Higher habitat valuations tended to strengthen our results further. Lower habitat valuations weakened the conclusion but even at values much lower (half) than the assumption we used, most of our conclusions still stand. However, it should be noted that our habitat analysis is quite crude and does not take into the account the impacts that the options might play in altering the quality of the habitat. In particular, armoring the coast may lower habitat values by even more than we have estimated. On the other hand, nourishment programs have construction impacts and can also devalue ecosystems. Any analysis of beach nourishment needs to carefully consider in more detail the true ecological impacts over time.

7. CONCLUSIONS

7.1 GENERAL FINDINGS

- Ceasing Sand Mining is the most important erosion mitigation strategy in Southern Monterey Bay
- Beach recreation and habitat values have higher long term values than private property
- The benefits of sand placement (both nourishment and opportunistic sand placement) to the beach ecology are believed to be overstated in this analysis, due to a notable lack of data on the impact and duration of nourishment activities on the sandy beach ecosystem.
- Different planning horizons support use of different tools
- Public trust is an important legal component to land use planning measures however the land use planning measure most likely to trigger a takings claim is a setback regulation.
- Land use tools require a significant amount of time and effort to implement
- Most all tools require substantial funding, start saving now
- This new economic analysis approach which includes traditional storm damages as well as ecosystem services and recreational benefits supports evaluation of future scenarios
- Need to develop a standardized beach monitoring program for the region
- Results of these analyses would likely differ if climate change and sea level rise were factored into this report
- Need to continue to monitor current research on innovative erosion mitigation measures
- Pending identification of preferred measures, more detailed regulatory analysis will be required to implement each measure or the overall Subregional strategies.

7.2 LAND USE PLANNING MEASURES

- Analysis completed in this study shows that Rolling Easements are likely to be the least costly land use planning option.
- Land Use planning tools have the highest net benefits over the long term when compared to all other erosion mitigation measures.
- Managed retreat is more cost effective with higher net benefits over the long term than most of the traditional erosion mitigation strategies. Rolling easement, conservation easement and fee simple are all superior to armoring over these entire reaches.
- Inclusion of ecological and recreational benefits along with traditional property damages due to erosion shows status quo coastal management approaches of revetments or setbacks is not cost effective over the long term
- Setback policies differ across the region, with varying methods of calculating the distance
- Setbacks policies (as interpreted) do not maintain beaches after 25-50 years

7.3 SOFT ENGINEERING MEASURES

- Ceasing Sand Mining is the most important erosion mitigation strategy in SMB because it has the highest benefits and addresses the root cause of the high erosion rates in the region.

- The overall recreational and ecosystem service benefits to the communities in the region by the ceasing of sand mining from the beach is estimated to have a present value equal to \$116 million in 2010 dollars.
- The overall benefits from ceasing sand mining including avoided construction costs are \$718 million in 2010 dollars.
- Nourishment could be effective as a medium term solution but erosion of upland would occur within 25 year timeframe between nourishment cycles under existing erosion rates. The Sand City and Marina reaches are likely not suitable for nourishment given the high erosion rates.
- Nourishment likely need to be implemented more frequently than 25 years
- Opportunistic sand placement (SCOUP) has high benefit cost ratios (>5) but does not resolve long term erosion nor protect property because the rate and amounts of sand placed are low. Moreover the rate of sand placement considered exceeds identified resources.
- SCOUP appears moderately successful under lower erosion rates (~1.5ft/yr)
- Passive dewatering uncertain but low cost may make it a worthwhile experiment with monitoring

7.4 HARD ENGINEERING MEASURES

- Shoreline Armoring (Revetments and Seawalls) result in loss of beaches within ~5-50 year planning horizon
- Groins appear to be the most effective of the retention structures over the long term when net benefits are considered
- Retention structures (groins, reefs and breakwaters) increase the effectiveness of beach nourishment but are not cost effective (high costs to maintain with eroding region), except possibly in Del Monte location. We anticipate that a more detailed consideration of reefs and nourishment would increase the benefits but that the costs would still be greater than the land use and nourishment measures.
- Most retention structures options still show signs of upland erosion under high erosion rates at year 100

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APPENDICES

APPENDIX 1

COMPLETE LIST OF ALL EROSION MITIGATION MEASURES

- | | | |
|---------------------------------------|--|--|
| 1. Fee Simple Acquisition: | 18. Native Plants | 36. Branch Box Breakwaters |
| 2. Conservation Easements: | 19. Geotextile Core | 37. Floating Breakwaters |
| 3. Present Use Tax: | 20. Nearshore Placement | 38. Coir Logs |
| 4. Transfer of Development Credit | 21. Dredge Sand from Deep or Offshore Deposits | 39. Submerged Breakwaters |
| 5. Rolling Easements | 22. Added Courser Sand than Native | 40. Kelp Forest Restoration |
| 6. Removal/Relocation Managed Retreat | 23. Opportunistic Sand | 41. Beach Dewatering |
| 7. Structural or Habitat Adaption | 24. SCoup Efforts | 42. Pressure Equalizing Modules |
| 8. Bluff top Development (setback) | 25. Canyon Interception | 43. Seawalls |
| 9. Beach Level Development (setback) | 26. Rip-Current Interruption | 44. Revetments |
| 10. Controlling Surface Run-off | 27. Inter-littoral Cell Transfers | 45. Cave Fills |
| 11. Controlling Groundwater | 28. Berms/Beach Scraping | 46. Gabions |
| 12. Reservoir and Debris Basin | 29. Perched Beaches | 47. Mixed Structures |
| 13. Sand Mining | 30. Groins | 48. Cobble Nourishment |
| 14. Harbor By-Passing | 31. Breakwaters | 49. Dynamic Revetments |
| 15. Back-Passing | 32. Dune Nourishment | 50. Geotextile Revetment |
| 16. Subaerial Placement | 33. Delta Enhancement | 51. Floating Reefs |
| 17. Artificial Seaweed | 34. Headland Enhancement | 52. Rubber Dams |
| | 35. Geotextile Groins | 53. Visually Treated Walls or Revetments |
| | | 54. Cessation of Sand Mining |
| | | 55. Sand Fencing/Dune Guard Fencing |

APPENDIX 2

1. MONITORING PLAN

The purpose of this monitoring section is to provide recommendations on several types of monitoring that could be used to inform the overall evaluation of the success of each of these erosion mitigation measures. These include a variety of standard and more innovative techniques to understand how these alternatives are working scientifically, examine environmental impacts and measure how effective they are at mitigating erosion and maintaining beach width.

The monitoring techniques discussed include:

- Survey Methods
- Lidar
- Bluff Edge Monitoring
- Sand Tracers
- Time Lapse Video
- Photographic Documentation
- Groundwater Monitoring
- Biological Monitoring

All of these monitoring techniques would benefit from the establishment of a common system of geodetic control. For example, the state of Florida -Department of Environmental Protection, has established a system of benchmarked monuments from which all beach profiles and survey work is collected forming a basis for long-term standardized data collection.

1.1. Survey Methods

Beach, dune, bluff, and offshore surveying are recommended as a monitoring method for nearly all of the measures. Nearshore Placement, Beach and Dune Nourishment, Dredging Sand From Deep or Offshore Deposits, PEM's and Beach Dewatering, Inter-Littoral cell Transfers, Native Plant Re-Vegetation, Sand Fencing/Dune Guard Fencing, Berms/Beach Scraping, and Sand Mining Cessation all should be monitored in some way to ensure effectiveness and identify impacts, and all could benefit from some form of annual/biannual surveying technique.

1.1.1. Topographic Survey – Beach Profiling

PWA recommends that beach profiling be done twice a year for five years in order to monitor long-term beach change within the potentially impacted zones. Topographic changes will be evaluated primarily through the reoccupation of cross-sections established in the year zero survey of baseline conditions. Beach profiling is a cost effective way to monitor changes accurately, while ensuring that critical morphological changes are not missed. Another advantage of a total station survey is the ability to extend the survey into the tidal zone without worry of LIDAR rays bouncing off of the water surface. A limitation of this, however, is that the survey crew can only proceed into waters that are safely navigable by small boat and not deep enough to affect accuracy limits.

This method would be applicable on different levels for virtually all of the implemented measures, and is recommended to be used in conjunction with other survey methods in order to ground truth the varying sources of data.

1.1.2. Flown LIDAR

An alternative to beach profiling would be a biannual LIDAR flight along the affected zone. While LIDAR flights are fast and relatively cheap, they do not provide ideal accuracy limits, and key components of the survey can theoretically be obstructed by vegetation and structures. LIDAR flights are also limited to land-only measurements, as the beams bounce off of water. For this reason a flown LIDAR survey would be great for dune and bluff edge surveys, but would need to be accompanied by a hydrographic survey if employed along reaches where beach nourishment methods were being monitored.

This method of surveying would be useful for monitoring the effectiveness of Inter-Littoral Cell Transfers within the Southern Monterey Bay sandshed. An annual survey flown across the littoral cell from the submarine canyon to the Monterey rocks would give a big-picture idea of the longshore transport rates and educate for future transfers.

1.1.3. Terrestrial LIDAR

The most thorough of the land survey techniques, terrestrial LIDAR is very effective in beach environments due to minimal obstructions. The main hindrance to terrestrial LIDAR is its inability to survey through or around obstructions. These can be trees, buildings, bushes, or other tall immovable objects. Terrestrial LIDAR is accurate and fast, but expensive.

1.1.4. Hydrographic Survey

Bathymetric survey data would be essential for a majority of the measures, and it is recommended that a full scan of the coastline be done annually to ensure the progress of Beach Nourishment, Beach Level Setback, Placement of Dredged Material, Nearshore Placement, and Inter-Littoral Cell Transfer.

1.1.5. Vessel Mounted LIDAR

The CSUMB Seafloor Mapping Laboratory's (SFML) vessel-based topographic LIDAR system consists of a Riegl LMS-Z420i terrestrial laser scanner coupled with an Applanix Position and Orientation system for Marine Vessels (POS/MV), in a package that can be mounted on all SFML survey launches (12-34 ft) and vehicles. The LMS-Z420i has a range of 1km, a vertical accuracy of 10mm, a vertical scan swath angle of 80°, and measurement rates of up to 11,000 points/second. The POS/MV data from its inertial motion unit (IMU) and dual GPS receivers are post-processed in Applanix POSPAC software using Virtual Reference Station technology to generate a Smoothed Best Estimated Trajectory (SBET) that is a tightly coupled inertial/GPS solution for the geometric center of the Riegl sensor. This SBET consists of positioning ($\pm 2\text{cm}$) and attitude measurements (pitch, roll, and yaw, $\pm 0.02^\circ$) at 200hz, all tied directly to the ellipsoid. Riegl software is used to merge the SBET and laser data to generate a topographic point cloud in real-world coordinates and free of motion artifacts.

The LMS-Z420i is mounted atop the survey vessel in a fixed orientation (i.e. not rotating scan mode), and set to the system's highest scan rate. This allows continuous scanning of coastal features while the vessel travels parallel to shore or around offshore rocks and pinnacles. Vessel speed and range to the coastline are the two determining factors of final data resolution. Typically, at a range of 500-700m and an average vessel survey speed of 4 knots, the SFML's point cloud data have spatial densities higher than 1 point every 50 square centimeters. Due to the low, horizontal view point of this technique, vessel-based LIDAR, unlike aerial LIDAR, can miss flat terrain above the level of the sensor, and topographic lows behind berms and dunes. This limitation precludes the ability to measure second order dunes, but is an ideal tool for direct measurement of complex vertical and overhanging sea cliff faces where data density can be sparse or missing due to the downward looking viewpoint of aerial LIDAR. The flexible, rapidly mobilized vessel-based LiDAR system produces high-resolution terrain data, in a relatively cost effective manner compared to traditional airborne LiDAR surveys; for which high cost is one of the biggest limiting factors for repeat aerial LiDAR surveys. As a result, we have found vessel-mounted LiDAR to be an efficient and effective method for the detection and quantification of annual sea cliff geomorphic change, highly useful for coastal planning and monitoring.

1.2. Bluff Edge Monitoring

PWA recommends monitoring of the bluff edge to evaluate long-term changes and implications for the future. It is recommended that the bluff edge be delineated by field methods instead of interpretation of scanned data in order to minimize the possibility of misinterpretation. This can be effectively done using a handheld GPS unit on tracking mode. If this method is not preferred, digitizing an ortho-rectified aerial photo in GIS would be an acceptable alternative. PWA can perform both techniques effectively.

1.3. Sand Tracer

Sand tracer is essentially colored sand that is placed along with larger placements for purposes of tracing the direction and rate of sediment transport. While some consider it an ugly addition to a beach, it is the most effective method of telling whether or not the sand you place is going where you want it to go. Sand tracer would be a very cheap and effective monitoring method for use with Nearshore Placement and Inter-Littoral Cell Transfers.

1.4. Time-Lapse Video

Short term monitoring of beach change can be monitored by means of video imagery collected by shore-located cameras. The Naval Postgraduate School has been conducting this type of analysis in the past so continuation of this data collection has the ability to provide a historic data set. The main benefit of this option is the ability to track changes caused by large-scale storm events on a real-time scale. Time-lapse video would supplement beach profiling in a few beneficial ways. As opposed to biennial or yearly surveys, year-round video capture allows for more accurate diagnosis of the erosional or depositional events associated with beach change. Video capture of wave breaking patterns can help to further understand beach dynamics of localized regions, allowing for quicker and better response to failing alternatives.

Time-Lapse video would be an effective supplemental way to monitor the effectiveness and/or failure of submerged breakwaters, perched beaches, groins, emergent breakwaters, and seawalls.

In addition, new research and development has developed automated detection algorithms to analyze video imagery to count the number of users on the beach. This may be a way to improve the estimates of attendance and to better understand the patterns of human usage along the beaches of Southern Monterey Bay.

1.5. Photographic Documentation

A cheaper alternative to time-lapse video would be photographic documentation. Photographic documentation techniques are based on the principals of re-photography, also known as repeat photography. It is a technique of landscape study where scenes are re-photographed at specified time intervals to determine the nature of long-term and short-term change. Photos are taken at a preset angle and orientation from photographic benchmarks established during year zero post-construction monitoring. PWA has a long history of extensive re-photography associated with monitoring efforts conducted for past and current projects.

1.6. Groundwater Monitoring

It is recommended that monitoring of the groundwater level be done seasonally to understand the natural groundwater dynamics of the area. This monitoring can be done with piezometer installations around the site to evaluate where the water table sits both seasonally and spatially. PWA has experience installing and maintaining piezometers, and has the necessary instrumentation in-house available to rent.

This will be beneficial to both monitor the effectiveness of applied alternatives as well as educate future applications of PEMs, dewatering, and desalinization wells.

1.7. Biological Monitoring

1.7.1. Terrestrial

Terrestrial surveys should focus primarily on locations of sensitive and endangered species including the distribution of sensitive dune vegetation and habitats supporting endangered species such as the dune globose beetle, and legless lizard.

1.7.2. Intertidal

Intertidal monitoring should entail quadrant surveys along specified transect locations to assess the sandy beach ecosystem including invertebrates and wrack deposition. Additionally, shorebird counts of individual species during foraging activities and nesting locations should be included in this monitoring.

1.7.3. Subtidal

Subtidal field surveys should include diver surveys for biological monitoring of distribution of kelp, eelgrass, and rocky substrate.

APPENDIX 3

MRWPCA Costs

Summary of Cost Estimates for replacement of stretches of MRWPCA based on conversation with Jennifer Gonzalez 3/24/2010

Salinas study estimated roughly \$4.5M/ mile to relocate pipe infrastructure. This is through farm fields and soil, so estimate of \$5-7M per mile is more appropriate for relocating oceanfront pipes to under Del Monte Ave.

Interceptor Pipeline from South to North (Estimated subtotal - \$15M to \$21M)

- Wharf II to Monterey Pump Station (~1 mile) **\$5-10M**
- Monterey Pump Station to Tide Ave (~900' – private properties) **\$1-2M**
- Tide Ave (Ocean Harbor House) to Monterey Bay Beach Hotel (~3600') **\$5M**
- Monterey Bay Beach Hotel to Seaside Pump Station (~2900') **\$4M**
- To North, interceptor on seaward side of Highway 1 use **\$5M/mile (likely OK for awhile)**

Pump Stations (\$55M each)

- Monterey Pump Station (no estimate) not in 2004 report
- Reeside Pump Station (no estimate – outside study area)
- Seaside Pump Station cost estimate to relocate and rebuild **\$55M** (2004 dollars)
 - Note: Not on timeline at present. 2004 report suggested planning occur in 5 years, and rebuild in 10 years. However currently in Capital Improvement Plan for 10+ year time frame

Failures

- Minor – roughly 2 weeks to repair – fines are **\$3,000 /day**
- Catastrophic – Double cost estimates for emergency repairs

TOTAL ESTIMATE FOR REPLACEMENT RELOCATION - ~\$130M

California's Coastal Hazards

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ABSTRACT: The coast of California is experiencing a conflict of increasing magnitude between the natural hazards which affect the coastline and the increased desire of the 31.5 million residents, 80% of which live within 50 km of the coast, to live virtually at the water's edge. California's high population growth exacerbates the coastal hazard issue through unrelenting pressure for shoreline development and recreation. Over 1,500 km of the state's 1,760 km shoreline is actively eroding, yet development continues in areas subject to coastal hazards such as shoreline erosion and coastal flooding. Development of three different coastal geomorphic environments, coastal cliffs or bluffs, the beach itself, and coastal dunes has led to coastal storm damage over the past 15 years in excess of \$150 million. Careful investigation of the recent geologic history of oceanfront areas prior to development is relatively straightforward and is necessary to evaluate the hazards and risks present in any specific location. Seacliff stability and long term cliff erosion rates can be quantified and wave runup and inundation hazards can be evaluated.

Significant changes are needed in how to approach and deal with coastal hazards and the continuing pressure to develop in coastal areas. The marked inconsistencies among local governments and those state agencies who have responsibilities to regulate development indicate the lack of a guiding direction and the heavy influence of local economics and politics.

Through a process of hazard recognition and evaluation, and then a standardized set of avoidance, mitigation, or hazard reduction policies, the private and public losses from future shoreline erosion, storm impact, and sea level rise can be significantly reduced. The objective is to reduce the number of people, as well as dwellings, structures, and utilities, both public and private, directly exposed to the hazards of both shoreline erosion and wave impact and inundation.

INTRODUCTION

The physical environment of the west coast of the United States is strikingly different from that of either the east or the Gulf coasts. Even a casual visitor to the California shoreline will notice the obvious differences between the coastal mountains and seacliffs characteristic of California's western margin and the broad, flat coastal plains, sand dunes, and barrier islands of New Jersey or North Carolina. The east and west coasts of North America have very different geologic histories and, as a result, have very different landforms and pose substantially different problems or hazards for human use and occupation.

Coastal hazards are a function of the presence of human beings and their activities as they interact with naturally occurring coastal processes. With the exception of changes due to coastal erosion, the coastline has the same general configuration as it did in 1850 when the estimated population of California was 93,000. The state population grew steadily for the next 100 years, but following World War II, it virtually exploded; between 1950 and 1970 it nearly doubled, growing from 10.6 to 20 million (Figure 1). The 1993 population of 31.5 million represents a tripling since 1950. California now is the most populous of the United States with approximately 80% of the population living within 50 km of the shoreline. Each resident now has about 5 cm of coastline to enjoy, and the population is growing at about 1,500 people/day. At least half of the 1,760 km shoreline of California is inaccessible, however, and 85% of it is eroding. The population density and pressure on the coastline varies widely from rural Mendocino County

in the north, which has about 400 residents/km of coastline (2.4 m/person) to urban Los Angeles County in the south (Figure 2), with about 120,000 residents/mile (1 cm/person). These figures do not include the millions of visitors who flock to the California coast annually. As the population density increases, the competition for oceanfront property increases, along with the exposure to coastal geologic hazards. The population of California is projected to reach 50,000,000 by the year 2020.

Because areas with exceptionally high population are likely to have heavier use of coastal resources and higher concentrations of coastal development, it is clear that the

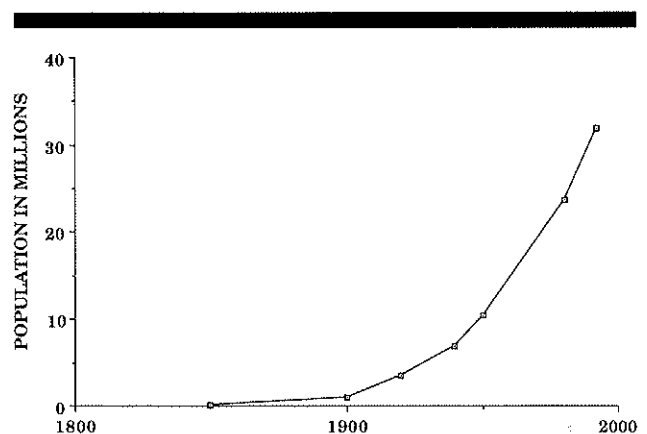


Figure 1. California's increasing population.



Figure 2. Index map for California place names.

type, magnitude, and distribution of coastal hazard risk will vary not only as a result of different physical conditions and geomorphic processes along the coastline, but also as a result of demographic variation.

This paper discusses shoreline erosion and the hazardous coastal environments of California. The nature of the physical environment and the hazards which affect this environment as well as the impacts of hazards on human



Figure 3. These Malibu area homes have been built at beach level on the alluvial fan of a coastal stream and are therefore exposed to wave runoff and inundation as well as debris flows and flooding from the stream.

occupation of the coastal zone are considered. Recommendations for evaluating the hazards and reducing their future impacts as California's coastal population continues to increase are discussed.

HAZARDOUS COASTAL ENVIRONMENTS

Coastal geologic hazards in California occur most frequently in the form of shoreline erosion (both seacliff and beach) and coastal flooding (both wave impact and inundation). Human-induced interference with coastal processes (littoral drift and sand supply) and coastal bluff stability (altering the stability of coastal bluff materials) can exacerbate hazard conditions.

There has been a growing realization in recent years that many human activities (including damming of coastal rivers and construction of jetties, breakwaters, and seawalls) are adversely affecting beach sand supply. The result is a reduction in beach stability and longevity, and therefore a loss of the protection provided to development either on the back beach or on the flanking bluffs or cliffs. Since the 1950's many southern California coastal streams have been dammed for water supply and flood control. The dams impound water but also trap sand destined for the coastal beaches and control the high-velocity, large discharge flood flows that transport the greatest volumes of sand to the beaches.

Along the urbanized seacliffs of southern California, geologic instability has been increased through the addition of large volumes of irrigation water required to maintain lawns and non-native vegetation in the yards of cliff-top homes. Landscape irrigation alone is estimated to add the equivalent of 125 to 150 cm of additional rainfall each year to garden and lawn areas which naturally might receive only 25 to 40 cm of rainfall. This excess water has led to a slow, steady rise in the water table that has progressively weakened cliff material and lubricated joint surfaces in the rocks along which slides and blocks falls are initiated. In addition, surface runoff discharged through culverts or storm drains at the top or along the face of bluffs leads to gullyng or failure of weakened surficial materials.

A 1971 regional inventory of the California shoreline classified only 14.2% of the coast as non-eroding. Of the remaining 85.8%, 128 km (7.3%) were classified as critical erosion (defined as areas where structures and/or utilities were threatened), with the remainder designated as non-critical erosion (U.S. ARMY CORPS OF ENGINEERS, 1971). A subsequent investigation by the California Department of Navigation and Ocean Development (HABEL and ARMSTRONG, 1978) defined the erosion problem somewhat differently. Approximately 160 km (10.9%) of coast were delineated as eroding with existing development threatened, and an additional 480 km (39.4%) were classified as

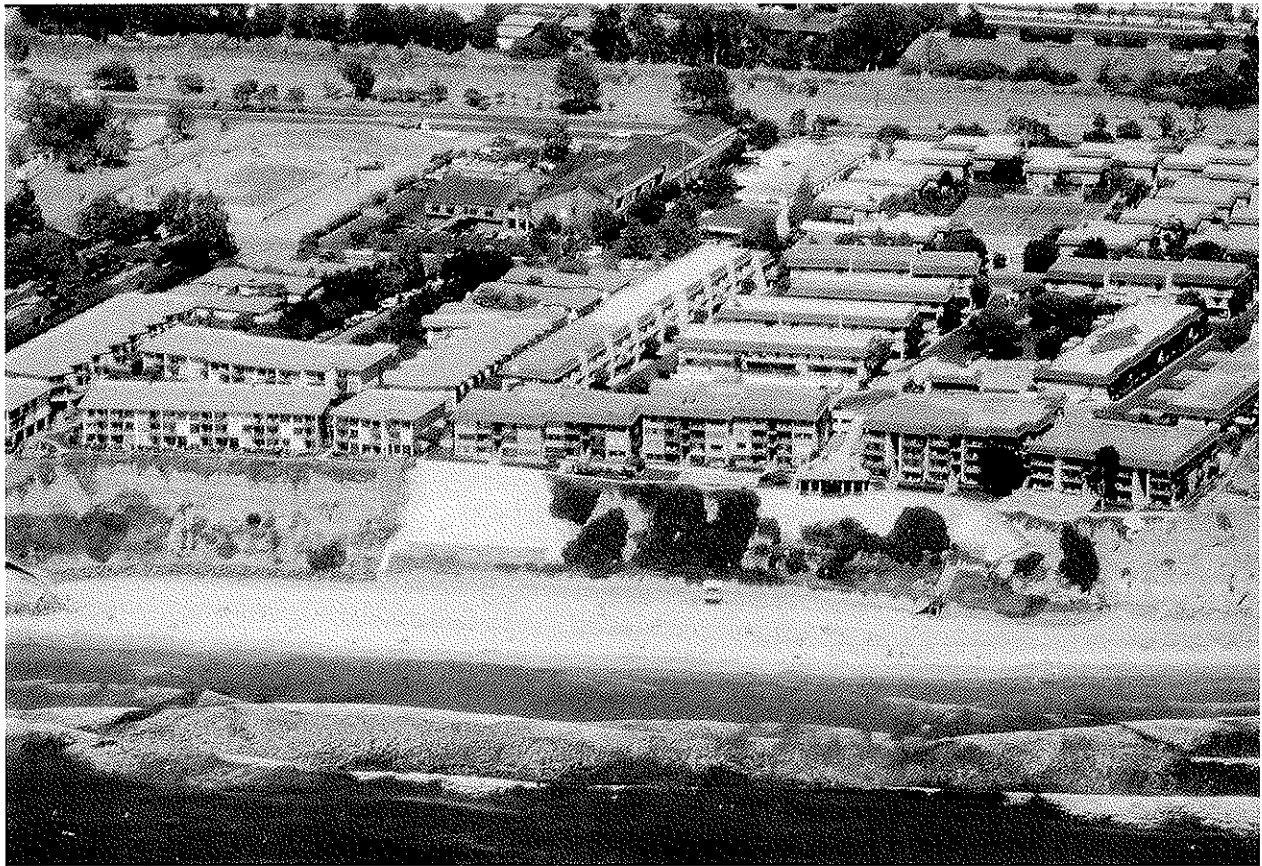


Figure 4. Intensive development of coastal bluffs in southern California.

eroding at a rate fast enough that future development would eventually be threatened. Thus a total of 640 km (39.4%) of the California shoreline was considered threatened due to high erosion rates.

The most recent inventory of hazardous coastal environments expands the scale of the problem areas again. In 1985, sixteen coastal geologists participated in the preparation of a statewide inventory of coastline conditions, classifying 500 km (28.6%) as high risk, and an additional 650 km (36.8%) as requiring caution (GRIGGS and SAVOY, 1985). These data indicate that two-thirds of the California coastline constitute a significant coastal hazard.

Several factors combine to complicate shoreline erosion in California.

(1) The process of cliff or bluff erosion tends to be an episodic one with the major erosion events taking place during the simultaneous occurrence of high tides and storm waves. Thus while we tend to utilize "average" annual erosion rate values (based on analysis of historic aerial photographs and/or maps) to describe the erosion risk or hazard at a particular location, the failure of coastal cliffs typically takes place in large incremental events during storm conditions.

(2) The process of cliff retreat or erosion is very site specific and due to a combination of (a) wave attack, (b) rainfall and runoff which produce gullying, mass move-

ments, and piping, and also (c) seismic shaking. These are all processes which take place on an infrequent and unpredictable time scale. As a result, unless an individual experiences a direct and catastrophic loss from such an event, the memory of the event diminishes rather quickly over time. As a result, the perception of the level of these hazards is quite low among the general population, particularly since many residents are relative newcomers to the state.

(3) The perception of the hazard from coastal erosion varies widely among different segments of the population for many reasons. For many, the prestige and value of owning oceanfront property reduces the perceived threat from natural hazards. That is, the locational advantages of shoreline property more than offset the potential losses posed by proximity to natural hazards. The incredibly high value of oceanfront property in the more densely populated southern and central portions of the state has led to extreme pressure on regulating agencies to allow development despite the presence of coastal hazards and risks (Figure 3).

Along the California coast there are three particular geomorphic environments where widespread development has taken place but that are potentially hazardous for any structure. These include: (1) eroding cliffs or bluffs, (2) the beach, and (3) active coastal dunes.

Eroding Cliffs or Bluffs

Eroding cliffs and bluffs represent California's most extensive coastal hazard. The net retreat or erosion of the cliffs or bluffs backing the beach is in striking contrast to the seasonal cycle of beach retreat and accretion. There is no seasonal reconstruction of eroded bluffs, at least by natural processes. The number of existing homes and "buildable" lots atop eroding seacliffs along the California coast is far greater than those either on the beach or on active dunes. In each case, the desire for unobstructed ocean views and convenient beach access have induced many to invest in property literally within a stone's throw of the water. Because of its location along an active plate margin, tectonic uplift of the California coast has provided many square kilometers of flat marine terraces which are easily developed. As a result, terrace bluff and cliff tops throughout much of southern California have been intensively developed with homes, condominiums, apartments, hotels and restaurants. The Del Mar, Oceanside, Encinitas, and Santa Barbara areas provide clear examples of this phenomenon (Figures 2 and 4). Although the extent of cliff top construction along the central and northern California coast is considerably less, there has still been considerable development in places like Santa Cruz, Capitola, and Pacifica (Figures 2 and 5).

Coastal cliff failure takes place as a result of three different processes: wave attack, subaerial erosion and mass movements, and seismic shaking.

The degree to which a seacliff yields to wave attack depends primarily upon its exposure to wave energy and the physical properties or strength of the materials making up the cliff. The lithology or hardness of the cliff rock and the presence of internal weaknesses such as joints or faults all directly affect the resistance of the material to wave attack or to slope failure through subaerial processes (Figure 6).

Although coastal erosion is relatively easy to document qualitatively, and many photographic records of this process exist (Figure 7) (see SHEPARD and WANLESS, 1971), a need also exists for a more quantitative documentation of the rates of cliff retreat. These values, expressed in cm/year, for example, are necessary if we are to compare rates of retreat between different areas or over different time periods, if we are to quantify the intensity or magnitude of shoreline processes and cliff resistance, and if there is a need to set safe setbacks for blufftop development.

All seacliff or bluff erosion rates need to be viewed with caution, however, and be placed in proper perspective. Typically these rates are determined from measurements on sequential aerial photographs and/or historic maps. These methods each have their limitations which need to be considered and understood before indiscriminately utilizing the "average" erosion rate data. For example, on a typical aerial photograph of 1:10,000 scale, a single millimeter on the photograph represents 10 m on the ground. The experience and skill of the interpreter, the methods and equipment used, scaling problems, photographic distortion, accurately locating points for repeat measurement, and the precise location of the cliff edge on photographs are some of the technical considerations and problems which need to be resolved before measurements can be taken and relied upon.

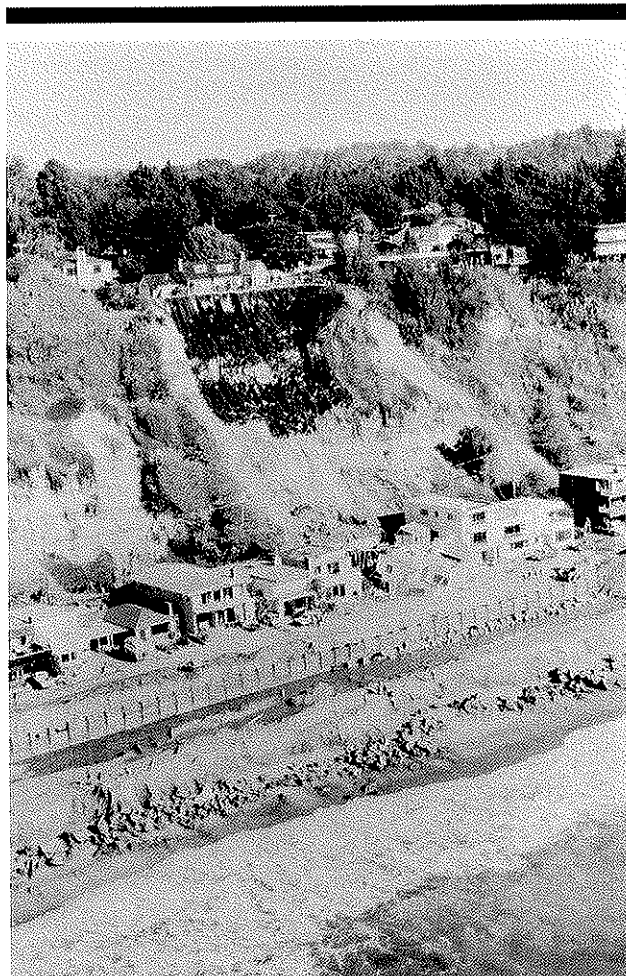


Figure 5. Development of coastal bluffs along northern Monterey Bay.

A common approach to quantifying rates of cliff retreat involves using an optical comparator to measure the distance from some distinct reference point, such as a street or a building, to the edge of the seacliff on sequential historic stereo aerial photographs. Each set of photographs must first be scaled by comparing known distances on the ground (distances between street intersections, for example, from field measurements) with the same distance on the photographs. Optical comparators allow for measurements as precise as 0.1 mm. Assuming the clarity of the photographs allow for this level of precision, then distance resolution of 1 to 3 meters on photographs with scales of 1:10,000 to 1:30,000 is possible. Dividing the change in distance between the cliff edge and the reference point over the number of years between photographs produces an "average" annual erosion rate (Figure 8).

The time span covered by the measurements (photos or maps) is also important in evaluating the reliability of the calculated retreat rate, as well as changes in retreat rates over time. Ten or even twenty years of record may not be representative of the long term conditions because of the episodic nature of the erosion process and the possibility that the short time period analyzed did not include any major storm or erosional events. Average erosion rates, particularly those based on short time intervals that may



Figure 6. The orientation and spacing of joints is a primary factor controlling cliff erosion and the resulting coastline configuration.

not include major storm years, need to be used and extrapolated with considerable caution and conservatism.

A comparison of relatively long term (62 years) seacliff retreat for a portion of the central California coast near Santa Cruz illustrates the site specific variability in erosion rates over time (Figure 8). The three sites are approximately 1 km apart but vary in "average" annual erosion rates from 10 cm/year to 45 cm/year. Additionally the temporal patterns vary from 26th Avenue where retreat has been relatively uniform over the entire 62 year period, to Moran where erosion was active in the 1930's and 1940's but was halted in the 1950's by the emplacement of protective rip rap. At 38th Avenue erosion of the bluff progressed rapidly between 1928 and 1940, was insignificant from 1940 to 1976, and then increased again from 1976 to 1990. In general, much of the California coast experienced above average storm activity and rainfall until about 1945, followed by about 30 years of relatively calm conditions and below average rainfall. Beginning in 1978, California has been in an era of increased precipitation and storm activity. These patterns seem to be expressed in the 35th Avenue erosion records.

Coastlines consisting of unweathered crystalline rock, such as the granite of the Monterey Peninsula, usually erode at imperceptibly slow rates, at least during the period of historic photographs. At some locations in this area virtually no change can be detected between photos taken 60 to 70 years ago and today (Griggs and Savoy, 1985).

Within these resistant areas erosion rates can vary considerably. Waves attack the weaker zones over time, the fractures and joints for example, to form inlets and coves. The more resistant rock is left behind as points, headlands and sea stacks.

In contrast, erosion rates in the weaker sedimentary rocks which make up most of the southern and central coast of California, are moderate to high (10 to 60 cm/year). Lithologic, stratigraphic and structural weaknesses or differences are the key factors affecting erosion rates in sedimentary rocks. Cliff erosion, as mentioned earlier, is due not only to waves undercutting the base of the cliff, but also to rockfalls, landsliding and slumping higher on the cliff face. The orientation and spacing of joints in the sandstones, siltstones, and mudstones which make up the cliffs surrounding northern Monterey Bay are the dominant factors affecting cliff retreat in this area (Griggs and Johnson, 1979) (Figure 6). The orientation of the coastline as well as the magnitude of rock fall failures and resulting erosion rates are directly related to the extent of jointing development.

The combination of several intersecting joints sets, weak rock exposed at the base of the cliff in the surf zone, lack of a protective beach, infiltration of surface runoff and landscape irrigation, and wedging by tree roots has led to continued large scale rock falls along the bluffs of the Capitola area of northern Monterey Bay. In March 1983, a slab 30 m long and 2 to 4 m wide collapsed and fell 15 m to the

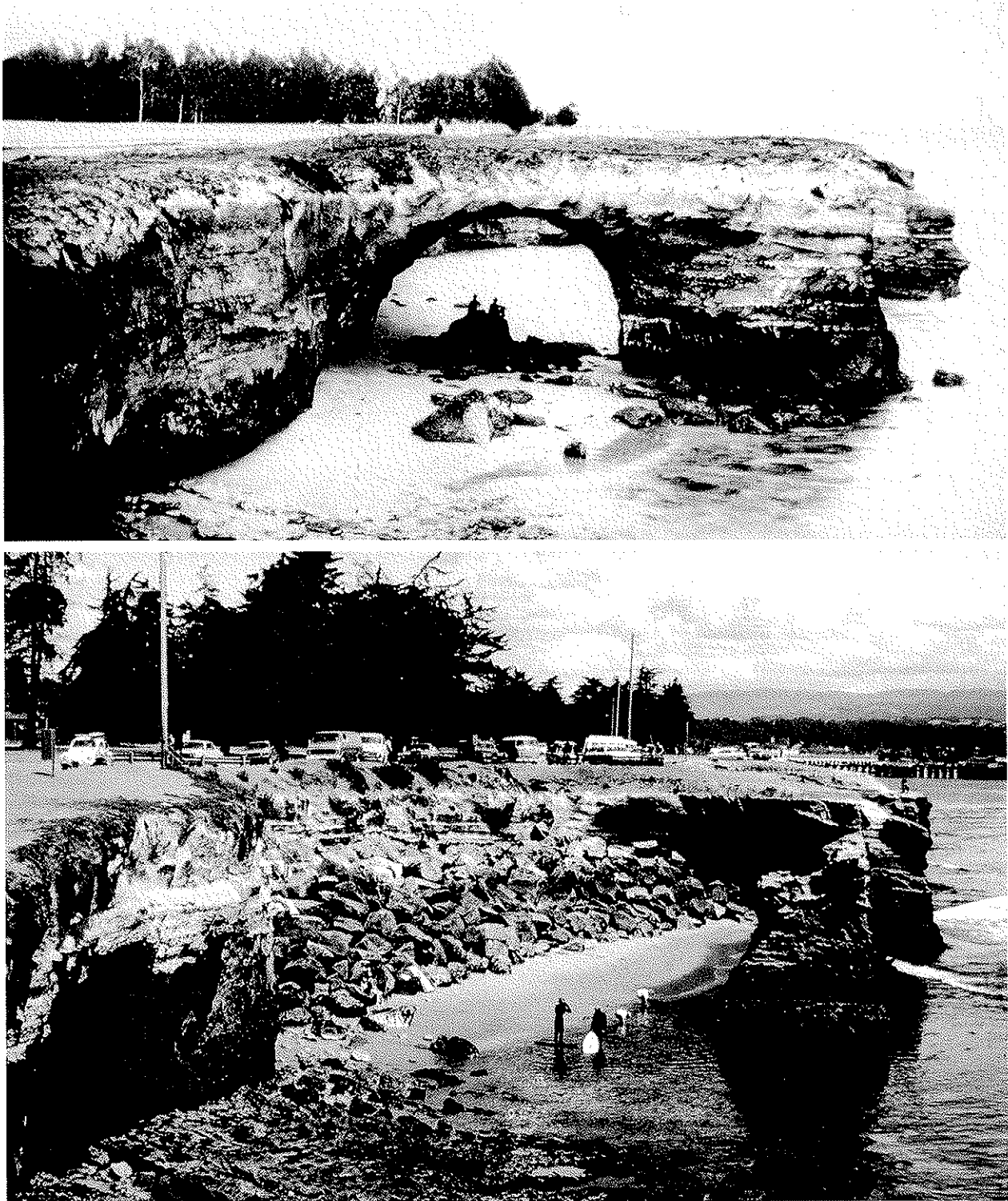


Figure 7. Historical photographs showing sequential bluff retreat along the central California coast.

beach below. During the October 17, 1989, Loma Prieta earthquake centered less than 15 km away, additional bluff retreat at Capitola undercut six apartment buildings which were already dangerously close to the bluff edge, leading ultimately to their demolition (Figure 9). Two other dwell-

ings have been relocated from the bluff edge over the past 20 years and the oceanfront public street has been abandoned. Average long term (60 years) erosion rates in the Capitola area range from about 20 to 45 cm/year based on aerial photo interpretation (GRIGGS and JOHNSON, 1979).

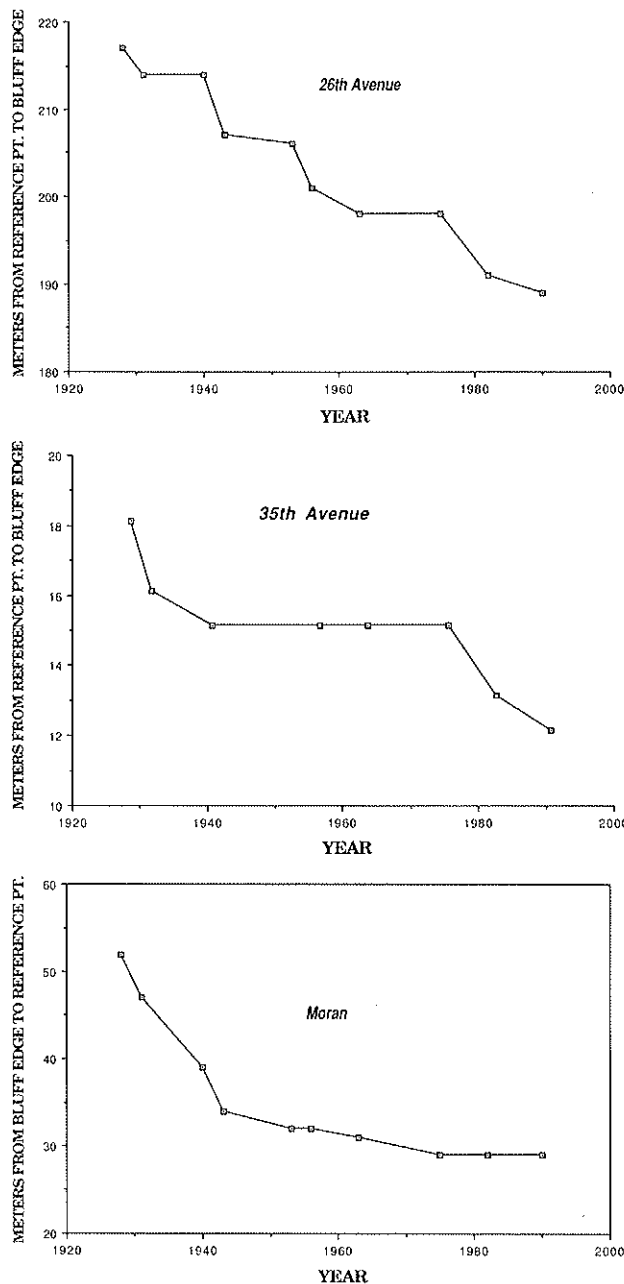


Figure 8. Plots of different historical cliff retreat rates along northern Monterey Bay.

Fifteen miles downcoast, along the southern coastline of Monterey Bay, the bluffs consist of weakly consolidated late Pleistocene dune sands which offer virtually no resistance to direct wave attack. Due in large degree to nearly a century of sand mining from the beach (at average rates of 250,000 m³/year) and therefore a deficit littoral budget and reduced beach width, as well as high wave energy due to the effects of wave refraction over Monterey Submarine Canyon, average erosion rates over the past half century have been very high, ranging from 60 to 240 cm/year (Figures 10 and 11).

Cliff failure during strong seismic shaking represents a significant but little appreciated coastal hazard, primarily

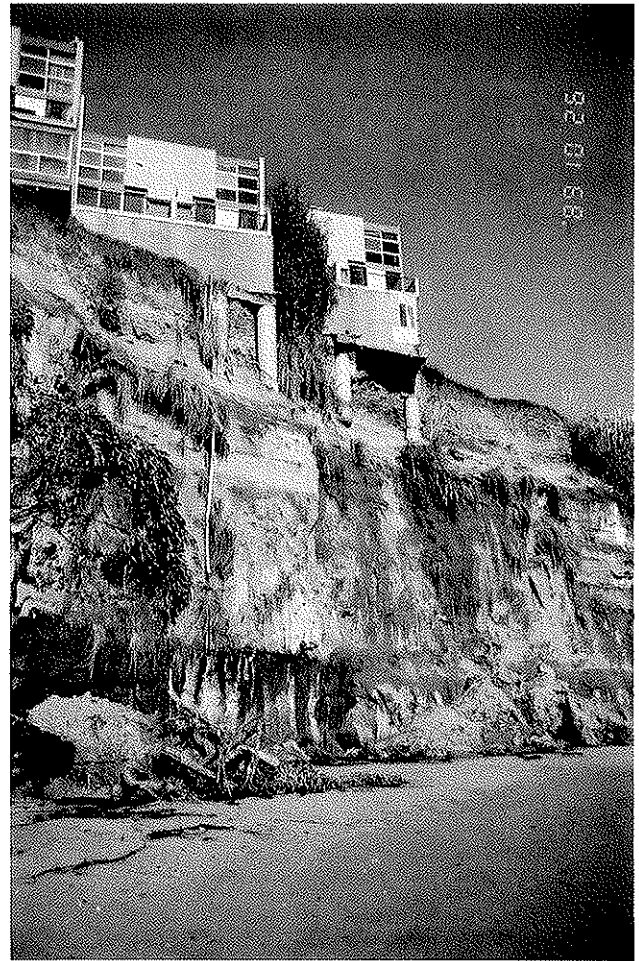


Figure 9. Bluff failure from a combination of marine, terrestrial, and seismic processes led to progressive undercutting of these bluff-top apartments in Capitola. The six units on the right were demolished following the 1989 Loma Prieta earthquake.

due to the infrequent nature of large earthquakes. The potential for earthquakes which can affect coastal bluffs is high along the entire length of the state's coastline. No part of the coastline of California is more than 25 km from an active fault (JENNINGS, 1975), and many areas are considerably closer.

Large earthquakes can cause instantaneous cliff retreat and also weaken sea cliffs through seismic shaking and the formation of cracks and fissures which increase their susceptibility to subsequent failure. In addition to the hazards to structures or utilities at the top of a cliff, there is a risk at the base of the seacliff due to the downslope movement, impact, and deposition of the rock or soil from upslope. It is evident from the intensity of development along most of California's coastal bluffs that the potential for cliff failure from seismic shaking was probably not a consideration at the time permits were issued and construction took place.

The October 17, 1989, Loma Prieta earthquake (magnitude 7.1) was the largest earthquake to strike the central coast since 1906 and was felt over an area of 1,000,000 km². This earthquake produced bluff failure along 240 km of

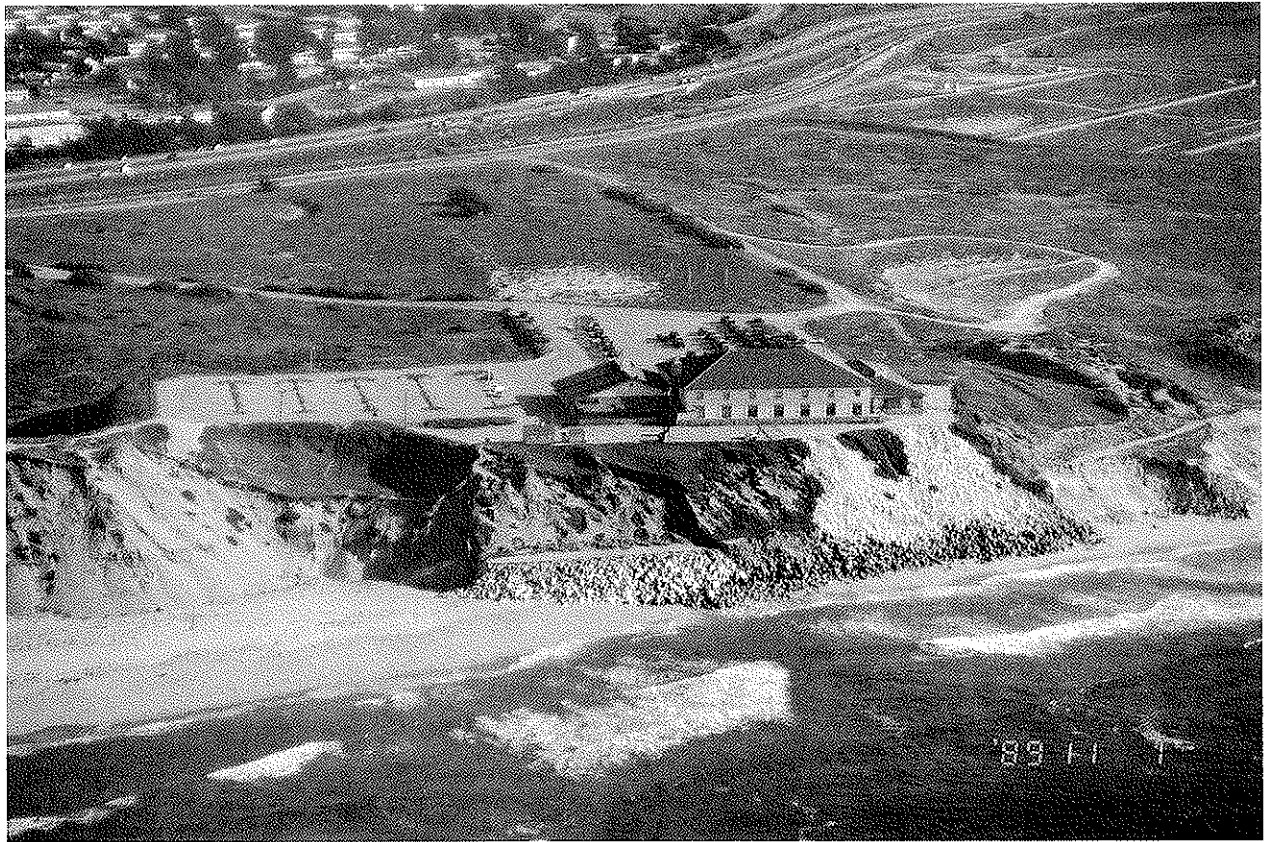


Figure 10. An officer's club at a military base in southern Monterey Bay has been threatened by continued erosion of these weakly consolidated sand dunes which has progressed at rates up to 240 cm/year for the past 40 years.

central California coast in a variety of rock types and slope conditions (PLANT and GRIGGS, 1990a,b, 1991) (Figure 12). Failure was most widespread closest to the epicenter where extensive bluff top cracking and collapse led to the demolition of three homes and six apartments and one death. The long term stability of the bluffs which experienced tensional cracking up to 10 m inland from the bluff edge is uncertain, although failure has taken place during subsequent winters.

Coastal communities from one end of the state to the other have lost entire oceanfront streets and lots through the ongoing process of bluff retreat over the past century. New developments are still being proposed on eroding or unstable bluffs, and older weekend cottages are being torn down and replaced by larger homes. When California's landmark Coastal Act was passed in 1972 and implemented, the issues of coastal hazards were not as apparent as they have become in the subsequent 15 years. Although statewide guidelines were established for determining the geological stability of blufftop development, there is no state policy establishing safe setbacks from the edge of a seacliff or bluff for any type of development. Some local jurisdictions use a predetermined, fixed setback, although these vary from as little as 10 to as much as 320 feet. Others employ a cliff retreat rate (supposedly site specific) and applicable over a specific time period or structural life span, most commonly a 50-year period.

An investigation of local government policies on coastal hazards in California (GRIGGS *et al.*, 1991, 1992) revealed the following limitations in the approaches to regulating blufftop development: (a) regulations apply only to new development and fail to include provisions governing major remodeling and enlargements of existing structures, an increasingly common practice; (b) the increasing use of variances in infill, thus propagating or increasing the level of hazard and risk; (c) prescribed structure-lifetimes (often based on 30-year mortgage periods) do not accurately reflect the reality of structure longevity in California, generally much greater than those prescribed; (d) geologic information is frequently incomplete and jurisdictions are often not adequately staffed to make necessary technical and scientific evaluations; (e) the perceived threat of litigation appears to lead local elected officials to approve development applications that are recommended for denial at the planning staff level. Any one of these limitations can override a primary intent to site development well away from hazards of bluff erosion.

Beach-Front Construction

All California beaches undergo seasonal changes in width in response to yearly variations in wave energy. Summer beaches are typically wider and offer considerably more protection to the seacliff, dunes, or bluffs landward of the beach. In the winter, beaches may be reduced in width by

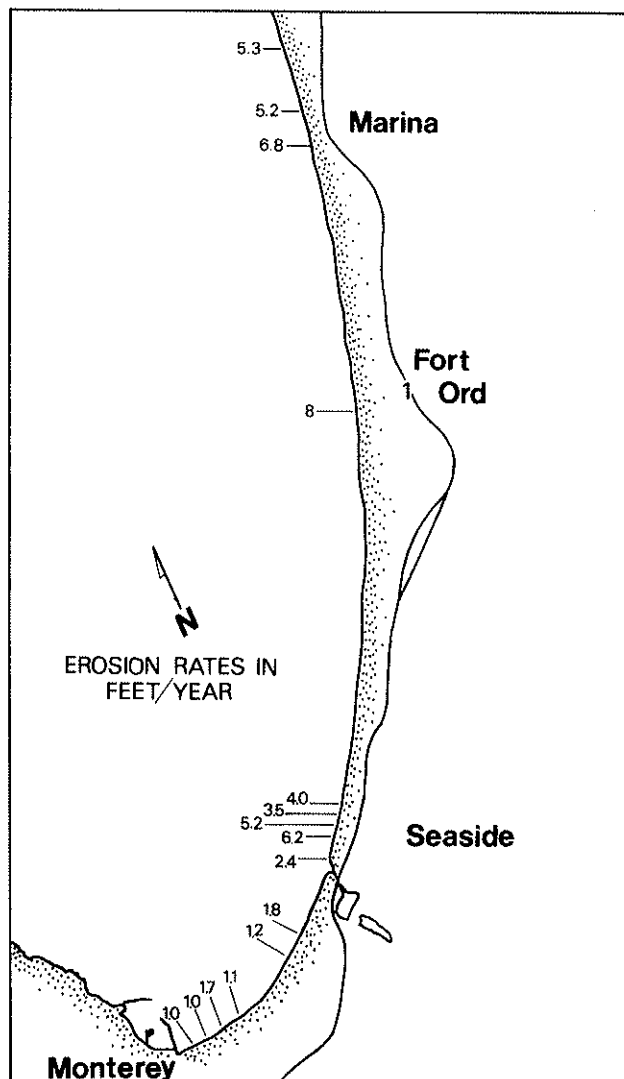


Figure 11. Longshore variations in historic bluff retreat rates in the unconsolidated dunes of southern Monterey Bay.

a 100 m between November and March, such that the waves reach further landward, attacking the bluffs or dunes directly (Griggs and Savoy, 1985).

Construction directly on the back beach is common along the California coast. Homes have been built both elevated on pilings or piers, but also on slabs at beach level. The presence of beach sand surrounding a house is ordinarily clear evidence that the site is at least intermittently subject to high tides and storm waves. There are many km of "private property" along the California shoreline which as geologists we would consider to be simply beach (Figure 13). When these parcels were originally surveyed, however, they were determined to be above mean high tide and, therefore, became legal parcels of record. Many of these back beach areas have been intensively developed. Their legal status as private property exerts no significant effect on their exposure to wave impact and inundation. There are also many parcels of record which are now beneath the waves.

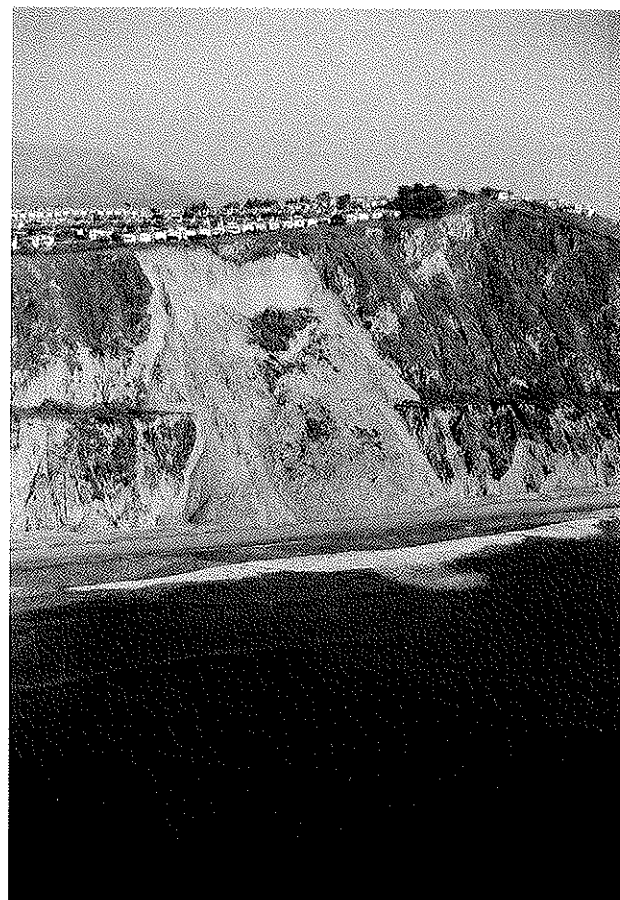


Figure 12. Failure of the weak material making up the coastal bluffs near San Francisco took place up to 120 km from the epicenter of the Loma Prieta earthquake.

Much of the \$150 million in coastal storm damage over the past 15 years in California occurred when waves attacked beach-front homes in places like Stinson Beach, Rio Del Mar, Malibu, Redondo Beach, Del Mar, Oceanside and Imperial Beach (Figure 2). Storm damage took place during the winters of 1978, 1983 and 1988 when large storm waves arrived simultaneously with very high tides during a period of elevated sea level from El Nino events. Sand levels were lowered and the waves reached the homes and other structures on the back beach which were normally buffered by wide expanses of sand. Losses in 1983 included wave undermining of shallow piers, pilings or slabs so that homes collapsed onto the beach (Figure 14). Structures on low pilings were subject to wave uplift forces at high tide and raised off their foundations with consequent losses of utility connections. Waves also overtopped or destroyed low protective seawalls and revetments and then damaged or destroyed the house fronts facing the sea. Nonstructural damage included losses of decks, beach stairways, patios, yards and landscaping.

Events of this sort will not occur with any regularity or predictability, but they will occur. The fact that these homes are now located directly on or over beach sand is clear evidence of the shoreline processes which can be expected



Figure 13. Intense back beach development is widespread along the southern California coast.

at these locations. The storm damage to these beachfront areas during recent years is clear testimony that either these risks were not adequately evaluated or that the hazards of living on the beach were disregarded in the planning process. A partial explanation for this shortcoming lies in: (1) the relatively infrequent simultaneous occurrence of very high tides and large waves; (2) the tendency for people to have short disaster memories; (3) the large number of immigrants to California in recent years who have not experienced coastal hazards; and (4) the moderate climate and storm history of the 30 year period from 1946 to 1976, an era of rapid population growth and intense coastal development in California.

Many homes and protective structures were approved and built by planners, engineers, and contractors without firsthand experience with storms such as those that occurred during the winter of 1983, and therefore, suffered from inadequate setbacks, elevation, or design considerations (*i.e.*, wave runup elevation, scour depth, *et cetera*). Additionally, there is commonly a significant time lag between the collection of coastal process or hazard data by scientists and utilization of the data by engineers, such that many structures have been underdesigned through utilizing outdated, generic, or cookbook design criteria or physical process information.

Despite California's intense beach level development, neither the California Coastal Act nor the subsequent In-

terpretive Guidelines specifically recognized the hazards of direct wave impact or wave/tidal inundation (coastal flooding) on beach level structures (GRIGGS *et al.*, 1991, 1992). As a result, policies at the state's local government level on beach front construction vary widely. Most of the state's coastal jurisdictions have adopted Federal Emergency Management Agency (FEMA) Flood Insurance Rate Maps (FIRM) which delineate zones that are subject to different degrees or elevations of coastal flooding. Although these maps were originally developed for insurance purposes, they now have regulatory status. Many of California's local government planning departments expressed concern about the FEMA coastal maps (GRIGGS *et al.*, 1992). These maps have usually been prepared under federal government contract, and the consulting firms selected to conduct the actual work were not required to be familiar with the local coastal areas in which they proposed to work. As such, in many areas, the base-flood elevations were calculated using wave-runup models rather than utilizing historic storm or inundation data. As a result, some local governments are using FEMA base-flood maps that do not accurately reflect the actual coastal flood events that have taken place within their jurisdiction and which are based on inaccurate or outdated bathymetry. This problem needs to be addressed and resolved.

Wave-runup models require accurate data on beach and nearshore configurations and long-term wave data in order



Figure 14. Scour of up to 2.5 meters of sand during the winter storms of 1983 led to loss of support for shallow pilings and collapse of this home onto the beach.

to produce reliable results. There are few locations where accurate data exist for these key variables. Wide variation and seasonal and yearly changes in local beach and near-shore bottom slopes and elevations, as well as the lack of long-term wave data in most locations, require the use of estimates and assumptions that can lead to considerable error in model-based calculations of base-flood elevations. The use of inaccurate maps for siting structures in beach environments raises serious questions about the actual safety of such structures in light of Coastal Act Policy to "minimize risks to life and property in areas of high geologic, flood and fire hazard." The lack of state guidelines for safe development at beach-level has led to continued development and reconstruction in hazardous locations.

Maximum wave-runup can be quantified using actual historical data from a particular site. Hazard analysis for structures (whether homes or seawalls) proposed along the central California coast have used a combination of predicted tidal heights, atmospheric storm surge, short term wave setup, and sea level rise associated with global warming to approximate a maximum still water level (9.7 feet MSL or 2.97 m MSL), to which then must be added an actual wave height runup value of 2.45 m (8 feet) to produce a maximum wave runup elevation of 5.42 m (17.7 feet).

Top elevations of new seawalls or base elevations of new structures must be above this elevation.

Sand Dunes

In contrast to the east and Gulf coasts of the United States, the coast of California is a geologically active continental margin, such that the coast is typically backed by steep cliffs and coastal mountains, only occasionally broken by valleys and river mouths. As a result, sand dunes, which require a flat low-lying area on which to form, as well as an adequate supply of sand and a dominant wind direction, are restricted along the state's coastline. Extensive coastal dune fields have developed in the southern Monterey Bay, Pismo Beach, and along portions of the Los Angeles and Orange counties in southern California (Figure 2).

Sand dunes are integrally connected to the beach and form an important buffer to wave action as well as a reservoir of beach sand. The morphology of coastal dunes will change depending upon wave and wind conditions as well as sand supply. Winter storm waves will periodically erode or lower the protective beach and reach the base of the frontal dune where erosion of unconsolidated sands can occur rapidly (Figure 15). In subsequent months of lower wave conditions, the beach will accrete and excess sand, over time, will replenish the dunes. Dune stability can easily be altered by human intervention, such as grading, vegetation removal, or lowering of the water table during construction. Conversely, the planting of appropriate vegetation and a rise in the water table may lead to the stabilization of active, migrating dunes. Lessons learned centuries ago in the low countries of Europe and in parts of New England regarding the fragile nature of sand dunes have not always been appreciated in California.

The most extensive area of oceanfront dune development along the California coast is in Monterey Bay where numerous homes, condominiums, apartments, a hotel and other structures have been built directly on the crest of the frontal dune overlooking the ocean. Additional high density dune-front development has been proposed. Concerns exist with these existing and proposed developments. Where structures have been built directly on the frontal or primary dune on conventional foundations or shallow piles or piers, periodic dune erosion during episodes of high tides and storm waves can potentially undermine or threaten these buildings.

A post-construction analysis of the historic aerial photos of Pajaro Dunes (a major oceanfront dune area developed with homes and condominiums in central Monterey Bay in 1968) revealed that forty years before the development was constructed that storm waves had completely washed over a portion of the site (Figure 16). The washover area is now covered with 87 condominiums and several homes. The sequential aerial photos also indicated that the front edge of the foredune had alternately accreted and eroded as much as 10 m due to storm erosion and subsequent accretion. Unfortunately, neither the architects and engineers who planned the project nor the planners who reviewed it utilized the recorded storm history or the aerial photographic record to evaluate the geomorphic history of this site. Since the development was begun in 1968, storm waves combined with high tides have eroded the dunes and



Figure 15. Up to 20 meters of erosion of the frontal dune at Pajaro Dunes in central Monterey Bay took place during the winter of 1983, threatening a number of dune-front homes.

threatened homes during three different winters. During the winter of 1983, 10 to 20 meters of dune retreat occurred during a two day period of sustained high tides and large waves. A number of homes built directly atop the foredune were threatened (Figure 15). Only the emergency emplacement of several million dollars of rip-rap saved the homes from collapse as the foredune was eroded. A permanent revetment has subsequently been built at a cost of approximately \$5 million along 1.5 km of dune frontage. A fundamental understanding of dune dynamics and an evaluation of the historic aerial photographs and storm history of the area should have been part of the early planning of this site. The subsequent storm damage and protective effort could have been avoided with proper setbacks.

SUMMARY OF CALIFORNIA'S COASTAL HAZARDS

The conflict between accelerating oceanfront development and the hazards inherent at the water's edge is a policy dilemma of increasing magnitude in California. The coastline is caught between rising sea level and ocean storm waves from the front and the increasing waves of humanity from the rear.

Conflict between oceanfront development and coastal hazards is increasing for five reasons: (1) progressive erosion of shorefront property is undermining structures and utilities previously protected by adequate setbacks; (2) accelerated human-induced seacliff erosion due to cliff-top

construction with its increased runoff and landscape watering; (3) reduced widths of protective beaches due to diminished volumes of beach sand delivery to the coast; (4) increased frequency and magnitude of hazard due to larger storms bringing heavy rainfall and large waves; and (5) increased population migration to coastal communities (including an influx of people who have not experienced storm damage first hand) and the corresponding increased pressure to develop oceanfront property and recreational facilities.

The ongoing natural processes of cliff retreat, storm inundation and beach erosion were either not recognized, well-understood, or ignored by many developers and homebuyers in the past. Moreover, much of California's oceanfront development took place from the mid-1940's to the mid-1970's, a period generally characterized by below average rainfall and storm frequency. The wave impact and shoreline erosion accompanying the storms of the last decade, however, have been responsible for over \$150 million in damage. High tides and storm waves during the winter of 1983 inflicted greater than \$100 million in damage to oceanfront property; thirty-three oceanfront homes were completely destroyed, with an additional 3,000 homes and 900 businesses damaged. Further, public recreational facilities suffered an estimated \$35 million in damage. In mid-January 1988, an intense storm accompanied by strong winds and large waves struck southern California with little warning and produced an additional \$25 million in damage.



Figure 16. Comparison of 1928 and 1976 aerial photographs of the Pajaro Dunes area in central Monterey Bay. Note how construction has taken place both on the active dune front and also on an area near the river mouth which was subject to overwash prior to the 1928 photograph.

Although the physical and economic impacts of the large storms are the most widely publicized, the year-to-year public and private costs of intensive shoreline development and coastline modification are equally significant.

The two interrelated but distinct hazards which must be considered in coastal land use decisions are shoreline erosion, and wave impact and inundation. Although the type and magnitude of hazards vary widely along California's coast, it is generally only a matter of time before the threat is apparent to property owners. These owners, be they individuals or public entities, are then faced with four options: (1) do nothing and face the inevitable loss; (2) sell the property and pass the problem on; (3) move or relocate buildings or other improvements; or (4) attempt to control or reduce the hazard through some type of protective structure or measure.

Over the past 50 years, the typical response to coastal hazards in California has been the construction of seawalls and revetments intended to protect eroding or wave-impacted shorelines. At present, an astonishing 208 km—approximately 12% of the state's entire 1,760 km shoreline—has been "protected" or armored. Protective structures have usually been constructed only after existing shoreline development has been threatened. Rarely did a protection strategy precede development.

Significant changes are needed in how to approach and deal with coastal hazards and the continuing pressure to develop in coastal areas. The marked inconsistencies among local governments and those state agencies who have responsibilities to regulate development indicate the lack of a guiding direction and the heavy influence of local economics and politics.

Through a process of hazard recognition and evaluation, and then a standardized set of avoidance, mitigation, or hazard reduction policies, the private and public losses

from future shoreline erosion, storm impact, and sea level rise can be significantly reduced. The objective is to reduce the number of people, as well as dwellings, structures, and utilities, both public and private, directly exposed to the hazards of both shoreline erosion and wave impact and inundation (GRIGGS *et al.*, 1992).

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National Assessment of Shoreline Change Part 3: Historical Shoreline Change and Associated Coastal Land Loss Along Sandy Shorelines of the California Coast

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**U.S. Department of the Interior
U.S. Geological Survey**

National Assessment of Shoreline Change Part 3: Historical Shoreline Change and Associated Coastal Land Loss Along Sandy Shorelines of the California Coast

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**U.S. Department of the Interior
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EXECUTIVE SUMMARY

Beach erosion is a chronic problem along many open-ocean shores of the United States. As coastal populations continue to grow and community infrastructures are threatened by erosion, there is increased demand for accurate information regarding past and present trends and rates of shoreline movement. There is also a need for a comprehensive analysis of shoreline movement that is consistent from one coastal region to another. To meet these national needs, the U.S. Geological Survey is conducting an analysis of historical shoreline changes along open-ocean sandy shores of the conterminous United States and parts of Hawaii and Alaska. One purpose of this work is to develop standard repeatable methods for mapping and analyzing shoreline movement so that periodic updates regarding coastal erosion and land loss can be made nationally that are systematic and internally consistent. In the case of this study, the shoreline being measured is the boundary between the ocean water surface and the sandy beach.

This report on the California Coast represents the first of two reports on long-term sandy shoreline change for the western U.S., the second of which will include the coast of the Pacific NW, including Oregon and Washington. A report for the Gulf of Mexico shoreline was completed in 2004 and is available at: <http://pubs.usgs.gov/of/2004/1043/>. This report summarizes the methods of analysis, interprets the results, provides explanations regarding long-term and short-term trends and rates of change, and describes how different coastal communities are responding to coastal erosion. Shoreline change evaluations are based on comparing three historical shorelines digitized from maps, with a recent shoreline derived from lidar (Light Detection and Ranging) topographic surveys. The historical shorelines generally represent the following periods: 1800s, 1920s-1930s, and 1950s-1970s, whereas the lidar shoreline is from 1998-2002. *Long-term* rates of change are calculated using all four shorelines (1800s to lidar shoreline), whereas *short-term* rates of change are calculated for only the most recent period (1950s-1970s to lidar shoreline). The rates of change presented in this report represent past conditions and therefore are not intended for predicting future shoreline positions or rates of change. Due to the geomorphology of the California Coast (rocky coastline instead of beach) as well as to data gaps in some areas, this report presents beach erosion rates for 45% of California's 1100 km of coast.

The average rate of *long-term* shoreline change for the State of California was 0.2 ± 0.1 m/yr, an accretional trend. This is based on shoreline change rates averaged from 14,562 individual transects, of which 40% were eroding. Of the transects on which the shoreline was eroding, the *long-term* erosion rates were generally lowest in Southern California

where coastal engineering projects have greatly altered the natural shoreline movement. On a regional scale, *long-term* accretion rates were either equal to (Central California) or greater than (Northern and Southern California) the *long-term* erosion rates, yielding the net accretional trend for the entire state. This accretional trend is most likely due to changes in the large volumes of sediment that are added to the system from large rivers and to the impact from coastal engineering and beach nourishment projects.

The average rate of *short-term* shoreline change for the state was erosional. The *net short-term* rate as averaged along 16,142 transects was -0.2 ± 0.4 m/yr. Of the transects used to measure *short-term* change, 66% had erosional trends. In addition erosion rates were higher in the *short-term* period, possibly related to the localized artificial nourishment that occurred over much of the 20th century but that has recently slowed or stopped (Flick, 1993; Wiegel, 1994). *Short-term* accretion rates were highest in Northern California where the overall magnitudes of shoreline change are systematically higher than in Central and Southern California. The most stable (low erosion and accretion rates) California beaches were most commonly found in Central California.

Seawalls and/or riprap revetments have been constructed in all three sections of California, although many of these structures were built to protect houses and infrastructures from the erosion of coastal cliffs and bluffs rather than to protect against long-term beach erosion. California permits shoreline stabilization structures where homes, buildings or other community infrastructure are imminently threatened by erosion.

A second California report that is following this publication will include analyses and reports on long-term coastal cliff erosion, as this hazard is of equal or greater concern to coastal communities in many areas along the California Coast.

INTRODUCTION

U.S. Geological Survey National Assessment of Shoreline Change

Sandy ocean beaches represent some of the most popular tourist and recreational destinations in the United States, and also constitute some of the most valuable real estate in the country. These changing and ephemeral interfaces between water and land are the sites of intense residential and commercial development even though they are frequently subjected to a range of natural hazards that can include flooding, storm impacts, coastal erosion and tsunami inundation. Because population and economic trends have made the coasts so valuable, the U.S. Geological Survey (USGS) is conducting a National Assessment of Coastal Change Haz-

ards. One component of this effort, the National Assessment of Shoreline Change, documents changes in shoreline position as a proxy for coastal change. Shoreline position is one of the most commonly monitored indicators of environmental change (Morton, 1996), and it is easily understood by those who are interested in historical movement of beaches.

A principal purpose of the USGS shoreline change research is to develop a repeatable surveying methodology so that shorelines for the continental U.S., and portions of Hawaii and Alaska, can be periodically and systematically updated in an internally consistent manner. In addition, new methods for developing datum-based shorelines and assessing coastal change can provide the opportunity to achieve more comprehensive assessments of error in the future. The primary objectives of this effort are: (1) to develop and implement improved methods of assessing and monitoring shoreline movement, (2) to obtain a better understanding of the processes controlling shoreline movement, and (3) to enter into partnerships to facilitate data dissemination.

Achieving these ongoing objectives requires research that (1) examines the original sources of shoreline data (maps, air photos, global positioning system (GPS), lidar), (2) evaluates the utility of different shoreline proxies (geomorphic feature, water mark, tidal datum, elevation contour) including the errors associated with each method, (3) investigates the bias and potential errors associated with integrating different shoreline proxies from different sources, (4) develops standard uniform methods of shoreline change analysis, (5) determines the effects of human activities on shoreline movement and rates of change, and (6) investigates alternative mathematical methods for calculating historical rates of change and forecasting future rates of change.

This report summarizes historical changes in the California sandy shoreline, both accretion and erosion, but emphasizes the erosion hazard because of its impacts on natural resources and the economy. The descriptions of coastal land loss for each region (Figure 1) within the state provide a more comprehensive view of coastal processes and key references that can be used to learn more about coastal change in a regional context.

Disclaimer

Results of the National Assessment of Shoreline Change are organized by coastal regions. This report for California is part of a series of reports that will include text summarizing methods, results, and implications of the results in addition to maps, via Internet Map Server (IMS), illustrating rates of shoreline change. Rates of shoreline change are being published for the purpose of regional characterization. The shoreline change results and products prepared by the USGS are not intended for comprehensive detailed site specific analysis of shoreline movement, nor are they intended to replace any official sources of shoreline change information identified by local or state government

agencies, or other federal entities that are used for regulatory purposes. Rates of shoreline change presented herein may differ from other published rates, and differences do not necessarily indicate that the other rates are inaccurate. Some discrepancies are expected, considering the many possible ways of determining shoreline positions and rates of change, and the inherent uncertainty in calculating these rates. Rates of shoreline change presented in this report represent shoreline movement under past conditions. The results are not intended for predicting future shoreline positions or future rates of shoreline change.

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Figure 1. Index map of California showing the fifteen regions discussed in the text.

detailed review by Gary Griggs was invaluable and greatly improved the report.

THE ROLE OF STATE AND FEDERAL GOVERNMENTS

One reason for conducting this National Assessment of Shoreline Change is that there is no widely accepted standardized method of analyzing shoreline changes. Each state or region has its own data needs and coastal zone management responsibilities (e.g. construction set-back lines), and therefore different techniques and standards are used to compile shorelines and to calculate rates of shoreline movement. Consequently, existing calculated rates of shoreline change and projected shoreline positions are inconsistent from state to state and even within states, such as in California, and cannot be compared directly. These inconsistencies were clearly demonstrated by the Federal Emergency Management Agency (FEMA) sponsored erosion studies (Crowell and Leatherman, 1999) that were used as the basis for evaluating erosion hazards (The Heinz Center, 2000). Within California, the FEMA sponsored erosion studies only addressed coastal cliff erosion, not sandy shoreline erosion. The USGS National Assessment of Shoreline Change represents the first time that shorelines from original data sources have been compiled and rates of shoreline change have been calculated on a national scale using internally consistent methods. The results of this analysis allow direct comparison of rates of change from one coastal segment to another and form the basis for future comparison of shoreline position.

Several federal agencies (USGS, FEMA, NOAA, U.S. Army Corps of Engineers (USACE) have regulatory or administrative responsibilities pertaining to shorelines. Yet these responsibilities are quite different, requiring different approaches and offering substantial opportunities for cooperation. For example, the USACE is authorized and funded by Congress to report on the economic and environmental implications of shoreline change and the costs of erosion mitigation. Their National Shoreline Management Study (Stauble and Brumbaugh, 2003) is being conducted using existing shoreline data. The USGS will share data and information, such as the lidar-derived shoreline and rates of change, in support of their effort. NOAA has the mandate to establish the official shoreline boundary for the nation using tidal datums. Their emphasis is on safe navigation and using the shoreline to generate nautical charts. NOAA also has a developing program (V datum), which will greatly assist other agencies in establishing alternative shorelines for a variety of purposes where the official shoreline is inappropriate. FEMA is authorized and partially funded by Congress to map coastal (and riverine) flood hazard areas. These maps and associated information are used for flood risk assessment, floodplain management, and setting insurance rates through the National Flood Insurance Program

(NFIP). Because of perceived deficiencies in the way the NFIP considers coastal erosion, Congress authorized FEMA to report on the economic impact of erosion hazards on coastal communities, and on the NFIP. To accomplish this, FEMA contracted state agencies and academic researchers to conduct a pilot study of erosion hazards that included shoreline change data for limited geographic areas. The USGS is responsible for conducting research pertaining to coastal change hazards including shoreline change, understanding the processes that cause coastal change, and developing models to predict future change. The USGS is the only government agency that has a dedicated program to monitor coastal change into the future using consistent methods nationwide. Such a program is critically important to assess national issues, such as the coastal impacts of sea level rise.

PRIOR NATIONAL AND CALIFORNIA COAST SHORELINE ASSESSMENTS

There are very few studies of regional sandy shoreline erosion for California. The USACE (1971) conducted the first national assessment of coastal erosion that included California. That study identified areas of critical and non-critical erosion on the basis of economic development and potential for property loss, but rates of shoreline movement were not quantified. Numerous analyses have been conducted for specific sites by private consultants or contractors, or cities and counties where erosion rates have been required for regulatory or management purposes. Some of these analyses were incorporated into Dolan and others (1985), and Griggs and Savoy (1985), where rates of change were presented on maps, and the long-term trends of erosion and accretion were summarized in an accompanying text. The Griggs and Savoy (1985) compilation has recently been updated (Griggs and others, 2005a), although most of the erosion hazards addressed therein pertain to coastal cliff and bluff erosion, with the exception of Southern California.

Since these earlier works, methods of obtaining, analyzing, displaying, and storing shoreline data have improved substantially, and coastal change has continued. Furthermore, coastal scientists have not agreed on standard methods for analyzing and reporting shoreline changes, nor have they identified rigorous mathematical tests that are widely accepted for quantifying the change and associated errors. Consequently, there are critical needs for (1) a nationwide compilation of reliable shoreline data including the most recent shoreline position, and (2) a standardization of methods for obtaining and comparing shoreline positions and mathematically analyzing the trends.

METHODS OF ANALYZING SHORELINE CHANGE

Compilation of Historical Shorelines

Coastal scientists in U.S. universities and government agencies have been quantifying rates of shoreline movement and studying coastal change for decades. Before GPS and lidar technologies were developed, the most commonly used sources of historical shoreline position were NOAA Topographic Sheets (T-sheets, see Shalowitz, 1964) and aerial photographs. Ideally, extraction of shoreline position from these data sources involves geo-referencing and removing distortions from maps or aerial photographs, followed by digitizing shoreline position. Depending on coastal location, data source, and scientific preference, different proxies for shoreline position are used to document coastal change, including the high water line (for discussion of the high water line (HWL) see Shalowitz, 1964), wet-dry line, vegetation line, dune toe or crest, toe or berm of the beach, cliff base or top, and the line of mean high water (MHW).

The USGS National Assessment of Shoreline Change analysis for California incorporates shoreline positions from 4 time periods and three unique data sources. To maintain consistency at a national scale, these four periods are mid- to late 1800s, 1920s-1930s, 1950s-1970s, and post-1997. Several organizations have provided the USGS with digital maps and/or shoreline data (Table 1). The historical shorelines from the 1850-1890s and 1920s-1930s were digitized from scanned and georeferenced historical T-sheets. In addition, shorelines were digitized from USGS Digital Raster Graphic (DRG) maps where data gaps in the T-sheets existed, as these were the only source of shoreline data that could be located for the data gap areas. These occurred for the third period (1950s-1970s) for most of Central and Northern California. The modern (post-1997) shoreline represents a MHW elevation derived from lidar data.

Shorelines were compiled for the state following the guidelines established for selected periods (mid- to late 1800s, 1920s-1930s, 1950s-1970s, and post-1997) as closely as possible. Table 2 lists the final range of years (and months where known) for shorelines compiled for each period by region.

Delineation of a Modern (Lidar-derived) Shoreline

The most recent shoreline used in this National Assessment (post-1997) was derived from lidar (Light Detection and Ranging) data. The USGS, in collaboration with NASA, has been using the NASA Airborne Topographic Mapper (ATM) to map coastal areas since 1997 (Krabill and others, 2000; Sallenger and others, 2003). The ATM surveys ground elevation using an elliptically rotating blue-green laser. GPS (global positioning system) positions and inertial navigation systems are used to correct for aircraft pitch, roll, and heading, providing ground elevations with accuracies of about ± 15 cm (Sallenger and others, 2003). The lidar surveys used to extract shorelines for this report were conducted either in 1998 or 2002 (Table 2).

To compare with historical shorelines, an operational MHW shoreline was extracted from the lidar surveys using a method developed by Stockdon and others (2002) (Figure 2). Shorelines were extracted from cross-shore profiles which consist of bands of lidar data 10 m wide in the alongshore direction and spaced every 20 m along the coast. A least-squares linear regression line is passed through the 2-D cluster of data that encompasses the operational MHW datum (Table 3) and is limited to the seaward-sloping foreshore. The regression equation is then used to derive the horizontal intersection of the operational MHW datum with the profile, giving the shoreline position for that profile. Repeating this procedure at successive profiles 20 m apart generates points that can be connected to create a continuous shoreline.

Table 1. Providers and original sources of historical shorelines for each California region.

Section	Organization	Original Data Source	Spatial Coverage
Northern California	NOAA Coastal Services Center	NOAA T-sheets	Oregon Border to Tomales Point
	U.S. Geological Survey	DRGs	
	NOAA Vectorization Project	NOAA T-sheets	
Central California	NOAA Coastal Services Center	Scanned NOAA T-sheets	Tomales Point to El Capitan Beach
	NOAA Vectorization Project	NOAA T-sheets	
	U.S. Geological Survey	DRGs	Tomales Point to Point Estero
Southern California	NOAA Coastal Services Center	Scanned NOAA T-sheets	El Capitan Beach to Mexico Border
	NOAA Vectorization Project	NOAA T-sheets	

Table 2. Dates of compiled shorelines in different regions for selected periods.

Region	Selected Periods					
	1800s	1920s - 1930s	1950s - 1970s	month	post-1998	month
Klamath	1859-1870	1926-1929	1955-1964	June, July	2002	Sept.
Eureka	1854-1870	1929	1956-1968	June, July, Aug.	2002	Sept.
Navarro	1870-1874	1929-1935	1957-1968	n/a	2002	Oct.
Russian River	1862-188	1929-1930	1952-1971	July, Nov.	2002	Oct.
San Francisco N	1853-1862	1929-1931	1952	July	1998	Apr.
San Francisco S	1853-1900	1929-1932	1946-1953	June, July, Aug. Oct.	1998	Apr.
Monterey Bay	1853-1910	1932-1933	1945-1952	July, Aug.	1998	Apr.
Big Sur	1876-1891	1933-1934	1947-1976	Mar., May, June	1998/2002	Apr./Oct.
Morro Bay	1871-1887	1934	1947-1976	Mar.	1998/2002	Apr./Oct.
Santa Barbara. N	1869-1888	1933-1934	1976	Mar.	1998	Apr.
Santa Barbara S	1855-1871	1932-1934	1974-1976	Feb., Mar., Oct.	1998	Apr.
Santa Monica	1857-1877	1933	1972-1974	Mar.	1998	Apr.
San Pedro	1859-1885	1920-1934	1971-1974	Mar.	1998	Apr.
Oceanside	1886-1889	1933-1934	1972	Mar.	1998	Apr.
San Diego	1852-1889	1933	1972	Mar.	1998	Apr.

To determine the operational MHW elevation, California was divided into 3 sections (Northern, Central and Southern California). For each section, the operational MHW elevation represents an average of MHW elevations from individual open-ocean or near open-ocean tide gauges (Weber and others, 2005). A list of tide gauges and MHW elevations used in each section is presented in Table 3. The lidar-extracted MHW shoreline is not necessarily the same as a MHW shoreline surveyed by a licensed land surveyor. This is because the operational MHW elevation used for the lidar shoreline is an average of the MHW elevations at several tide gauges. Furthermore, the lidar-extracted shoreline is intended only as a reference feature for measuring shoreline change. It is not intended to establish legal boundaries.

Because inland bays generally are not suitable sites for extraction of a lidar shoreline and because this report focuses on the open-ocean coasts, extensive bay areas such as San Francisco and Tomales Bay shorelines were not included in the shoreline change analysis. Also, lidar data were not available for all sandy beaches in California; gaps exist in Northern California along the sandy shorelines near Arcata and Eureka, as well as along a stretch of coast around San Simeon and Cambria in Central California. When lidar data are available for these gaps, the shoreline change analyses will be conducted and provided as on-line updates and in future reports.

Geographic Information System (GIS) Procedures

NOAA T-sheet indexes were used to determine T-sheet availability for shorelines that were not already available as ESRI ArcGIS shapefiles. T-sheets were then requested from NOAA and received as scanned TIF images. Existing digital shorelines for each period were compiled and a quality assessment was performed.

Scanned TIF image T-sheets were rectified using Erdas Imagine geographic imaging software by placing at least 6 well-spaced ground control points (GCPs) on selected T-sheet graticules in geographic coordinates. Some T-sheets produced before 1930 required additional coordinate transformation information from NOAA to convert from the United States Standard Datum (USSD) to the North American Datum of 1927 (NAD27). The datum transformation was applied to T-sheet graticule coordinates prior to rectification. Total Root Mean Square (RMS) error for the rectification process was maintained below 1 pixel, which is approximately 4 m at a scale of 1:20,000 and approximately 1.5 m at a scale of 1:10,000. Typically the resulting RMS was much lower than one pixel. Newly geo-referenced T-sheets were loaded in ArcGIS and shorelines were digitized. All shoreline vectors were converted to the Universal Transverse Mercator (UTM) projection with the North American Datum of 1983 (NAD83).

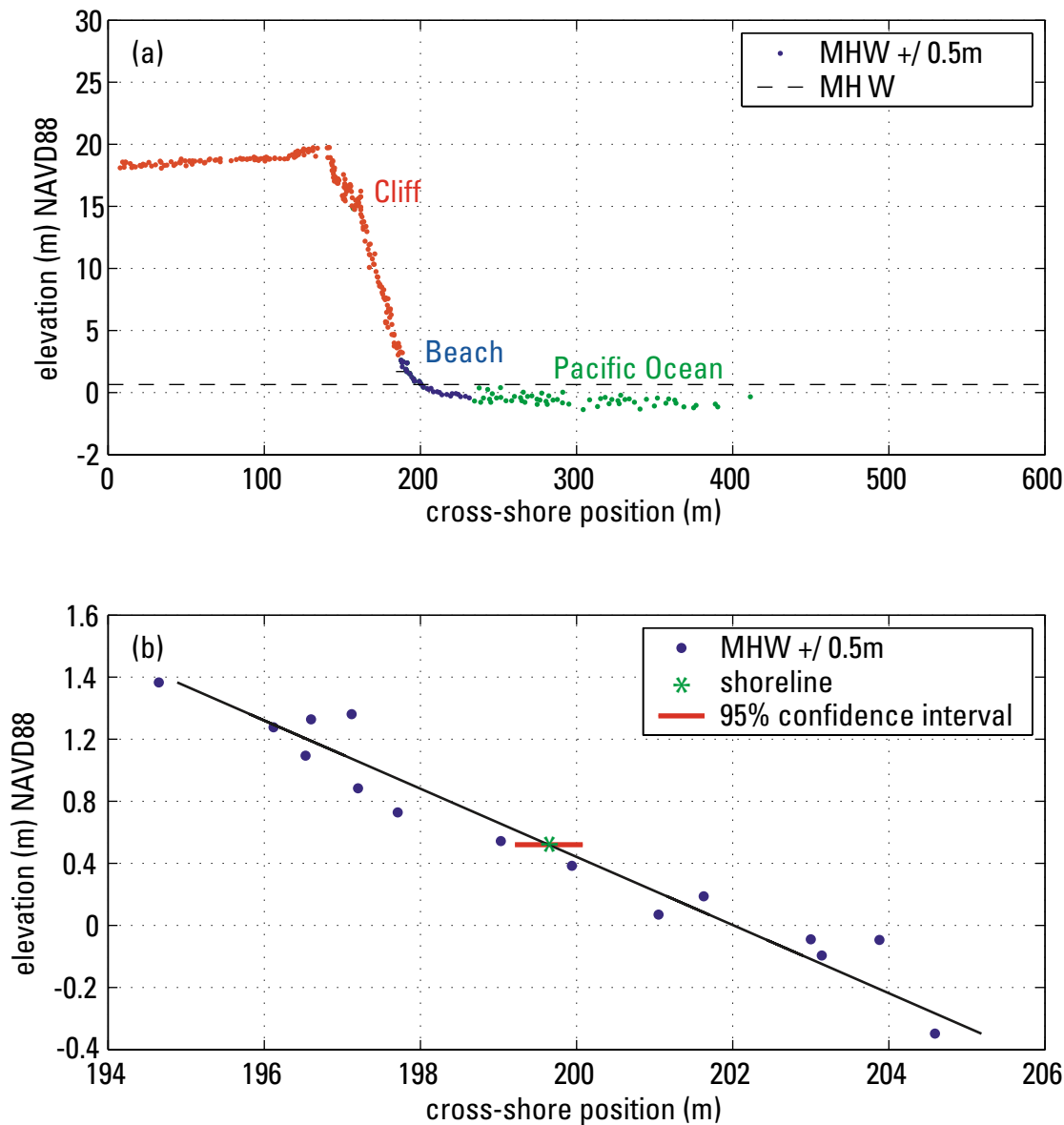


Figure 2. Example of a lidar profile from April 10, 1998 at Santa Cruz, California for (a) the entire cross-shore region and (b) an expanded view of the foreshore region. (a) Laser returns off of the water's surface are seen as green symbols seaward of $x = 230$ m. Blue symbols indicate data points within ± 0.5 m of the operational MHW datum. Red symbols indicate data points along the cliff face and top. (b) The asterisk marks the cross-shore position of the operational MHW shoreline on the foreshore. The horizontal error bar represents the 95% confidence interval about the estimate. After Stockdon and others (2002).

Shorelines from all sources were merged to produce a single shoreline for each of the 4 time periods by section of California (Northern, Central and Southern). Final shorelines were coded with 6 attribute fields (ID, Type, Date, Description, Source, and Accuracy) to prepare for calculating shoreline change rates with the Digital Shoreline Analysis System (DSAS; Thieler and others, 2003).

Calculation and Presentation of Rates of Change

Rates of long-term shoreline change were generated in a GIS with the Digital Shoreline Analysis System (DSAS),

an ArcGIS tool developed by the USGS in cooperation with TPMC Environmental Services. The tool is designed to efficiently lead a user through the major steps of shoreline change analysis. This ArcGIS tool contains three main components that define a baseline, generate orthogonal transects at a user-defined separation along the coast, and calculate rates of change (linear regression, endpoint rate, average of rates, average of endpoints, jackknife). The extension utilizes Visual Basic scripts to develop transects and rates, and uses the Visual Basic programming environment to automate and customize the user interface.

Baselines were constructed seaward of, and parallel to, the general trend of the four shorelines. The coastline of

Table 3. List of tide gauge measurements used to calculate mean high water elevation.

	Site Name	MHW above NAVD88 (m)	Average of MHW
Northern California	Crescent City, CA	1.80	1.81
	Trinidad Bay, CA	1.76	
	Arena Cove, CA	1.52	
Central California	Arena Cove, CA	1.52	1.46
	Point Reyes, CA	1.49	
	Monterey Harbor, CA	1.40	
	San Simeon, CA	1.43	
Southern California	Port San Luis, CA	1.37	1.33
	Santa Barbara, CA	1.35	
	Rincon Island, CA	1.34	
	Santa Monica, CA	1.35	
	Huntington Beach, CA	1.32	
	La Jolla, CA	1.28	
	Imperial Beach, CA	1.33	

California, and hence the baselines, are curvilinear. Using DSAS, transects were spaced 50 m apart. Transects were manually eliminated to prevent calculation of rates in areas where less than four shorelines were intersected. Fewer than four shorelines can result from one or more of the following conditions (Figure 3): 1) the position of a river mouth has changed or migrated, 2) shoreline segments were missing (data gaps), 3) a harbor or other coastal structure eliminated one or more of the shorelines, and 4) no lidar shoreline is available for rocky coasts.

Long-term rates of shoreline change were calculated at each transect using a linear regression applied to all four shoreline positions from the earliest (1800s) to the most recent (derived from lidar). Linear regression was selected because it has been shown to be the most statistically robust quantitative method when a limited number of shorelines are available (Crowell and others, 1997). It is also the most commonly applied statistical technique for expressing shoreline movement and estimating rates of change (Crowell and Leatherman, 1999). *Short-term* rates of shoreline change were calculated using the endpoint method comparing the 1970s and most recent (lidar-derived) shoreline positions. Long-term rates and short-term rates of shoreline change, as defined here, are used throughout the report.

Beach Alterations and Shoreline Definitions that Influence Rates of Change

Human Activities

Attempts to stabilize the shore can greatly influence rates of shoreline change. Activities such as beach nourishment or emplacement of shoreline stabilization structures tend to alter coastal processes, sediment transport, and shoreline position. For example, beach nourishment

artificially causes rapid, temporary shoreline accretion. Depending on the frequency of beach nourishment, the placement of large volumes of sand on the beach will bias the rates of observed shoreline change toward accretion or stability, even though the natural beach, in the absence of nourishment, may have an erosional trend. In addition, the emplacement of shoreline protection structures such as seawalls, bulkheads and revetments can result in both active and passive erosion of the beach. In the case of passive erosion, the back beach area is fixed by the structure, and the beach in front gradually narrows. Eventually erosion will cease (until the structure fails), thus indicating a stable shoreline in the shoreline change record. Active erosion associated with shoreline protection structures refers to the acceleration of shoreline erosion in front of a structure caused by the alteration of wave, tide and current patterns.

Clayton (1991), Flick (1993) and Wiegel (1994) provide a summary of identifiable beach nourishment projects on the U.S. West Coast that had been conducted up to the late 1980s. These records were used to identify shoreline segments that had been influenced by beach nourishment. Only projects that pre-date the lidar shoreline were included. There is no distinction made between large volume, continuous projects and small volume, finite projects. According to Flick (1993), Wiegel (1994), and many others, beaches along the coast of Southern California were extensively nourished from the early part of the 20th-century through the mid-1970s. Nourishment programs became far less frequent in the post-1970s era.

Differentiating between natural rates of erosion and the influences of beach nourishment is difficult because studies have not been conducted to specifically address this issue. In addition, available data may be inadequate to address this question because there are not enough shoreline positions immediately before, after, and between nourishment projects. Human responses to shoreline erosion, including beach

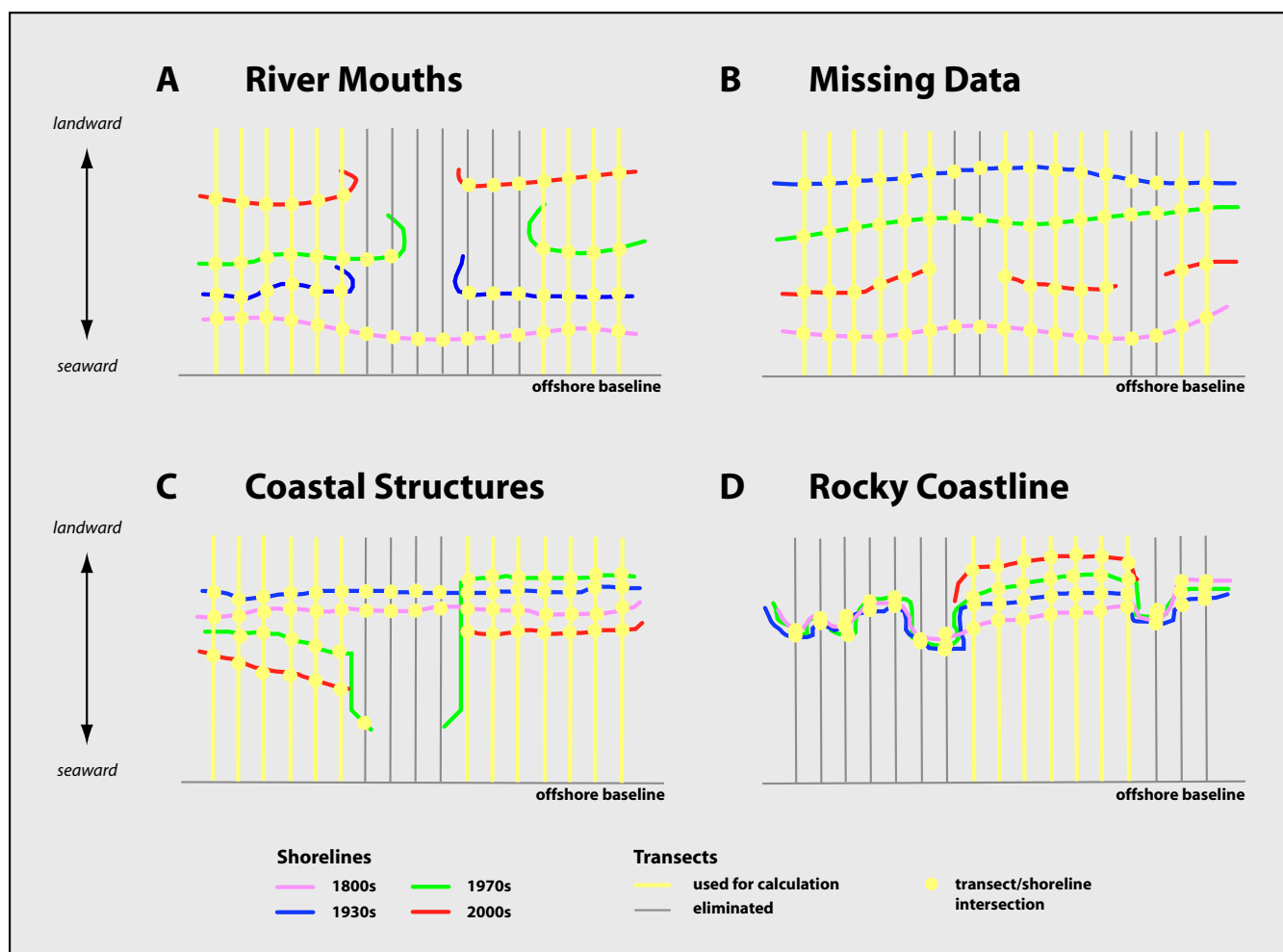


Figure 3. Examples of common conditions where transects are eliminated in the absence of four shoreline intersections.

nourishment and emplacement of structures, are included in the discussion of the results of the shoreline change analysis.

Shoreline Definitions

Inclusion of a lidar-derived shoreline represents a new approach to the investigation of shoreline change. The three pre-lidar historical shorelines come from topographic maps that use the HWL as the shoreline proxy. For more than 150 years, the HWL has served as the most commonly used shoreline because it could be visually identified in the field. With advanced technologies, such as GPS and lidar, it is now possible to objectively define the shoreline on the basis of an elevation or a tidal datum, such as MHW. Changing the shoreline definition from a proxy-based physical feature that is uncontrolled in terms of an elevation datum (HWL) to a datum-based shoreline defined by an elevation contour (MHW) has important implications with regard to inferred changes in shoreline position and calculated rates of change.

Morton and others (2004) first compiled published and unpublished data to evaluate the horizontal and vertical differences in HWL determined from beach profiles,

aerial photographs, or GPS surveys, and the MHW derived from beach profiles, GPS surveys, or lidar surveys. We have updated this to include the most recent available analyses (Table 4). The HWL and MHW positions were established at the same time, or within a few weeks of one another at multiple sites around the U.S. where the beach and wave characteristics are diverse. Comparing these HWL and MHW positions assumes that the observed proxy-datum offsets are entirely artifacts of shoreline definition and are not related to actual changes in the beach profile due to sediment transport (erosion or accretion processes) between the survey dates. This is a relatively safe assumption considering the short intervals between surveys or the knowledge that a particular shoreline segment is relatively stable. Moore and others (2006) avoided the need for this assumption by deriving HWL and MHW shorelines from aerial photography and lidar data collected during the same tidal cycle.

Table 4 shows that average absolute horizontal and vertical offsets between the HWL and MHW range from a few meters to more than 50 m, and vertical offsets can be as much as 2 m. Most of the horizontal offsets are less than 20

m, and most of the vertical offsets are less than 1 m. Offsets are typically greatest on relatively flat beaches where high waves produce high wave runup (i.e. southwest Washington). Conversely, offsets are least where beaches are relatively steep and wave runup is low. For the data analyzed by Morton and others (2004), the MHW was seaward of the HWL on virtually all of the transects (Table 4). This nearly systematic horizontal offset between the HWL and the MHW causes shoreline positions and calculated rates of change to imply slower erosion, a change from erosion to accretion, or faster accretion than actual shoreline movement can account for.

The recent study by Moore and others (2006) illustrated that overall, the importance of incorporating a proxy-datum offset into shoreline change analysis depends on several factors including the magnitude of the offset, the length of time over which rates are being measured and the statistical significance of the shoreline change rates. This proxy-datum offset is particularly important when averaging shoreline change rates alongshore. Since the proxy-datum offset is a bias, virtually always acting in the same direction, the error associated with the apparent shoreline change rate shift does not cancel during averaging and it is important to

quantify the bias in order to account for the rate shift. The shoreline change rates presented in this report have been calculated by accounting for the proxy-datum bias using the methodology described below.

Estimating the proxy-datum bias and the bias uncertainty

Comparison of HWL shorelines and a MHW datum-based shoreline for a single-day survey on Assateague Island (Moore and others, 2006) revealed an average horizontal offset between shoreline indicators of 18.8 m (Table 4). Vertical offsets were also substantial and were strongly correlated with foreshore beach slope. A simple total water level model, that combines the effects of tidal variations and wave runup, (Ruggiero and others, 1996; Ruggiero and others, 2001; Ruggiero and others, 2003) successfully reproduced these vertical offsets suggesting that the proxy-datum offset is primarily governed by wave runup. In order to estimate the proxy-datum bias for the State of California we use the approach outlined in Moore and others (2006) with the improvement of including the wave runup formula-

Table 4. Absolute horizontal and vertical differences between high water and mean high water shorelines (modified from Morton and others, 2004).

Location	Survey Date HWL	Survey Date MHWL	Length of Shore (km)	No. of Observations	Average Horizontal Offset (m)	Average Vertical Offset (m)	% MHWL with Seaward Offset	Data Source or Reference
Galveston Is., TX ¹	01-27-95	01-27-95	Point	1	18	0.6	100	
North Padre Is., TX ¹	08-16-95	08-16-95	1.6	6	8	0.4	100	Morton and Speed, 1998
	09-14-95	09-14-95	1.6	6	8	0.2	100	
	09-28-95	09-28-95	1.6	6	12	0.2	100	
	10-06-95	10-06-95	1.6	6	6	0.3	100	
Duck, NC ²	1994-1996 ²		Point	111	40	2.0	100	Pajak and Leatherman, 2002
Klipsan, WA ³	05-26-99	05-28-99	3.0	171	22	0.5	100	Ruggiero and others, 2003
	09-21-99	09-24-99	3.0	171	52	0.8	100	
Ocean Shores, WA ³	05-26-99	05-28-99	4.0	200	23	1.0	100	
	07-27-99	07-22-99	4.0	200	8	0.2	100	
	05-06-01	05-07-01	4.0	200	30	1.0	100	
Oysterville, WA ³	09-21-99	09-10-99	3.5	201	49	0.9	100	
Assateague Is., MD/ VA ⁴	03-16-98, 03-17-98	04-03-98	58.6	1172	11	0.7	99	National Park Service (M. Duffy)
	09-29-99, 10-28-99	10-01-99	60.0	1200	20	1.6	100	
	06-13-01, 06-14-01	06-05-01	52.4	1049	8	0.6	92	
	10-01-02	09-12-02	47.7	953	22	1.4	98	Coastal Research and Engineering, Inc. (M. Byrnes)
	05-06-02	05-06-02	47	470	18.8	1.2–1.3	100	Moore and others, 2006

¹ Simultaneous measurement of HWL and MHWL at beach profiles coordinated with tide gauge measurements

² Video camera projections of HWL for 111 days during a three-year period and MHWL from generalized beach profiles

³ Nearly simultaneous aerial photographs (HWL) and GPS surveys (MHWL)

⁴ Nearly simultaneous GPS (HWL) and lidar surveys (MHWL)

tion of Stockdon and others (2006). The horizontal offset between HWL and MWH shorelines can be estimated by:

Equation (1)

$$(X_{HWL} - X_{MWH})_{offset} = \frac{Z_T + 1.1 \left[(0.35 \tan \beta (H_o L_o)^{1/2}) + \left[H_o L_o (0.563 \tan \beta^2 + 0.004) \right]^{1/2} \right]}{\tan \beta} Z_{MWH}$$

where Z_T is the tide level, $\tan \beta$ is the beach slope, H_o is the deepwater significant wave height, and L_o is the deep-water wave length given by linear theory as $gT^2/2\pi$, where g is the acceleration due to gravity and T is the peak wave period.

In order to calculate the bias, as well as the bias uncertainty, for this regional shoreline change analysis, long-term best estimates and measures of uncertainty are derived for beach slope, wave height, wave length, and tide level. The best estimate for beach slope was derived by averaging individual lidar transect slope estimates within 1-km blocks along the coast. We take the long-term mean wave height and length to be the best estimate to use in the bias calculation. The long-term mean wave height is derived from USACE Wave Information Studies (WIS) hindcasts while the long-term mean wave length is derived from long-term buoy records (NDBC and CDIP) along the California Coast. Finally, the best estimate of the tide level responsible for generating HWL shorelines is taken as the elevation of MHW (see Table 3) (Weber and List, 2005). The measures of uncertainty for the beach slope, wave height, and wave length are estimated as the difference between the 95% exceedance statistic and the 50% exceedance statistic of the cumulative distributions. This gives a 90% confidence interval on each of the cumulative distributions. The uncertainty of assuming that the tide responsible for leaving HWL-type shorelines was at MHW is calculated simply by MHHW-MHW.

The proxy-datum bias, and the associated uncertainty, is calculated at each of the 1-km blocks in which the average beach slope has been calculated. The nearest WIS station, wave buoy, and tide gage to each individual 1-km block were used in the application of Equation 1. Once the bias was calculated, it was incorporated into DSAS and applied on a transect-by-transect basis, so that the estimated bias is removed from the final long- and short-term shoreline change rates. The bias, averaged over 815 1-km sec-

tions of the California coast, was approximately 18 m with an average uncertainty of approximately 8.7m.

Uncertainties and Errors

Documented trends and calculated rates of shoreline change are only as reliable as: (1) measurement errors that determine the accuracy of each shoreline position, (2) sampling errors that account for the variability of shoreline position, and (3) statistical errors associated with compiling and comparing shoreline positions. Anders and Byrnes (1991), Crowell and others (1991), Thieler and Danforth (1994), and Moore (2000), provided general estimates of the typical measurement errors associated with mapping methods and materials for historical shorelines, registry of shoreline position relative to geographic coordinates, and shoreline digitizing.

For this analysis we report estimates of individual shoreline position uncertainty (Table 5) and shoreline change uncertainty for the regional averages presented in Table 6A-C. Uncertainties associated with shoreline change on individual transects can be calculated using similar methods as are used for the regional averages as discussed below for both long- and short-term analyses.

The largest shoreline position errors were errors of ± 10 m, which were attributed to scales and inaccuracies in the original surveys (T-sheets) and typical positioning errors associated with DRGs (± 15 m). Stockdon and others (2002) provided estimates of GPS positioning errors (± 1 m) and regression errors (± 1.5 m) associated with derivation of the MHW elevation from the lidar data. A previously unreported error term in shoreline change analyses is the uncertainty in HWL shorelines due to variations in water levels. Our estimates of the uncertainty associated with the proxy-datum bias in effect quantify this error term for the first time. Following the methodology of Taylor (1997), Equation 1 was used to translate the estimates of the uncertainty of each parameter into an estimate of the uncertainty of the proxy-datum bias. Equation 1 can also be used to demonstrate that the uncertainty of the proxy-datum bias is equivalent to the uncertainty in any individual HWL shoreline.

Sampling errors relating to the local short-term variability of true shoreline positions (Morton, 1991; Douglas

Table 5. Maximum estimated measurement errors for California shorelines.

Measurement Errors (m)	Time Period*				
	1	2	3a	3b	4
Georeferencing (E_g)	4	4	4	4	--
Digitizing (E_d)	1	1	1	1	--
T-sheet survey/T-sheet, DRG position (E_t)	10	10	3	15	--
Shoreline position uncertainty (E_s)	8.7	8.7	8.7	8.7	1.5
Total shoreline position error (E_{sp}) (m)	13.9	13.9	10.1	17.8	1.5
Annualized short-term rate error (m/yr)	0.4				

*Time periods: 1=1800s; 2=1920s-1930s; 3a=1970s; 3b=1950s; 4=post-1997

Table 6A. Average shoreline change rates for Northern California

Analysis Region	No. of Transects		Average of Rates (m/yr)		Erosion Rate (m/yr)		% Erosion		Accretion Rate (m/yr)		% Accretion	
	LT	ST	LT	ST	LT	ST	LT	ST	LT	ST	LT	ST
Klamath	1430	1573	0.7±0.1	0.4±0.4	-0.4±0.1	-0.6±0.4	25	48	1.0±0.1	1.3±0.4	75	52
Eureka	493	652	0.7±0.2	0.4±0.4	-0.2±0.3	-0.9±0.4	4	51	0.7±0.2	1.8±0.4	96	49
Navarro	608	656	0.1±0.1	0.0±0.4	-0.1±0.1	-0.5±0.4	28	50	0.2±0.1	0.6±0.4	72	50
Russian River	435	483	0.2±0.1	0.4±0.4	-0.2±0.1	-0.4±0.4	28	35	0.3±0.1	0.8±0.4	72	65
No. California	2966	3364	0.5±0.1	0.3±0.4	-0.3±0.1	-0.6±0.4	23	47	0.7±0.1	1.2±0.4	77	53

Note: LT = long-term; ST = short-term

Table 6B. Average shoreline change rates for Central California

Analysis Region	No. of Transects		Average of Rates (m/yr)		Erosion Rate (m/yr)		% Erosion		Accretion Rate (m/yr)		% Accretion	
	LT	ST	LT	ST	LT	ST	LT	ST	LT	ST	LT	ST
San Francisco N	902	1039	0.1±0.1	-0.5±0.4	-0.2±0.1	-0.7±0.4	46	81	0.3±0.1	0.5±0.4	54	19
San Francisco S	1125	1150	-0.2±0.1	-0.5±0.4	-0.4±0.1	-0.7±0.4	76	81	0.1±0.1	0.5±0.4	24	19
Monterey Bay	1013	1031	-0.2±0.1	-0.6±0.4	-0.6±0.1	-0.8±0.4	41	77	0.4±0.1	0.3±0.4	59	23
Big Sur	512	533	0.0±0.1	-0.2±0.4	-0.1±0.1	-0.5±0.4	39	65	0.2±0.1	0.4±0.4	61	35
Morro Bay	447	458	0.1±0.1	-0.7±0.4	-0.1±0.1	-1.0±0.4	35	80	0.3±0.1	0.4±0.4	65	20
Santa Barbara N	1983	2267	0.0±0.1	-0.6±0.4	-0.2±0.1	-1.0±0.4	56	80	0.2±0.1	0.9±0.4	44	20
Central California	5982	6478	0.0±0.1	-0.5±0.4	-0.3±0.1	-0.8±0.4	53	79	0.2±0.1	0.6±0.4	47	21

Note: LT = long-term; ST = short-term

Table 6C. Average shoreline change rates for Southern California

Analysis Region	No. of Transects		Average of Rates (m/yr)		Erosion Rate (m/yr)		% Erosion		Accretion Rate (m/yr)		% Accretion	
	LT	ST	LT	ST	LT	ST	LT	ST	LT	ST	LT	ST
Santa Barbara S	1692	1760	0.1±0.1	-0.5±0.4	-0.2±0.1	-1.2±0.4	56	72	0.5±0.1	1.1±0.4	44	28
Santa Monica	1319	1504	0.4±0.1	-0.1±0.4	-0.1±0.1	-0.5±0.4	31	60	0.7±0.1	0.9±0.4	69	40
San Pedro	605	925	0.5±0.1	0.5±0.4	-0.3±0.2	-0.5±0.4	12	35	0.6±0.1	1.0±0.4	88	65
Oceanside	1561	1587	0.2±0.1	-0.1±0.4	-0.1±0.1	-0.6±0.4	31	67	0.3±0.1	0.9±0.4	69	33
San Diego	437	524	0.9±0.1	-0.8±0.4	-0.1±0.1	-1.0±0.4	21	90	1.2±0.2	0.5±0.4	79	10
So. California	5614	6300	0.3±0.1	-0.1±0.4	-0.2±0.1	-0.8±0.4	36	64	0.6±0.1	0.9±0.4	64	35

Note: LT = long-term; ST = short-term

and Crowell, 2000) are less well known. Along the California coast, as in many locales worldwide, there is pronounced cyclical erosion and accretion of the shoreline. This variability is driven by variations in wave conditions from summer to winter, years with severe versus average storms or swells, and episodic events like El Niños or hurricanes. In addition, the seasonal shoreline variability also has a high spatial variability, depending on the orientation of the coast with respect to the wave direction and effects of refraction or reflection from headlands, offshore islands and manmade structures. As a result, an uncertainty term quantifying seasonal shoreline variability for regionally averaged shoreline change rates is a rough estimate at best. Site specific, temporally dense data are required to evaluate short-term shoreline variability. The lack of reliable high frequency data regarding short-term variability (of true shoreline position) at most coastal sites limits the ability to quantify this uncertainty into the overall shoreline position uncertainty. Studies that do exist for California (Shepard, 1950; Bascom, 1954; Johnson, 1971) focus on changes in beach width or profile. An estimate of the variability in the position of the MSL intersect on the beach from eleven profile envelopes from La Jolla (Shepard, 1950) is approximately 9 m. In Monterey Bay, similar qualitative estimates from 9 profiles, surveyed over 15 years (Dingler and Reiss, 2002), suggests an average variability envelope of the MHW of approximately 40 m. However, these data include both the 1982-83 and 1997-98 El Niños and thus incorporate extreme conditions. One of the most extensive records to date is the 20-year record of beach profiles surveyed by the Army Corps of Engineers at Duck, N.C. Using 460 shoreline positions from the Duck profile data, Barton and others (2003) showed that the envelope of shoreline positions around a relatively stable shoreline was about ± 20 m.

Due to the lack of accurate, systematic data regarding the seasonal variation of the shoreline along the California coast, the error values reported here do not include an uncertainty term for the seasonal shoreline position variability in the quantification of errors associated with the regionally averaged shoreline change rates. For the long-term shoreline change analysis we assume that the seasonal variability in each shoreline is random and uncorrelated to the others and that the regression error will account for this uncertainty (see *Linear regression (long-term) shoreline change error* below). For the short-term analysis it is likely, at least in Northern and Central California, that due to the length of time over which our rates are calculated, the seasonal variability uncertainty term has a negligible impact on the total error value. In Northern and Central California, the shorelines from the most recent historical shoreline DRGs are based on aerial photographs from the 1940s and 1950s. Table 2 includes not only the years of the data sources, but also the months of the photography on which the T-sheet maps were based for the most recent historical shoreline. In Southern California nearly all of the source data are from the winter months, as is the lidar data. Therefore, the sea-

sonal variability term is again assumed not to have a measurable impact on the error term for the regionally averaged rates presented in this report. Independent comparisons of our shoreline change results with published rates in Southern Monterey Bay (Thornton and others, 2006) are in close agreement, even in the short-term. However, we recommend that anyone using the data associated with this report for a more site-specific analysis incorporate an error term to account for seasonal shoreline position variability.

Estimates of the maximum positional errors for this study are provided in Table 5 to show how each error contributes to inaccuracy in the shoreline position. The annualized error for short-term shoreline change is calculated and subsequently incorporated into the shoreline change rate calculations as outlined below. The uncertainty on the short-term (end-point) rates, using a best estimate for California shorelines is ± 0.4 m/yr (Table 5 and Table 6A-C).

End-point (short-term) shoreline change error

The total error for the end-point shoreline change rate, (E_{sp}) (Equation 2), is calculated by taking the square root of the sum of the squares (or adding in quadrature) of: georeferencing error (E_g), digitizing error (E_d), T-sheet survey or DRG error (E_r), and shoreline position error (E_p), similar to the methods outlined by Crowell and others (1993). Values for each of the error terms are given in Table 5. The georeferencing error represents the elected maximum acceptable RMS error for T-sheets at a scale of 1:20,000 in this study. The georeferencing error is applied to the historical shorelines that are derived from T-sheets only. The digitizing error reflects the maximum error specified in past studies (Anders and Byrnes, 1991; Crowell and others, 1991; Moore, 2000), and is applied to the historical shorelines only. The maximum T-sheet survey error, determined by Shalowitz (1964), incorporates all of the errors associated with the mapping process including distance to rodged points, plane table position, and identification of the HWL. The maximum DRG error is the stated accuracy of USGS Topographic Quadrangle maps from which the DRGs are derived; National Map Accuracy Standards give ± 15 m as the maximum acceptable error. The T-sheet survey error is applied to all historical shorelines; however, note that the error associated with the 1950s-1970s era T-sheets is considerably lower than the older T-sheets; this difference is based on findings by Ruggiero and others (2003), as well as the fact that more recent shorelines are derived from aerial photos or other sources. Shoreline position error is the maximum error associated with the derivation of the lidar shoreline (Stockdon and others, 2002) for lidar data and the average bias uncertainty (8.7 m) for the historical shore-

lines. Thus, the total shoreline position error as shown in Table 5 for each shoreline is expressed by:

Equation (2)

$$E_{sp} = \sqrt{E_g^2 + E_d^2 + E_t^2 + E_p^2}$$

A separate E_{sp} is calculated for each period. For the short-term shoreline change rates only these values can be combined and annualized to provide an error estimation for the shoreline change rate at any given transect. The annualized error (E_a) is expressed by:

Equation (3)

$$E_a = \frac{\sqrt{E_{sp1}^2 + E_{sp2}^2}}{\text{time}}$$

For determining short-term uncertainty error at a specific location (at an individual transect) we can add the uncertainty terms from Table 5 to get a total uncertainty of the shoreline change rate at a given location. Dividing this total by the time between shoreline dates provides the error on the short-term change rate at that location.

Linear regression (long-term) shoreline change error

Linear regression is the most commonly applied statistical technique for expressing shoreline movement and estimating rates of change (Crowell and Leatherman, 1999) where there are a statistically valid number of samples. Because linear regression fails to recognize the potential for temporal differences in trend (trend reversals) and accelerations or decelerations (Morton, 1991; 1996), average trends and rates of shoreline change in this study were calculated for both long-term (entire period) and short-term (most recent) time scales. Long-term rates of shoreline change were determined at each transect by taking the slope of the regression line applied to all four shoreline positions. The resulting rates are reported in units of m/yr (Table 6A-C). Uncertainties for the average shoreline change rates are reported as the $\pm$ values in Table 6A-C.

Two uncertainty terms arise in the calculation of the long-term shoreline change rates. The first term is the 90% confidence interval of the linear regression shoreline change rate for each transect. The second term arises from the uncertainty in our best estimates of the proxy-datum offsets. We calculate linear regression slopes using shoreline data that has been adjusted based on our best estimate of the proxy-datum bias as well as data that has been adjusted according to our best estimate of the $\pm$ the bias uncertainty. From this analysis we get a best estimate of the shoreline change rate and an uncertainty of the rate due to the bias uncertainty. At each transect we can add the regression error and the proxy-datum bias uncertainty error to get a

total uncertainty of the shoreline change rate at a given location.

However, in terms of calculating regionally-averaged shoreline change rate uncertainties the two terms discussed above need to be treated differently. Because the 90% confidence interval on the linear regression of each transect is assumed to be random and independent, when averaged over many transects the resulting average uncertainty associated with this term can be quite small; the greater the number of transects over which the uncertainty is averaged, the smaller the uncertainty on the average rate. However, for the second term we need to account for the fact that the proxy-datum offset is a bias and always acts in one direction. Therefore, the regionally averaged shoreline change rate uncertainty associated with the proxy-datum bias is simply the average value of the error resulting from the uncertainty of the proxy-datum bias. The regionally averaged total shoreline change uncertainty terms can be expressed by:

Equation (4)

$$U = \frac{\sqrt{\sum_{i=1}^n C_i^2}}{n} + \frac{\sum_{i=1}^n B_i}{n}$$

where U is the alongshore averaged shoreline change rate uncertainty, C is the linear regression 90% confidence interval, B is the shoreline change rate uncertainty associated with the proxy-datum bias, and n is the number of transects included in average.

Field observations and prior studies of shoreline movement within each analysis region in California suggest that the trends and relative rates of change presented in this study are as accurate as the methodology allows. Reliability of the mapped results increases as both the persistence of the trend and the magnitude of the rates increase. Stated another way, confidence in the analytical results is greatest where the rates of shoreline erosion or accretion are high and the trend has persisted for decades. On the other hand, confidence in the absolute results decreases where the shoreline is relatively stable and the rates of change are low. This is because minor differences in historical or lidar shoreline positions can substantially alter the regression line and the calculated results. Data confidence also decreases in areas where frequent trends reversals occur.

Advanced technology such as GPS and lidar can better constrain shoreline positions, reduce the methodological errors, and improve the accuracy (reduce the error) of future shorelines. Establishing a datum-based shoreline (lidar derived MHW) as the standard for comparison provides, for the first time, the ability to perform an error analysis that is both quantitative and meaningful, in terms of its application. In the future, each electronic MHW shoreline could be presented with an accompanying error bar that would define the alongshore envelope of confidence. Subsequent shorelines

and associated confidence envelopes would provide a more precise basis for determining the statistical significance of observed shoreline change. Unfortunately, the use of lidar or any other shoreline mapping technology will still require distinguishing between short-term variability in shoreline position and the long-term trend of shoreline change.

GEOLOGIC HISTORY AND SETTING

California straddles the boundary between the Pacific and North American tectonic plates (Figure 4). The diverse landscape and complex geology of the California coast is largely a result of the interactions between these plates. Lateral movement between the two plates occurs along the San Andreas Fault Zone (SAFZ), which extends nearly 1300 kilometers from the Gulf of California to Shelter Cove near Point Delgada in Humboldt County (Figure 5). Lateral movement on the fault zone averages 2.5-3 cm/yr (Harden, 1998) with a total accumulated displacement from slip during earthquakes and aseismic creep of at least 560 kilometers since lateral movement began about 15-25 million years ago.

Inman and Nordstrom (1971) recognized the importance of tectonic setting to the development of coasts worldwide. They developed a coastal classification scheme based upon the position of a given coast relative to plate movement. Within this classification scheme they recognized three first-order classes: collision coasts, trailing-edge coasts, and marginal sea coasts. Collision coasts (i.e. active margins) are characterized as being relatively straight and mountainous, having the presence of coastal cliffs and raised marine terraces, and bordered by narrow continental shelves. Coastal watersheds are typically steep and undergo high rates of erosion. Although the California coast south of Cape Mendocino presently borders a transform margin dominated by lateral movement, and is therefore not strictly collision controlled, it maintains many of the characteristics of a collision coast. Between Cape Mendocino and the Oregon border, the coast is a collision coast.

Movement along the SAFZ has created three broad geomorphic provinces (Figure 4) along the coast: Coast Ranges, Transverse Ranges, and Peninsular Ranges (California Geological Survey, 2002a). The northwest trending Coast Ranges run roughly parallel to the SAFZ and extend from the Oregon border in the north to the east-west trending Transverse Ranges in the south. The Coast Ranges are composed mostly of uplifted Mesozoic and Cenozoic marine sedimentary rocks that typically form a terraced and wave-cut coastline. The range is broken by the depression forming San Francisco Bay.

The Transverse Ranges trend roughly east-west and lie oblique to the general northwest trend of the California coast. They extend from the San Bernardino Mountains to the offshore islands of San Miguel, Santa Rosa, and Santa Cruz. Intense north-south compression from SAFZ move-

ment has resulted in very high uplift rates in this region (California Geological Survey, 2002a). Tertiary sedimentary rocks are the dominant rock type of the Transverse Ranges along the coast.

The Peninsular Ranges extend from the Transverse Ranges to the Mexican border, and, like the Coast Ranges, trend in a northwest direction. Along the coast they are composed mostly of Tertiary sedimentary rocks and further inland are characterized by Sierra Nevada-type rocks including granitics and older metamorphic rocks (Figure 6). The Los Angeles basin and offshore islands of Santa Catalina, Santa Barbara, San Clemente, and San Nicolas are considered part of the province.

To summarize, the features of the California coast have formed over millions of years of interaction between two large tectonic plates that continues today. Proximity to an active tectonic margin results in features such as: diverse rock types in close juxtaposition, high relief, high erosion rates of the land surface, and high rates of sediment supply to the coast. Block uplift and subsidence between high-angle reverse faults occur within the broader transform margin scenario. Segmentation of the coast through these types of vertical crustal movements, as well as horizontal (strike-slip) displacement forms important structural foundations for coastal sedimentary environments.

General Geology of the California Coast

The diverse morphology of the California coast is primarily a result of the local geology where lithology, geologic structure, and vertical tectonic movement play a prominent role in the configuration of the coast. Figure 6 is a generalized geologic map showing the major rock types of California (California Geological Survey, 2002b). Tertiary and Mesozoic sedimentary rocks are clearly the dominant coastal rock type; they are mostly marine in origin and represent sediment deposition, lithification, and uplift along the Pacific-American plate subduction / transform boundary. The Mesozoic rocks, which include the Franciscan Complex, are typically sandstone and shale from oceanic crust and deeper marine settings. The Tertiary rocks such as those of the Monterey Formation tend to be sandstone, shale, and conglomerate from more shallow marine environments closer to the continental margin. Crystalline rocks are also present along the coast and are most common near San Francisco and Monterey.

The strength of the rocks exposed along the coast is a critical parameter in determining the erodability of the coast (Benumoff and others, 2000; Hapke, 2005). Stronger rocks form prominent headlands that resist erosion and often form natural boundaries to littoral and aeolian transport. Weaker rocks erode more quickly and form embayments where coastal sediment may accumulate. Monterey Bay is an excellent example of an embayed coast where resistant rocks in Santa Cruz and Monterey (Figure 5) form headlands and the interior of the bay is backed by easily eroded



Figure 4. Major tectonic elements and geomorphic provinces of California (modified from California Geological Survey, 2002a and CGS website: (http://www.consrv.ca.gov/cgs/information/publications/teacher_features/faults.htm).



Figure 5. Index map showing locations of place names discussed in Geologic History and Geomorphology section.



Figure 6. Simplified geologic map of California (modified from California Geological Survey generalized geologic map available on-line at: <http://www.consrv.ca.gov/cgs/rghm/rgm/index.htm>).

Quaternary shallow marine, aeolian, and fluvial deposits. Coastal cliffs tend to be either high, steeply-dipping coastal mountains that plunge directly into the sea, or, broad near-planar marine terraces.

Marine terraces are prominent features for much of the California coast and are best developed where uplifted marine clastic rocks form the bedrock. Terrace preservation varies from moderate to poor in the other rock types that form coastal slopes including metamorphic, granitic, and ophiolitic terranes. Marine terraces form when coastal cliff retreat generates wave-cut platforms, most notably during sea-level highstands, and are preserved as a slightly seaward-sloping planar surface during tectonic uplift (Anderson and others, 1999). Local uplift rates, duration of marine planation, and terrace composition determine the width and elevation of the terraces - they are typically 10s of meters high and 100s of meters wide. The terrace surface often contains beach, dune, or alluvial deposits and when combined with terrace erosional material they can provide an important component of sediment contribution to the coast. Weaker rock types with an abundant sand component may contribute a significant amount of sediment to the beach system (up to ~10-30%; Hearon and Willis, 2002; Inman and Masters, 1991; Runyan and Griggs, 2002). Table 7 shows the approximate amount of different rock types for the cliffed portion of the California coast (~72% of the 1760 km long coast). Cliff retreat rates vary dramatically from very low in granitic terranes to several meters per year in cliffs formed in poorly-consolidated sediment. In addition to providing sediment to the coast, marine terraces are important features because of their low surface relief and proximity to the ocean they are the sites of numerous developments along the California coast (Griggs and others, 2005c).

Climate

The climate of California is strongly influenced by a persistent zone of high pressure in the north Pacific, a southerly flowing cold water ocean current, and the Sierra Nevada mountains, which block the continental air from affecting the coastal climate. During the summer months the northward migration of the semi-permanent North Pacific High diverts most storm tracks to the north. California

seldom receives rain from Pacific storms during the summer but coastal fog is widespread. Cold upwelling waters at the surface come into contact with the relatively warm moist air from the Pacific causing massive fog banks to form. During the winter the North Pacific High migrates southward directing storms towards California. Occasionally storms will arrive from the southwest and are accompanied by relatively warm temperatures and heavy rains (often referred to as the pineapple express). Average annual precipitation varies dramatically from north to south with 80 inches and above in the north and only about 10 inches reaching the San Diego area.

The seasonal weather patterns are modified during El Niño and La Niña events. During El Niños California's climate is typically characterized by above normal rainfall, warmer sea-surface temperatures, and large waves from Pacific-generated storms often resulting in increased beach erosion. The 1997-98 ENSO (El Niño – Southern Oscillation) was a significant climatic event responsible for widespread coastal flooding and beach loss (USGS/UCSC/NASA/NOAA Collaborative Research Group, 1998). La Niñas are generally accompanied by colder ocean temperatures, drier conditions, and less severe storms. El Niño's and La Niña's generally last for 6 to 18 months and their occurrence and intensity are related to longer term atmospheric variations termed the Pacific Decadal Oscillation (PDO). The PDO is an ENSO-like phenomenon that lasts for 20 to 30 years and consists of warm and cool phases (Zhang and others, 1997). The cool phase, which is likened to an extended La Niña, is characterized by a cool wedge of lower than normal sea-surface heights and ocean temperatures in the eastern equatorial Pacific resulting in cooler temperatures and lower rainfall in California. Conditions during the warm phase are reversed and are similar to extended El Niño conditions. Because phases tend to last between 20-30 years, with the last warm phase starting in 1977, some believe that we have entered a cool phase marked by the inception of the 1998/99 La Niña event as discussed in Hare and Mantua (2002).

Table 7. Coastal cliff rock type along the California coast (from Runyan and Griggs, 2002).

Rock Type	Km of Coast	% of Cliffed Coast
Pliocene Marine	688	39%
Unconsolidated Quaternary	480	28%
Miocene, Oligocene, Tertiary and Cretaceous Marine	335	19%
Older Metamorphic & Sedimentary (Franciscan)	177	10%
Granitic	53	3%
Tertiary and Miocene Volcanic	18	1%

Coastal Processes

Waves

Waves and currents are the primary forces that move sediment in the littoral zone and annual wave height variations are responsible for seasonal erosion and accretion patterns. Wave characteristics along the California coast depend on weather patterns, geographical effects such as offshore islands, storm climatology, coastline orientation and local bathymetry. The offshore wave climate of California is characterized by four regimes (Figure 7): Northern Pacific swell, Southern Hemisphere swell, northwest wind waves, and by locally driven seas (Storlazzi and Wingfield, 2005). North Pacific swell is generated by extra tropical storms, mid-latitude low-pressure systems, and cold fronts that originate in the North Pacific. Southern swell is dominant in the summertime and generated by winter storms in the Southern Hemisphere. Northwest wind waves generated by daily sea breeze conditions are more common in the northern part of the state and are strongest in the spring and early summer months. Local seas are driven by wind and storms along the coast. Given the variety of local and seasonal variations in wave climate, the predominant direction of nearshore sediment transport along the California coast is from north-to-south (Hearon and Willis, 2002). Wave climate varies along the California coast and can regionally summarized as follows (after Storlazzi and Wingfield, 2005):

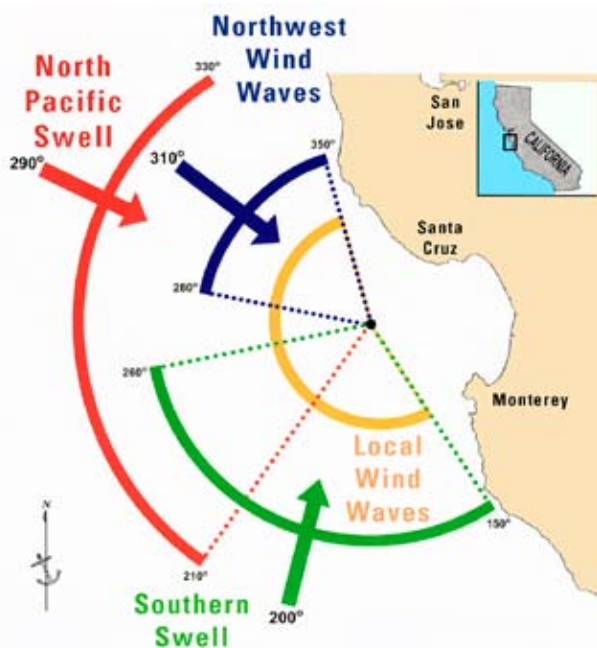


Figure 7. General wave directions for central California based on offshore wave buoy data (modified from Storlazzi and Wingfield, 2005).

In northern California the average wave height is greatest from November to February and averages about 3 m, with approximately 20% of the time wave heights are greater than 4 m. Summer wave heights are smaller with mean values around 1.8 m with waves higher than 4 m being extremely rare. Early winter is the most common time for waves to exceed 6 m. During El Niño winter months mean annual wave heights are 0.3 m – 1.2 m greater than normal winter months. El Niño driven storms typically approach from the west or southwest and may cause local littoral drift to the north – counter to the predominant southerly drift. La Niña winter months have slightly higher than average wave height values of 0.1 m – 0.4 m whereas during the summers wave heights are smaller than average.

Central California is a transition zone between harsh stormy waves of the northeast Pacific and milder conditions of Southern California. North Pacific Swell is the largest swell to impact the region with heights between 2m – 10m and periods ranging between 10 – 25 seconds. These waves, which are generated by storms in the North Pacific, occur most commonly between October and May. Northwest wind waves are generated from sea breeze and are dominant from April to October. The height of these waves typically varies between 1 and 4 meters with a period of 3 to 10 seconds. Southern Swell occurs between April and October and typical wave heights range from 0.3 – 3 m with a period of 10 – 25 seconds. Local wind-driven waves are generated by storms passing through central California. They generally occur between October and April with typical heights 1 and 4 meters and periods of 3 to 10 seconds.

In southern California peak wave heights are greatest from November to February and average about 2.4 m during this time. In the summer wave heights are smaller with mean values around 1.8 m. Waves greater than four meters occur about 11% of the time at Point Conception (Figure 5) and are most common during the month of March. Waves that damage the Southern California coast originate from extra-tropical storms in the northeast Pacific or Southern Hemisphere, although the second case is rare (Newberger, 1982). During El Niño winter months, wave heights at Point Conception are 0.7 m above average. In general, the southern region of the West Coast experiences more storms and higher wave energy during ENSO events (Seymour, 1998). Wave conditions along the southern California coast are extremely variable due to coastal configuration, bathymetry, orientation of coastline and the presence of several large offshore islands. Wave height measurements can be substantially different over distances of a few miles (Newberger, 1982). The Channel Islands block waves approaching from the south and Point Conception blocks waves from the north. Waves that propagate into the channel are severely refracted by irregular shallow bathymetry, producing large spatial variations in swell wave height and direction (Guza and O'Reilly, 2001).

Tides

California has a mixed semidiurnal tidal regime of two unequal high and low tides a day with total open-coast elevation changes of about 2.1 m in Crescent City and 1.6 m in La Jolla (Figure 5). The two daily high and low tides are unequal in amplitude with the lower-low tide of the day usually following the higher-high. The monthly tidal variations are dominated by the spring-neap cycle with spring tides occurring during full and new moons and neap tides occurring during half moons. The highest monthly tides during summer and winter months are higher than the highest tides in fall or spring. Tide ranges increase from the south to north along the coast and higher tide ranges occur in San Diego and San Francisco Bays than in adjacent open coast areas (Flick, R.E., 1998).

Tidal range influences beach processes along the California coast because it determines the extent of beach exposure and inundation throughout the tidal cycle. Especially crucial to beach erosion episodes are the timing and height of the highest tides in conjunction with the maximum wave height and surge developed during storms. Comparisons between impacts of the 1982-83 and 1997-98 El Niño storms on California's coast (Storlazzi and Griggs,

1998; Storlazzi and others, 2000) show that greater damage occurred in the 1982-83 event, in part, because the high tides were slightly higher and peak waves coincided with maximum high tides. The differences in tidal height between these two El Niño winters is primarily due to the 4.4-yr lunar perigee cycle with a small contribution from the 18.6 year lunar node cycle (Flick, 1998). This cycle enhanced peak high tides in 1982-83, 1986-87, 1990-91, 1995-96, and 1999-2000.

Long-term trends in California tide records are consistent with the general rise in mean sea level over the last century recorded throughout the world. Figure 8 shows long-term trends in mean sea level for selected California tide gauges as reported by the National Ocean Service (http://140.90.121.76/sltrends/sltrends_states.shtml?region=ca), and analyzed by Flick and others (2003). Both San Francisco and San Diego exhibit about 20 cm of sea-level rise over 93 years whereas Los Angeles exhibits a lower total rise of only 6 cm over 76 years. Crescent City, an exception to the sea-level rise trends, shows a relative sea-level fall of 3.2 cm over 66 years that is most likely the result of local tectonic uplift.

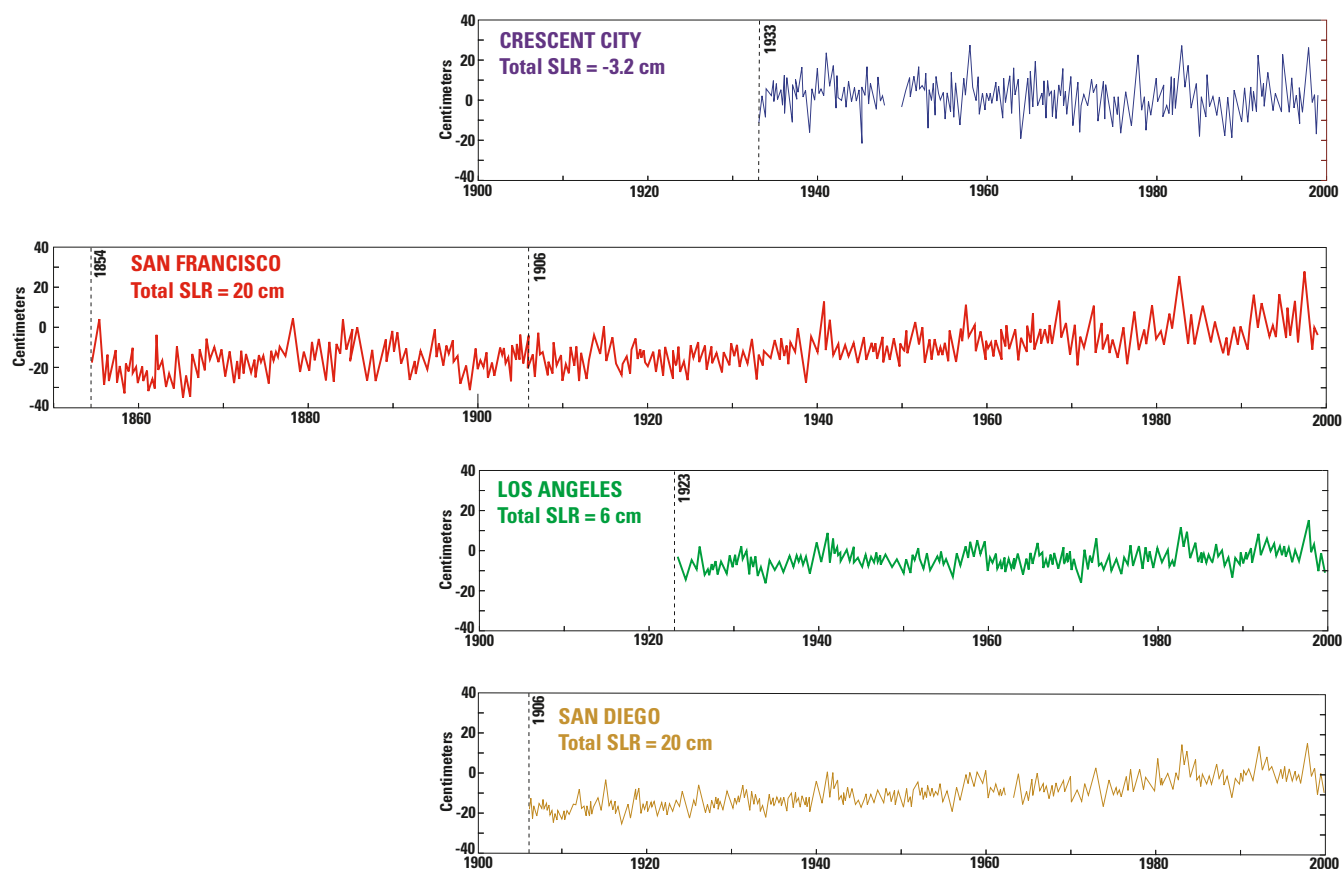


Figure 8. Monthly mean sea level for selected tide gauges along the California coast. Mean sea-level trends, based on the total sea level rise (SLR) for each site are: Crescent City -0.48 mm/yr, San Francisco +2.13 mm/yr, Los Angeles +0.84 mm/yr, and San Diego +2.15 mm/yr. Data are from the National Ocean Service.

Winds

Winds are important for generating waves that drive littoral sediment transport and for blowing sand off beaches resulting in potential sand loss from the littoral system. The wind climate of California is strongly influenced by the North Pacific High that creates a predominant northwesterly air flow over most of the state. The intensity and position of the North Pacific High often determines the direction and strength of winds affecting coastal California. The North Pacific High is stronger and located more northerly during summer months and moves south and weakens during winter months, allowing storms to reach the state. Coastal wind flow is predominantly parallel to the coast either from the northwest or the southeast. When winds are from the northwest, flow is along the coast but Ekman transport induces an onshore component, which is strengthened by local sea breezes (Zhiqian and others, 1997). Associated with northwest winds is the creation of a jet effect in the vicinity of some of the more prominent headlands. Strong jets of air and large eddies are projected around headlands such as Point Reyes, Point Sur, and Point Arguello (Figure 5). Wind speeds in the immediate vicinity of these major headlands can be two or three times as great as the wind flow at nearby areas.

In general, wind flow from the north is more aligned with the coast, the strongest flow is pushed offshore, and there is usually no associated daily sea breeze. During strong northern flows high wind speeds extends over a large area from Northern California to Point Conception. During northeast or east flow conditions the along-coast variability is significantly larger and winds are weaker (Zhiqian and others, 1997).

These wind patterns are altered by the passage of Pacific storms most of which arrive in the winter. As a storm approaches, the cold fronts are marked by strong easterly or southeasterly winds that can reach speeds of 50 km/hr or more. After the storm passes winds turn toward the southwest. With the passage of the rare warm front, storm winds can reach 30 – 40 km/hr. In Southern California, after the passage of a cold front, Santa Ana winds will often blow down from the north to northeast. These winds are sometimes extremely intense and can blow between 90 to 145 km/hr and extend 160 kilometers seaward. Although it is rare, when Santa Ana winds blow during the summer they produce hot and dry conditions that increase the fire danger.

Currents

The California current system forms the eastern edge of the North Pacific gyre and is primarily driven by wind stress patterns over the North Pacific Ocean (California Coastal Commission, 1997). Changes of the ocean circulation pattern are caused by the interactions between the

sub-tropical high pressure cell over the North Pacific and the atmospheric thermal low over California and Nevada. The interaction between these pressure regions results in a dominant southward-directed wind along the coast of California in spring and summer driving the California Current towards the equator (Hickey, 1979). Maximum southward wind along the California coast occurs between Cape Mendocino and San Francisco in the spring (Nelson, 1977). The associated Ekman transport moves water perpendicularly away from the coast allowing cold, nutrient-rich waters to upwell from the deep (Newberger, 1982).

During the late fall and early winter southward winds weaken, reducing upwelling and allowing a near-shore, northward-flowing current north of Point Conception called the Davidson Current, to prevail (Hickey, 1979). In the Southern California Bight (coastal Southern California and offshore waters) a counter-clockwise eddy occurs called the Southern California Countercurrent. It is a northwestward-flowing current south of Point Conception and inshore from the Channel Islands. The current runs shore parallel until it reaches Point Conception where one branch flows southwest joining the California Current and the other branch continues northward as a narrow countercurrent (Newberger, 1982). The Southern California Counter current occurs in all seasons but is best developed in winter (Maloney and Chan, 1974).

Littoral cells and transport directions

The prevailing southerly transport direction for California littoral sediment is driven by North Pacific swell and northwest wind waves (see Figure 7). There are local reversals in this prevailing direction due to orientation of the coast and/or southerly wave events. Littoral cells are segments of the coast with distinct sediment sources, defined longshore transport pathways, and sinks where the sediment is removed from the littoral system. Conceptually, the cell boundaries delineate an area where the sediment budget can be balanced for quantitative analysis. Southern California littoral cells were first defined by Inman and Chamberlain (1960) and statewide littoral cells were identified by Habel and Armstrong (1978). In California the cells are typically bound by either prominent rocky headlands that block littoral transport around them, or, submarine canyons that cross the continental shelf to a shallow enough depth as to intercept alongshore moving sediment. Submarine canyons are clearly the largest sink for beach sand loss in California with an estimated removal from some of the larger canyons at: Scripps and La Jolla – 270,000 m³/yr, Mugu – 765,000 m³/yr and Monterey – 230,000 m³/yr (Griggs and others, 2005b). Once sediment enters the submarine canyon system it is permanently lost from the littoral system. Another large sediment sinks are coastal dune fields where wind-blown sand is removed from the active littoral system. However, unlike submarine canyons, subsequent erosion of the dunes can re-supply adjacent beaches with sand. Figure 9 shows

the boundaries of littoral cells and coastal watersheds along the California coast. The boundaries between many of these cells, however, and the amounts and rates of sediment transport are poorly understood. Long-term harbor dredge records are one of the best long-term sources of longshore transport rates (Table 8) where harbor dredging is undertaken.

Sand Sources

The primary sources of coastal sediment for California are the fluvial drainage systems that reach the coast. These systems range from short, steep, ephemeral streams that deliver a wide mix of sediment grain sizes, to more mature rivers which often have well-developed estuaries. California's coastal streams have exceptionally high sediment loads due to the steep landscapes, geologically young and tectonically active terrain, and, in central and Southern California,

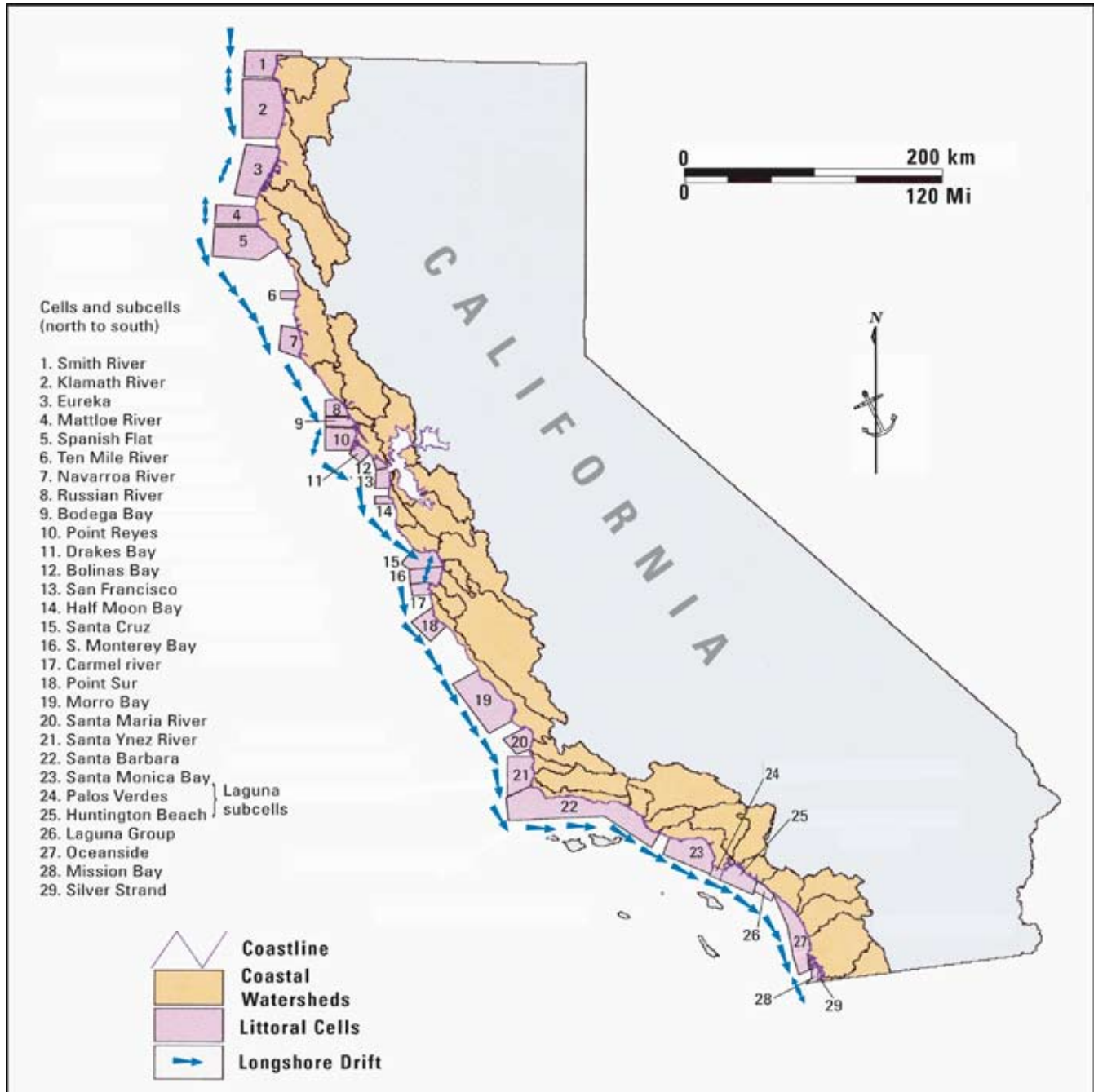


Figure 9. Map showing major littoral cell boundaries, coastal watersheds, and conceptual net longshore drift directions for the California coast, modified from Habel and Armstrong (1977), Griggs and others (2005b), and U.S. Army Corps of Engineers (2003).

relatively sparse vegetation cover (Willis, 2002a). Sediment yield per size of drainage basin for California rivers is typically very high when compared to other regions of the U.S.

Estimated sand and gravel discharge for the major California streams that enter the open coast is shown in Figure 10. Average annual bedload discharges range from a few thousand m³/yr for the smaller creeks to nearly 3 million m³/yr for the Eel River in northern California (Willis, 2002a and b) (Figure 5). These estimates should be considered maximum estimates of beach-quality material supplied from coastal streams because of numerous uncertainties and assumptions, and the fact that they include sand finer than 0.125 mm which is unlikely to remain in an energetic beach environment. In addition to the rivers shown in Figure 10, the large Sacramento and San Joaquin Rivers empty into San Francisco Bay (Figure 5), the largest estuary on the west coast. A large ebb-tidal delta has formed at the entrance to the bay. Numerous smaller ungauged streams also reach the coast and can supply significant amounts of sediment because of their steep, easily erodible watersheds (Willis, 2002b). On average 70 to 95% of the beach sand in California is derived from coastal streams (Runyon and Griggs, 2002; Willis, 2002a). In general, sand and gravel discharges from coastal watersheds decrease from north to south (primarily rainfall controlled), although the Transverse Range has a relatively high sediment discharge (lithology and vegetation controlled). Infrequent severe floods are thought to be responsible for delivering the majority of sediment to the coast and a single large storm can deliver more sand to the beaches than years of low to moderate rainfall. In addition, sediment discharge during extreme events can lead to open-coast ephemeral delta formation (Richmond, 1988) and delivery of abundant coarse-grained sediment. El Niño years are typically times of significant sediment introduction to the coast because of increased likelihood of extreme rainfall events (Inman and Jenkins, 1999).

Coastal cliffs are the next major source and sand supply varies with cliff lithology and strength. In some areas such as the Oceanside littoral cell, the coastal bluffs have been found to be a major source of beach sand (Young and Ashford, 2006). Softer cliffs composed of coastal sand deposits provide the most beach quality sediment when eroded. Subordinate sources of coastal sediment include

marine planation of submerged rock, material of biologic origin such as shells, and possibly onshore transport of relict shelf sediment.

GEOMORPHOLOGY OF THE CALIFORNIA COAST

The California coast encompasses a wide range of coastal landforms a product of complex geology and dynamic coastal processes. Coastal landforms include steep cliffs, uplifted terraces, beaches, dunes, barrier spits, estuaries and lagoons (Figure 11).

Cliffs

Nearly three-fourths of the California coastline are backed by cliffs which fall into two broad general categories: high steep cliffs and marine terraces. High cliffs occur where mountains directly border the coast such as along the Big Sur coast and most of northern California. The high cliffs may be hundreds of meters or more in height, they occupy about 13% of the California coastline, and are typically composed of more resistant rock types such as granite and rocks of the Franciscan Complex (Griggs and Patsch, 2004). Marine terraces and coastal bluffs, which were discussed earlier, form about 60% of the remaining coast and are common from Mendocino to San Diego. Where tectonic uplift has persisted, multiple terraces are often preserved.

Beaches

Beaches are ubiquitous features of the California coast and are important for a number of reasons: a) they act as a natural buffer that protects coastal land during storms, b) they are a valuable recreational and economic resource, and c) they provide habitat such as nesting sites for the endangered snowy plover and haul-outs for protected marine mammals. California beaches are not as long and continuous as those along passive margins (e.g. the U.S. South Atlantic and Gulf coasts) in part because the young and steep nature of the coast has not allowed enough geologic time for extensive sandy coastal plains to develop. Beach types found in California include pocket beaches, long expanses of linear to gently curved beaches, barrier spit beaches at stream mouths, and cusped headlands. Pocket beaches are bound by headlands, and occur in both small stream valley and cliffed-coast settings. Pocket beaches are probably the most common beach type in California, although their total length is smaller than the total length of California's linear beaches. Long expanses of beach typically front the major dune complexes, larger stream valleys, and coastal plain or concaved areas (e.g. Monterey Bay and

Table 8. Estimated annual littoral drift rates and directions along the California Coast (after Griggs and others, 2005b).

Location	Annual Rate (m ³)	Direction
Santa Cruz	230,000	East
Santa Barbara	230,000	East
Ventura	460,000-765,000	Southeast
Santa Monica	210,000	Southeast
Oceanside	270,000	South

Santa Monica Bay). Cluffed coastlines can be fronted by both permanent and seasonal beaches. Permanent beaches occur where there is abundant sediment supply, both along-shore and offshore. Seasonal beaches, which typically are present in the summer months and are lost during winter months, are common along exposed coasts with a limited offshore supply of sand.

Because of the relatively high wave energy and a steeper and narrower continental shelf along the California coast, pronounced deltas do not form. Instead, barrier spits and ebb and tidal bars develop where the streams reach the sea. Beaches that form at the mouths of stream valleys and embayments are typically a mixture of both fluvial- and littoral-derived sediment (mostly sand). The barriers are typically barren to sparsely vegetated indicating an unstable

substrate prone to occasional marine overwash and breaching. Seasonal changes in wave climate and rainfall result in a concomitant change in barrier style. In winter, periods of high waves and heavy rainfall cause overwash and channelization of the barrier spits, reducing their overall size. During the summer months, there are smaller waves and low precipitation and the barrier spits may completely block stream mouths due to reduced stream flow and beach accretion.

Seasonal beach change in California is caused by annual variations in wave climate that produce narrow beaches during winter months and wide beaches during the calmer summer months (Dingler and Reiss, 2002). Dramatic beach erosion, both in rate and amount, occurs during large storms. Subsequent recovery is less rapid, often

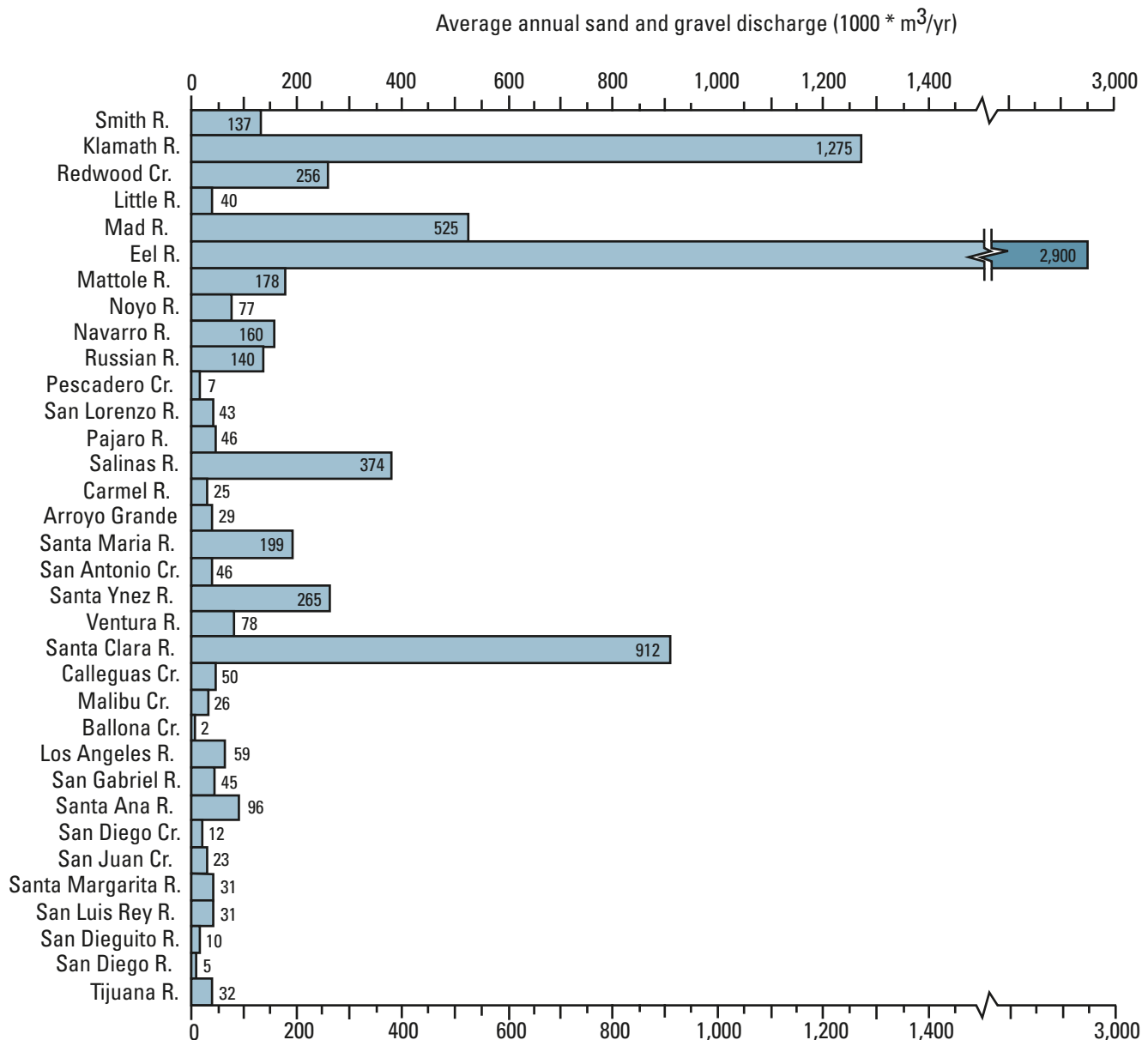


Figure 10. Average annual sand and gravel discharge from major rivers in California.

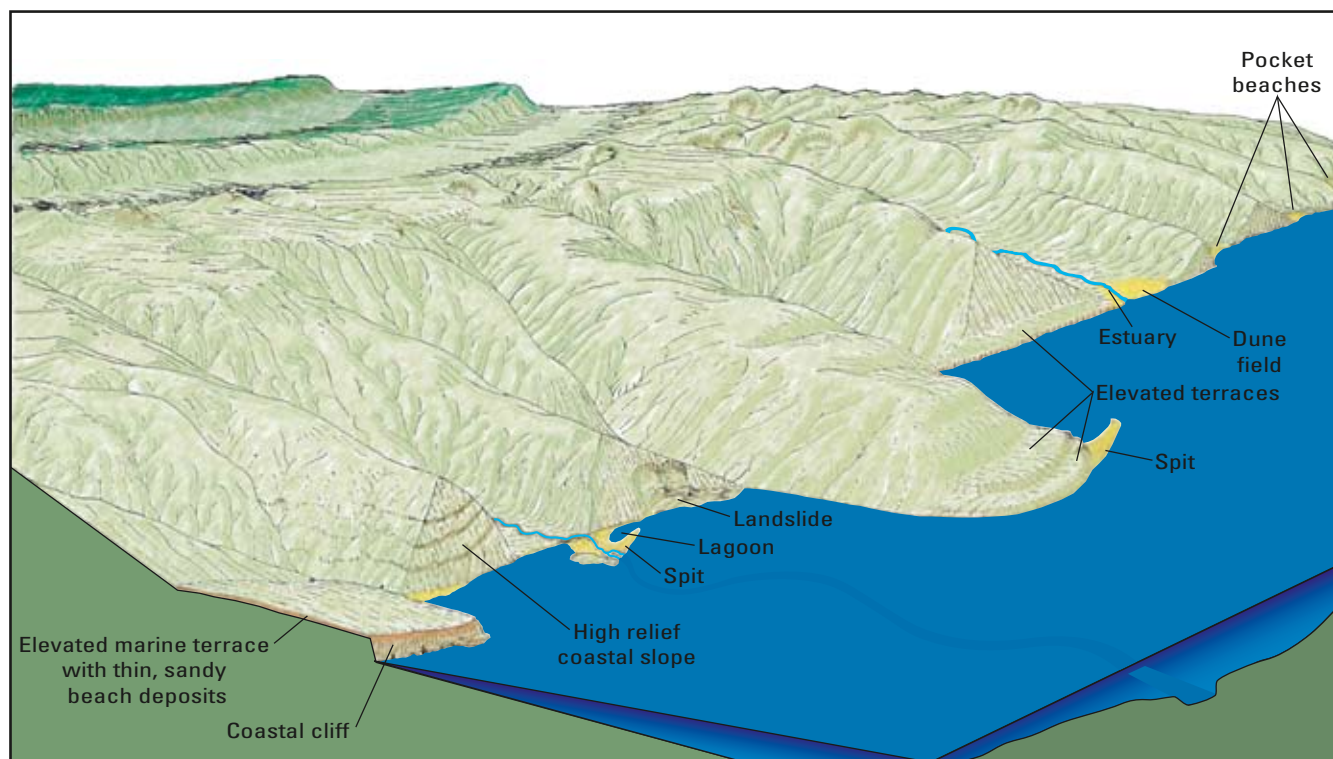


Figure 11. Sketch of common coastal landforms of California.

requiring several months for the beach to achieve its pre-storm configuration. Beaches without an abundant offshore sand supply take much longer to recover (Brown and others, 1998). Figure 12 illustrates the seasonal change in beach profile shape during the intense 1997-98 El Niño winter season at Cowells Beach in Santa Cruz.

Coastal Dune Complexes

Cooper (1967) mapped the coastal dunes of California and recognized that coastal dune complexes are best developed where there is: a) a nearby source of fluvial-supplied sediment, b) a structural high at the coast, such as a headland, to trap littoral drift or a low-relief stretch so dunes can migrate inland, and, c) strong consistent onshore winds. Orme (1992) further noted that dune fields are best preserved in coastal areas that have undergone net tectonic subsidence or limited uplift in the Quaternary. Aeolian deposits are often interbedded with fluvial and nearshore facies and the larger complexes represent multiple episodes of dune building. In many areas the modern dunes represent surficial deposits overlying older, and larger, dune systems. There is some indication (Orme, 1992) that significant coastal dune building occurs at lower sea-level positions when large quantities of sand are exposed on the emergent continental shelf.

Modern dune building removes sediment from the littoral supply; in some places this can be a substantial portion of the littoral sediment budget. For example, it has been estimated that about 150,000 m³ of sand are blown inland

each year along the 55 km stretch of coastline from Pismo Beach to Point Arguello (Figure 5) (Griggs and others, 2005c). Where the present coastline is undergoing retreat, such as in southern Monterey Bay, the dunes are reworked and supply sediment to the beach. The major dune complexes of California are shown in Figure 13 along with their effective wind directions.

Estuaries and Lagoons

U.S. West Coast estuaries and coastal lagoons typically form in drowned-stream valleys cut below the level of the uplifted coastal plain (Peterson and Phipps, 1992) or in subsiding coastal blocks. Four general types of estuarine/lagoon embayments occur in California: a) large embayments with high freshwater inflow, b) large embayments with relatively low freshwater inflow, c) large freshwater bodies with limited intertidal environments, and, d) ephemeral streams with limited estuarine environments.

The largest California estuary is the San Francisco Bay system that forms the outlet for the contiguous Sacramento-San Joaquin Delta watershed. This is a large embayment (~4,100 km²) with high freshwater inflow that drains more than 40% of the land area of the State of California (Chin and others, 2004). Bay environments include marshes, intertidal mudflats, and subtidal channels. The remainder of estuaries in California are much smaller in size but typically contain the same depositional environments.

Embayments currently with low fluvial input, such as Bolinas Lagoon, Drakes Estero, Tomales Bay, Bodega Bay,

Elkhorn Slough, and Morro Bay (Figure 5), appear to be structurally controlled depressions not presently connected to a major fluvial source. In these examples, the embayment size is large compared to present stream discharge. Embayment downcutting was probably enhanced during lower sea-level stands and the subsequent period of higher Holocene sea level resulted in bay infilling. At present, many of the morphologic bay features appear to be tidally controlled.

The major rivers of California are typically characterized by relatively high flow but narrow confined estuaries. These drainages are characterized by well-defined stream channels entering a restricted coastal depositional plain, and the location of the stream mouth is often controlled by a geologic feature such as a resistant headland. Intertidal environments are relatively limited in size because of extensive floodplain deposition (abundant sand). The rivers are the main suppliers of sand to the California coast (Figure 10). Fine-grained sediment typically bypasses the coastal zone and is deposited in deeper water. Ephemeral streams are similar to the larger rivers but on a smaller scale.

General Characteristics of the California Coast Sections

Northern Section: Oregon Border to Tomales Bay

The coast of Northern California (Figure 14A) can be characterized as a rugged landscape with high rainfall and low population. Steep coastal cliffs dissected by numerous streams result in high sediment loads delivered to the coast. Franciscan Complex rocks are common and the more resistant units often result in an irregular coast with steep cliffs, small offshore islands and sea stacks. Barrier spits and beaches are common features at stream valleys and embayments with the largest barrier in the region extending across Humboldt Bay. Large dune complexes occur south of Smith River, between the Little and Eel Rivers, and south of Tenmile River (Figure 13). Other large dune fields are present north of headlands at Point Arena and Bodega Head, and at the entrance to Tomales Bay (Figure 5). Marine terraces and wave-cut bluffs are common between the areas dominated by the steep mountain cliffs. The terraces south of Cape Mendocino are Holocene features that are undergoing rapid uplift. According to Savoy and others (2005), as much as 1 m of uplift occurred during a single earthquake in 1992 along the Cascadia subduction zone. The heads of Mattole and Delgada submarine canyons reach into shallow water where they can intercept littoral transport.

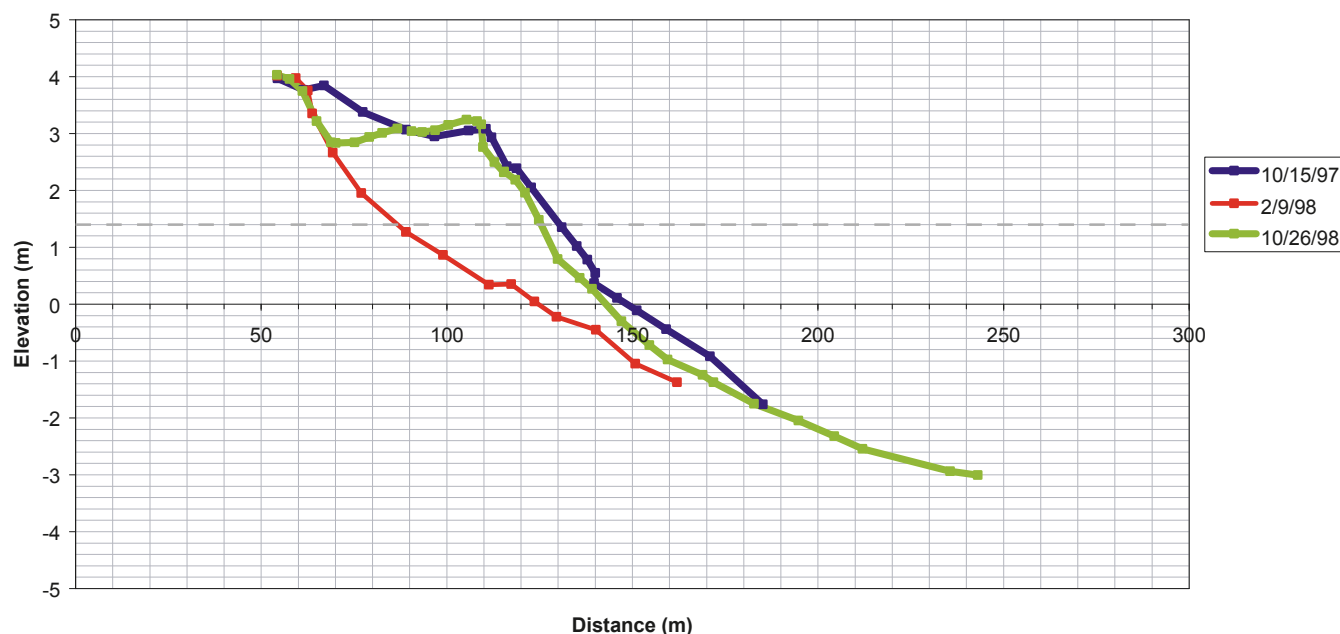


Figure 12. Beach profiles from Cowells Beach in Santa Cruz illustrating beach erosion over an El Niño winter and the subsequent recovery the following summer. The dashed gray line is the MHW elevation. From unpublished USGS data.

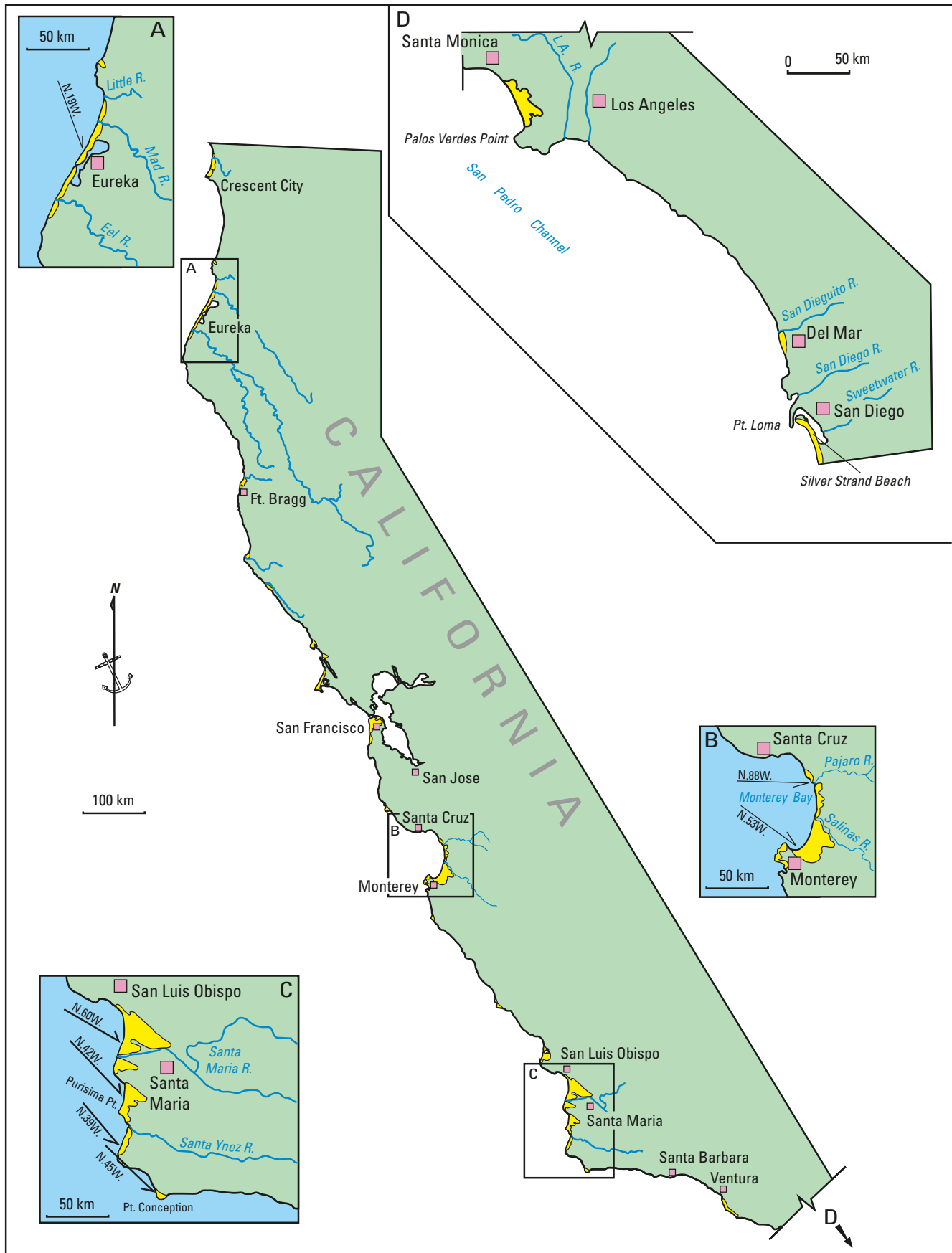


Figure 13. Map showing the major coastal dune complexes of California (modified from Cooper, 1967).



Figure 14A. Index map showing the four analysis regions in Northern California and various locations as discussed in the text.

Central Section: Tomales Bay to Point Conception

Central California (Figure 14B) is the most diverse coastal region of the state having characteristics of both the north and south regions plus a few unique features of its own. This section represents the transition zone between the relatively wet and high wave energy north and the drier and lower wave energy southern section. Unique embayments at Tomales, San Francisco, Monterey, and Morro-Estero Bays (Figure 5) form natural harbors along the rugged coastline. Marine terraces and coastal bluffs are well developed south of Point Reyes, in the Monterey Bay region, parts of the southern Big Sur coast, and stretches along the San Luis Obispo County coast. High relief coastal slopes occur at the Marin Headlands and Devils Slide north and south of San Francisco respectively, and along most of the Big Sur coast. Between Morro Bay and Point Conception, coastal mountains of the San Luis Range, Point Sal Ridge, and the Santa Ynez Mountains of the western Transverse Ranges alternate with intervening basins forming the greater Santa Maria basin. There are large dune complexes at Point Reyes, southern Monterey Bay, Morro Bay, and near the mouths of the Santa Maria and Santa Ynez Rivers (Figure 5). The Santa Maria and Santa Ynez Rivers are presently dammed resulting in a significant reduction of sediment reaching the coast from past conditions. The heads of Monterey, Carmel, and Partington submarine canyons lie just offshore where they are thought to be major sinks for beach sand moving alongshore.

Southern Section: Point Conception to the Mexican Border

The coast of Southern California, extending from Point Conception to the Mexican border (Figure 14C), is markedly different from the rest of the state. Point Conception marks a dramatic change in coastal orientation due to tectonic movement along the Transverse Ranges that has resulted in an east-west trending coast. Further south, the coast gradually returns to the northwest-southeast trend. Coastal cliffs and marine terraces are widespread and are typically fronted by narrow beaches. Unusual boulder deltas occur in the Santa Barbara area, notably at El Capitan and Rincon (Figure 5), and are thought to be remnant flood deltas at the mouths of steep mountain creeks. The largest river in this section in this section is the Santa Clara River with an estimated average annual sand and gravel discharge of 912,000 m³ (Figure 10). Other notable rivers are the Ventura, Los Angeles, and Santa Ana. There are a number of submarine canyons with heads near the littoral zone, including: Mugu, Hueneme, Redondo, Dume, Newport, Scripps, and La Jolla canyons (Figure 5). The narrow coastal plains of the Santa Barbara area are replaced

by broader plains in Ventura-Oxnard, Santa Monica - Los Angeles Basin, and Mission Bay to Imperial Beach. The dune complexes are not as well developed as those in the rest of the state but moderately large dune fields occur near Oxnard, north of Palos Verdes, and at Silver Strand - Imperial beaches (Figure 5). This section is the most urbanized stretch of coast in California.

HISTORY OF INFRASTRUCTURE DEVELOPMENT

The first European to visit the coast of California is widely held to be Juan Rodriguez Cabrillo, a Portuguese explorer who is credited with the “discovery” of California in 1542. The first permanent European settlement was established in what is now San Diego in 1769. Settlement of the coastal areas proceeded slowly in California, partly because of the dangerous nature of the Pacific coastal waters, and partly because access from inland was inhibited by the steep and rugged terrain. Northern California was settled primarily by Russian fur traders, and most coastal development in the State was restricted to large natural harbors such as San Diego Bay, Monterey Bay, San Francisco Bay and Humboldt Bay.

By 1850, the total population of California was only 93,000. Population grew over the years, but there was an explosion following World War II; the State’s population increased from 10 to 20 million between 1950 and 1970 (Pincetl, 2004) and in 2005 is about 36 million. Today, California is the most populous state in the union, and it is estimated that 80% of California residents live within 50 km of the coast (Griggs, 1994).

Much of the coast of Central and Northern California is very rugged, inaccessible and therefore undeveloped. This results in the focusing of developmental pressures over a smaller percentage of the coast resulting in variations in coastal hazards. Along much of the Northern California coast, the most important coastal hazards are large landslides that can damage coastal roads, and the rapid retreat of coastal cliffs where community infrastructure exists at the top or base of the cliff. Central California has a mixture of hazards; in addition to large coastal landslides and coastal cliff erosion, there are linear stretches of sandy shoreline that have been developed with homes and infrastructure. Southern California, which has the greatest percent of sandy shorelines also has the greatest percent of coastal armoring, engineering structures and nourishment programs. The wide, sandy beaches that exist today in Southern California were created and are maintained through a variety of coastal engineering projects and nourishment programs (Flick, 1993).

Practices such as damming coastal rivers and building various coastal engineering structures (groins, jetties and breakwaters) may be adversely affecting beach resources. During the post-World War II building boom, many homes

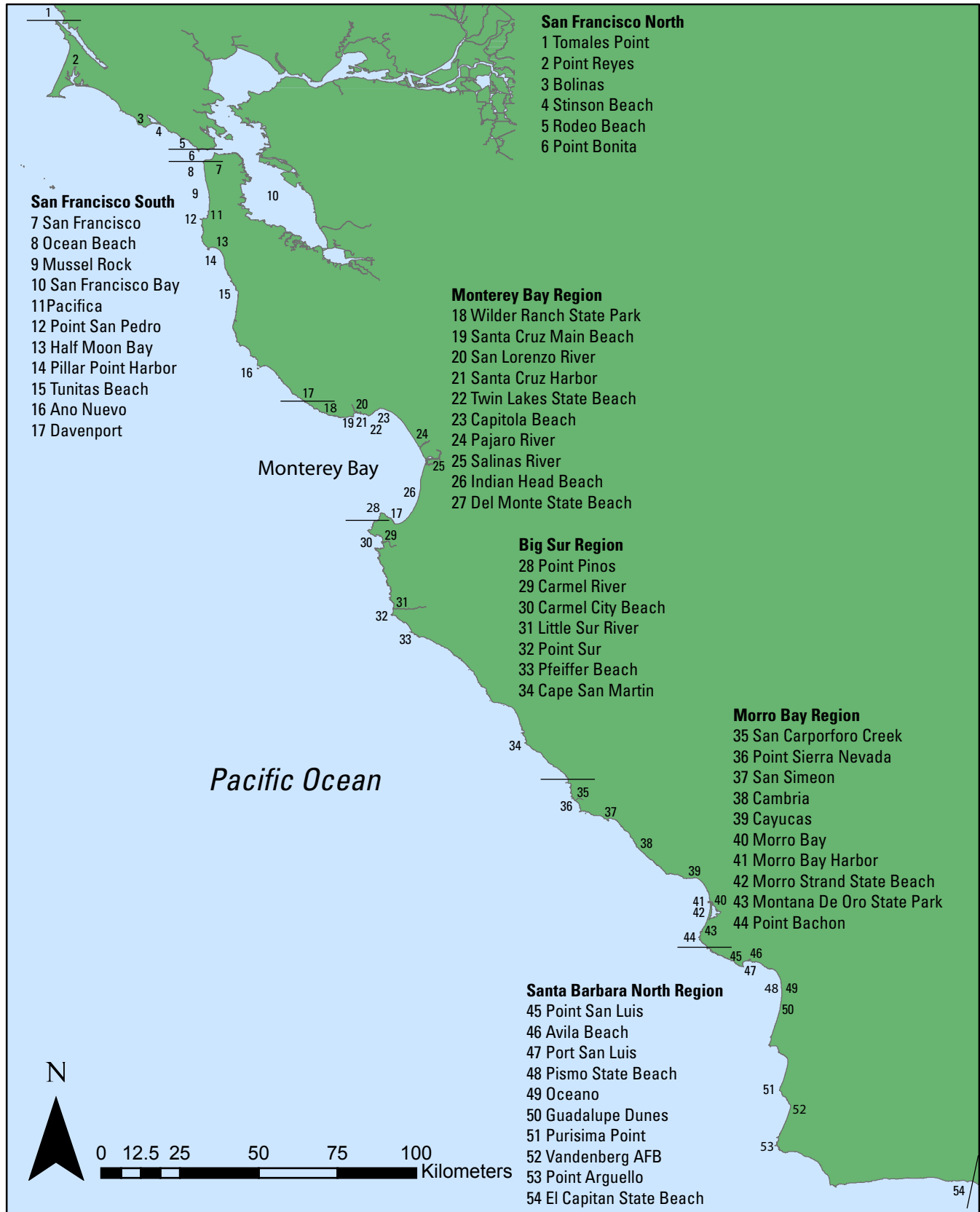


Figure 14B. Index map showing the six analysis regions in Central California and various locations as discussed in the text.

and communities were established on or near the coast, with houses often built on the sand, especially in Southern and parts of Central California. Eventually these homes were threatened by shoreline erosion, and the response was frequently to construct some type of protection structure. The California Coastal Act was passed in 1976, and with it the California Coastal Commission was formed. The Coastal Act requires statewide regulation and planning for coastal development, but also allows local governments to implement policies for coastal erosion hazard mitigation. The Coastal Commission has slowed the widespread emplacement of shoreline protection structures, but the Coastal Act states that such structures *shall be permitted* to protect existing development if it is threatened by erosion.

The post-World War II rapid increase in population and construction also coincided with a period of relative

climatic quiescence on the West Coast. The period from the 1940s through the early 1970s had no major El Niño events and average or below average number of damaging coastal storms (Storlazzi and Griggs, 2000). Rapid building took place near the coast during this time because it was considered desirable and not a high-hazard zone. This period also coincided with the development of several major coastal engineering projects in Southern California, which resulted in the addition of large volumes of sand to the beach systems. In the mid-1970s, the West Coast entered into a climatic period when the intensity and number of severe storms substantially increased. The destructive El Niño winters of 1982-83 and 1997-98 are evidence of this stormier period. Widespread damage to both public and private property occurred during those winters. According to Griggs and Fulton-Bennett (1988), total losses during the

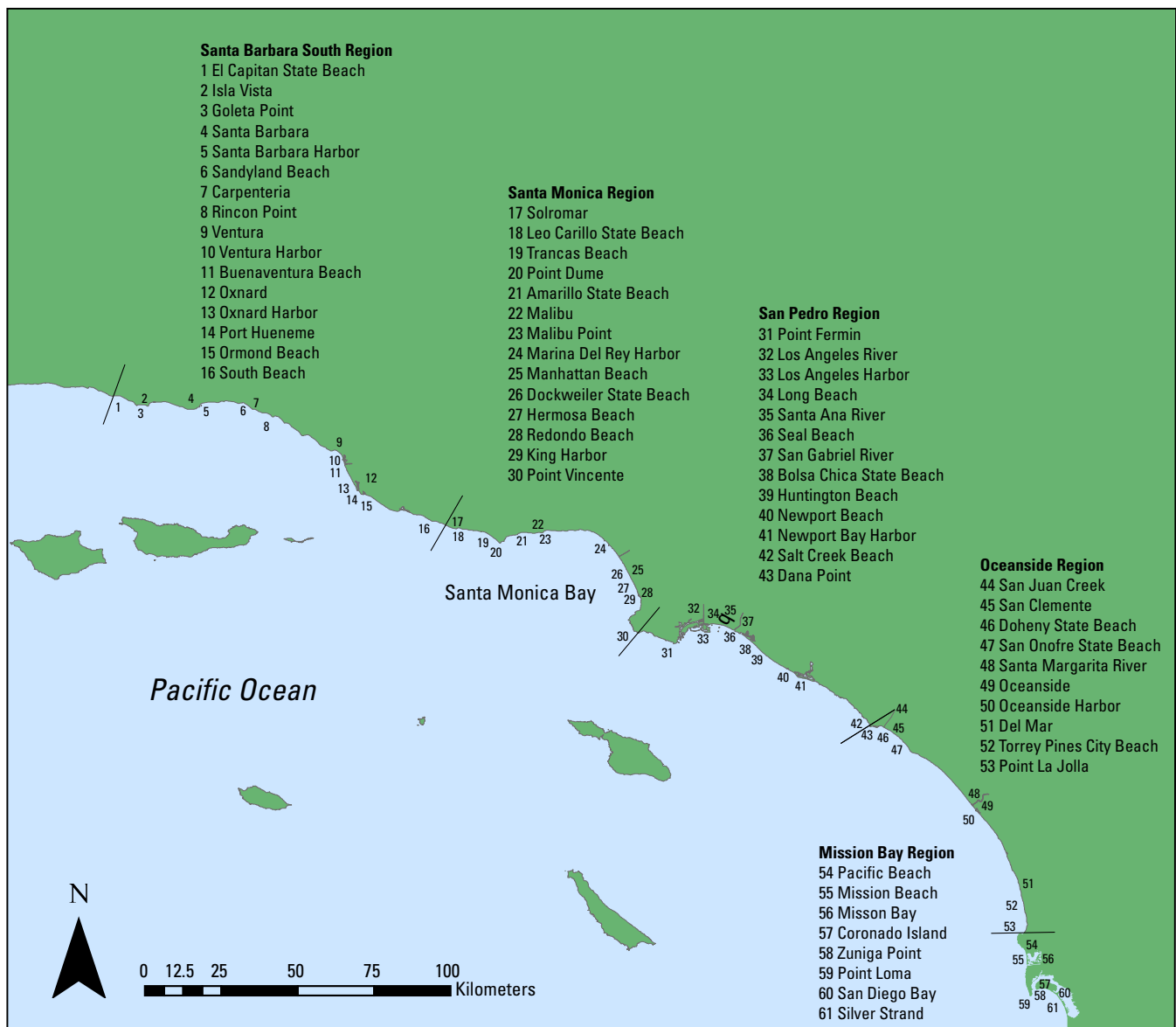


Figure 14C. Index map showing the five analysis regions in Southern California and various locations as discussed in the text.

winter of 1982-83 reached \$200 million (in 2006 dollars), and numerous houses, businesses and existing coastal protection structures were damaged.

HISTORICAL SHORELINE CHANGE ANALYSIS

This section presents the results of the California sandy shoreline (herein referred to as shoreline) change analysis and discusses, where applicable, the effects of engineering structures and beach nourishment programs on the rates of shoreline change. Each California section (Northern, Central and Southern) is subdivided into regions (Figure 1), which are based broadly on littoral cells and breaks in data coverage. Tables 6A-C summarize both long-term and short-term average rates of shoreline change within each region. Additionally, Tables 7A-C present the maximum and minimum erosion and accretion rates for each region in California.

The description of shoreline change includes information and discussion on human-induced changes. Most of the substantial erosion/accretion trends and/or reversals in trend are related to human intervention within the natural coastal system; these are virtually inseparable topics of discussion. In California, shorelines are eroding primarily because of an increase in storm intensity, sea-level rise, climatic changes, and as a consequence of human activities that disrupt the natural sediment supply.

In the discussions below, rates are referenced from Tables 6A-C and 7A-C, where shoreline change rates are presented as the region-average net rate for the *long-term* (1800s-1998/2001) and *short-term* (1950s/70s – 1998/2001) analysis, as well as by the magnitude of the erosion-only and accretion-only rates. Errors and uncertainty values are not shown in the text for clarity; refer to Table 6A-C for these values. To compare how net trends and rates may have changed from the long-term to the short-term, a statistical t-test was performed to determine whether the long-term and short-term rates were significantly different from one another at the 90% confidence interval. The t-test results found that in all regions except the San Pedro region, the change from long-term to short-term was statistically significant. Within the remaining 14 regions, the net shoreline change rate became more erosional from the long-term to the short-term with the exception of the Russian River region.

The average net rate of *long-term* shoreline change for California was 0.2 m/yr, an accretional trend. This is based on shoreline change rates averaged from 14,562 individual transects, of which 40% were eroding. Our analysis found that the only regions in California that experienced *long-term* negative net shoreline change were in Central California (San Francisco South and Monterey Bay regions), both with region-averaged rates of -0.2 m/yr (Table 6B). The highest region-averaged net rate was measured in the San Diego region (0.9 m/yr). Overall, Central California had

the lowest overall net *long-term* shoreline change, likely because of the lack of major coastal engineering projects, such as those that result in more accretional rates in Southern California by adding sediment to the littoral system. In addition, the high volumes of sediment input from rivers likely contribute to the lower overall erosional trend in Northern California. When the erosion versus accretion rates were separated out, the average *long-term* erosion rate for the state was found to be -0.2 m/yr.

The average net rate of *short-term* change for California was -0.2 m/yr, based on 16,142 transects, along which 66% were eroding. Negative (erosional) net *short-term* shoreline change was measured in 10 of the 15 regions. For those transects along which erosion was recorded, the average *short-term* erosion rate was -0.8 m/yr. The *short-term* average erosion rates were highest in Central California (Table 6B).

It is important to keep in mind that the change rates discussed in this report represent change measured through the date that the lidar was collected and thus may not reflect the most recent trends in shoreline change. In addition, although erosion rates in some areas are relatively low, many of California's beaches are narrow and even a small amount of local erosion may present serious hazards to the coastal resources and community infrastructure in a given area.

Northern California

The Northern California analysis extends from the Oregon border to Tomales Bay, a distance of approximately 550 km (Figure 1). For the presentation of the shoreline change analysis Northern California was divided into four regions: Klamath, Eureka, Navarro and Russian River (Figure 14A).

Much of Northern California is highly crenulated, rocky coastline with small sections of pocket beaches, except for near major river mouths such as the Klamath, Smith, Eel and Russian Rivers, and a few areas where steep coastal cliffs are fronted by narrow beaches. As a result of this geomorphology, there were many gaps in the data; the long-term change was measured along only 148 km of the shoreline, and short-term change over 168 km. Both long-term (0.5 m/yr) and short-term (0.3 m/yr) net shoreline change rates were accretional when averaged over all of the Northern California transects. Of the 2,966 transects along which long-term shoreline change was measured, 23% had erosional trends, with an average erosion rate of -0.3 m/yr (Table 6A). For the short-term analysis, the percent of beach eroding more than doubles, increasing to 47% and the average short-term erosion rate was -0.6 m/yr.

Klamath Region

The Klamath region covers approximately 112 km of coastline and extends from the Oregon border to Patrick's

Point (Figure 1). This region lies within the Smith and Klamath littoral cells (Figure 9), where rivers of the same names supply abundant sediment to the beach systems. The coastline here is sparsely developed, except for the area around Crescent City, and includes long stretches of State and National Park lands. The only significant engineering structures are the breakwaters protecting the Crescent City Harbor. According to Clayton (1991) there is harbor sand by-passing every several years; however the frequency is not consistent. In addition, the harbor was dredged in the 1970s, and material was placed north of the harbor to attempt to slow chronic bluff erosion (Savoy and others, 2005).

For the Klamath region, *long-term* change rates were measured along 71.5 km of shoreline. The net long-term rate, averaged over 1,430 transects, was 0.7 m/yr. Along those transects with a long-term erosional trend, the average erosion rate was -0.4 m/yr and was found along 25% of the coast. The average long-term accretion rate, which occurred along 75% of the coast in this region, was 1.0 m/yr (Table 6A). The long-term accretion rate in the Klamath region was the highest in Northern California. The maximum long-term erosion rate (-1.2 m/yr) occurred on the shoreline of a dynamic spit that extends across much of the Klamath River mouth (Table 9A).

The average *short-term* net shoreline change rate in the Klamath region is accretional (0.4 m/yr). Forty-eight percent of the coast along which short-term shoreline change was measured was erosional, and the average erosion rate was -0.6 m/yr. The remaining 52% of the measured coast in this region had a short-term accretion rate of 1.3 m/yr. The highest short-term erosion rate, -2.6 m/yr, was along Big Lagoon Beach, north of Patrick's Point (Table 9A; Figure 15). This area was heavily impacted during the 1982-83 El Niño winter storms (Figure 16), which may have influenced the short-term erosion rate.

The rate of net shoreline change in the Klamath region decreased from the *long-term* (0.7 m/yr) to the *short-term* (0.4 m/yr), and the percent of the coastline eroding increased from 25% in the *long-term* to 48% in the *short-term* (Table 6A).

North of the Crescent City Harbor, shoreline change becomes increasingly erosional in both the long- and short-term periods (Figure 15) near the harbor as opposed to areas further north. The highest accretion rates north of Crescent City were located immediately south of the Smith River mouth where there are extensive dune systems. There were local increases in the rates of accretion adjacent to the north and south breakwaters of the Crescent City Harbor (Figure 15). This area is composed of broad tidal flats, and the high rates may have been a function of the tide level when the shoreline data were collected.

South of the Klamath River mouth, the magnitude of shoreline change increased substantially. At the northern end of Redwood State Park where Ossagon Creek empties onto the beach at Gold Bluffs Beach, the highest accretion rates in the State were observed (4.8 m/yr long-term and 7.3 m/yr short-term). While most of the high accretion rates in other parts of the State were associated with engineering structures or beach nourishment, the accretion rates here were apparently natural.

Eureka Region

The Eureka region, which begins 6 km south of Trinidad Head and extends 74 km south to Cape Mendocino (Figures 14A and 17) falls within the Eureka littoral cell. Most of the coastline consists of sandy beaches as compared with the other Northern California regions. Long, linear beaches, dunes systems and spits have formed through deposition of sand by the Eel, Mad and Little Rivers. While still sparsely developed by California standards, the Eureka

Table 9A. Maximum and minimum shoreline change rates: Northern California

Region	Long-term (m/yr)	Location	Short-term (m/yr)	Location
Klamath				
Max. erosion	-1.2	Klamath River mouth, south side	-2.6	Big Lagoon Beach, 3.0 km north of Patrick's Point
Max. accretion	4.8	Gold Bluffs Beach, Prairie Creek Redwoods State Park	7.3	Gold Bluffs Beach, Prairie Creek Redwoods State Park
Eureka				
Max. erosion	-0.4	Eel River mouth, south side	-2.7	North Spit Beach, 0.8 km north of Humboldt Bay jetty
Max. accretion	2.5	Little River mouth, south side	4.7	Little River mouth, south side
Navarro				
Max. erosion	-0.6	DeHaven Creek Beach	-1.4	DeHaven Creek Beach
Max. accretion	0.7	Ten Mile Beach, 0.6 km south of the Ten Mile River mouth	3.3	Ten Mile Beach, north side of Ten Mile River mouth
Russian River				
Max. erosion	-0.7	Sonoma Coast State Beach, 1.3 km south of Russian River mouth	-1.6	Sonoma Coast State Beach, 1.5 km south of the Russian River mouth
Max. accretion	1.8	Dillon Beach	3.5	Dillon Beach

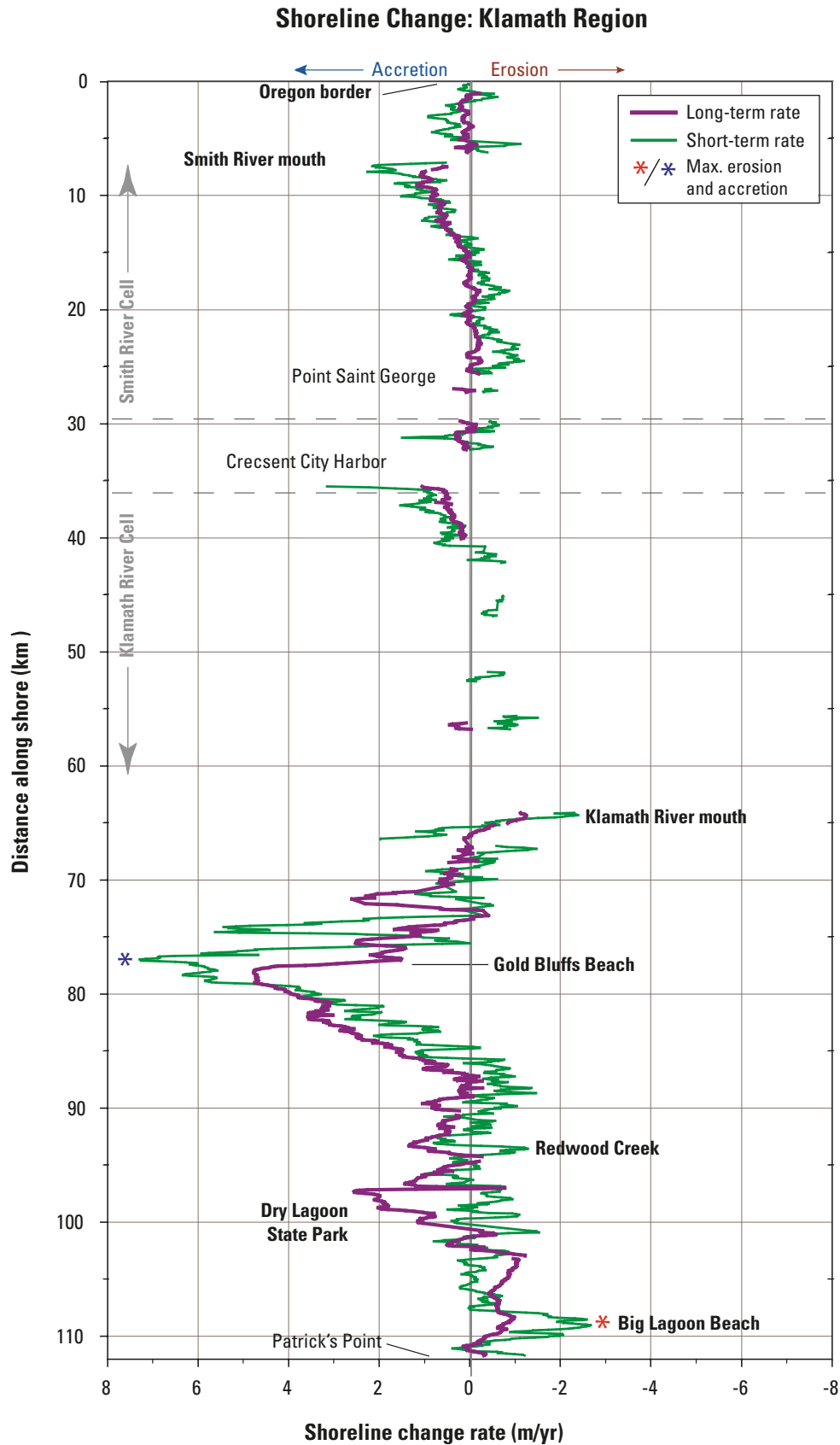


Figure 15. Shoreline change rates for the Klamath region. The maximum long-term erosion rate was -1.2 m/yr on the south side of the Klamath River mouth, and the maximum short-term erosion rate of -2.6 m/yr was measured at Big Lagoon County Park Beach.



Figure 16. Bluff erosion at Big Lagoon Beach after an El Niño storm in the winter of 1983 (photo: Gary Griggs, UCSC).

region, which includes the towns of Arcata and Eureka, is the most developed and populous coastal area of the Northern California regions. Humboldt Bay Harbor lies between Eureka and a seaward barrier spit and is the largest harbor in Northern California; jetties were constructed there in the 1800s to keep a channel in the spit open for boat traffic. North Spit and South Spit now converge at the Humboldt Bay jetties; unfortunately there is a gap in the lidar data for the spits, except immediately adjacent to the jetties. Therefore, we were unable to calculate long- or short-term rates for 18 km of sandy shoreline along the spits.

The *long-term* net shoreline change rate for the Eureka region was 0.7 m/yr, an accretional trend similar to that measured for the Klamath region. Virtually all of the shoreline was accreting at a long-term average rate of 0.7 m/yr, observed along 96% of the measured shoreline. The average long-term erosion rate for the Eureka region is -0.2 m/yr (Table 6A). Of the total 24.7 km of sandy shoreline that was measured, long-term erosion occurred along only 4% of the coast. The highest erosion rates were measured on either side of the Eel River mouth, where a maximum long-term rate of -0.4 m/yr, was observed (Table 9A).

Short-term net average shoreline change rates for the Eureka region, measured along 32.6 km of coastline, were 0.4 m/yr, a less accretional trend from the long-term rates. The average short-term erosion rate was -0.9 m/yr (Table

6A) and was measured along 51% of the analyzed coast. The average short-term accretion rate, 1.8 m/yr, was the highest average accretion rate in the State, and was measured along 49% of the analyzed coast.

Short-term change rates varied along coast, and were predominantly erosional near the Mad River, the North Spit of Humboldt Bay, and south of the Eel River. The maximum erosion rate (-2.7 m/yr) in this region was along North Spit Beach, immediately north of the Humboldt Bay jetty (Figure 18).

The highest accretion rates (both long- and short-term) occurred in the northern portion of the region, on the south side of the mouth of the Little River (Figure 17; Table 9A), along Little River State Beach. The beach here is backed by a substantial dune system. Similarly, in the southern part of the region, within the Eel River State Wildlife area, there was a strong accretional trend in both long- and short-term rates in an area that is backed by substantial dunes.

Navarro Region

The Navarro region extends along 207 km of coastline and contains both the Ten Mile and Navarro littoral cells (Figure 9). This section begins approximately 11 km south of Point Delgada and ends at Point Arena (Figures 14A and 19). The towns of Fort Bragg and Mendocino are

Shoreline Change: Eureka Region

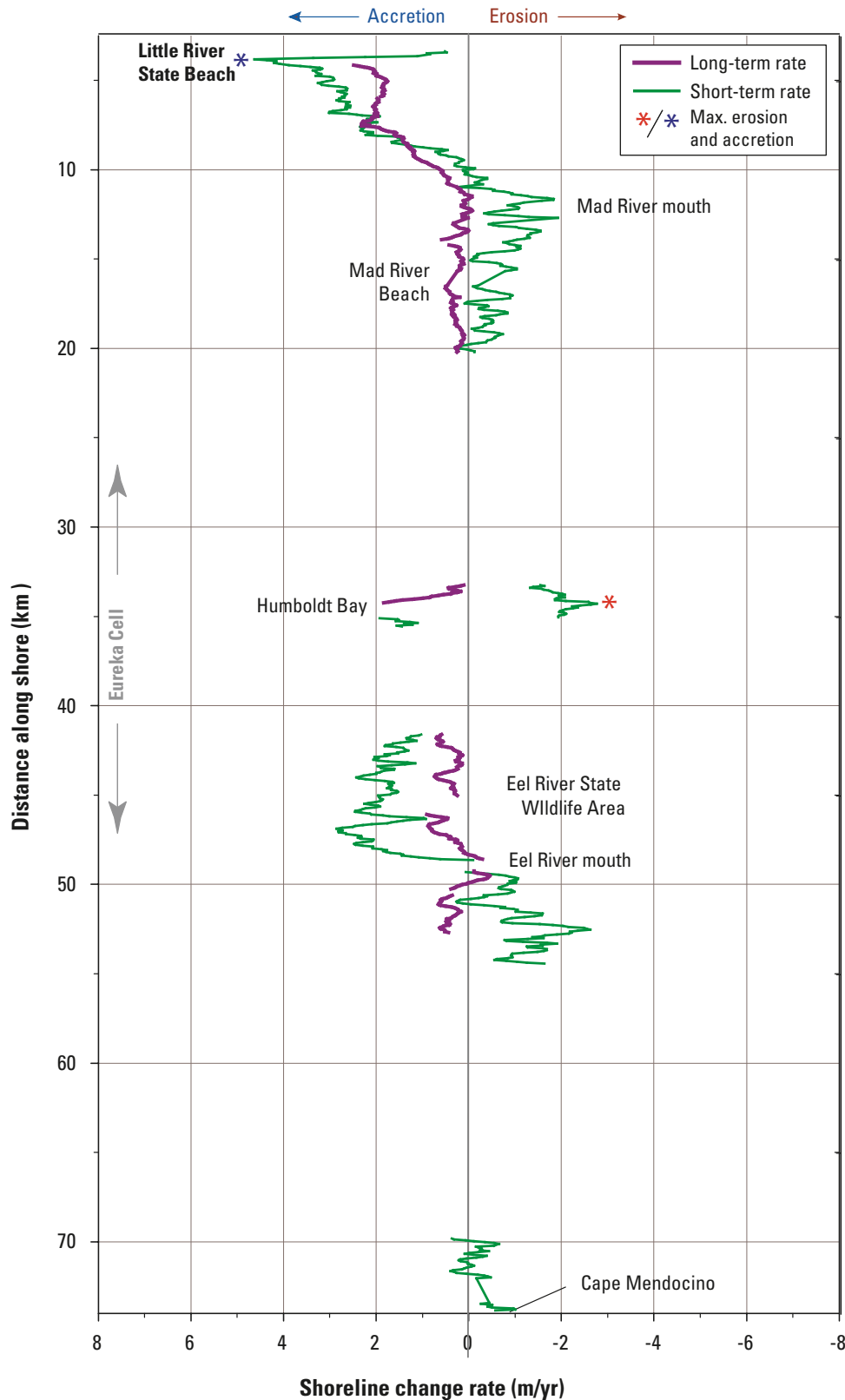


Figure 17. Shoreline change rates for the Eureka region. The maximum long-term erosion rate was -0.4 m/yr on the south side of the Eel River mouth, and the maximum short-term erosion rate of -2.7 m/yr was measured along North Spit Beach.



Figure 18. Spit and jetty on north side of Humboldt Bay Harbor in photograph taken in June 1987. North is to the left in the photograph. (photo: Copyright © 2002-2005 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.californiacoastline.org)

located within the Navarro region; otherwise, this stretch of coastline is very rugged, inaccessible, and there is little development. The only major coastal engineering structure along this coast is the breakwater at the Noya Harbor, on the south side of Fort Bragg. With a few exceptions, the coast in the Navarro region is crenulated and rocky with steep cliffs; there are some scattered pocket beaches and occasional narrow beaches fronting the cliffs that generally are not passable at high tide. Exceptions include the extensive beach and dune system south of the Ten Mile River mouth (Mac Kerricher State Park) (Figure 20), and several beaches formed in the vicinity of larger creek mouths, such as Westport-Union Landing State Beach, and Manchester Beach State Park (Figure 14A).

Of the 207 km of coastline in this region, only 31.5 km had measurable sandy shorelines for our *long-term* analysis, due primarily to the lack of continuous beaches. The net *long-term* shoreline change was accretion that averaged 0.1 m/yr. This rate was much lower than the average rates for the Eureka and Klamath regions discussed above. Along those transects where erosion was measured, the average long-term erosion rate was -0.1 m/yr, averaged along 28% of the coast (Table 6A). Long-term accretion, measured along 72% of the coast, averaged 0.2 m/yr. The maximum long-term erosion rate (-0.6 m/yr) was located within DeHaven Creek Beach north of Fort Bragg (Table 9A).

Long-term accretion rates reached a maximum of 0.7 m/yr along Ten Mile Beach south of the Ten Mile River mouth.

Net *short-term* shoreline change, as averaged along 32.8 km of coastline, was found to be undetectable at the significant figures appropriate for this analysis and therefore are reported as 0.0 m/yr in Table 6A. Of the measurable stretches of sandy shoreline, 50% eroded and 50% accreted. The average short-term erosion rate was -0.5 m/yr, and the accretion rate was 0.6 m/yr. The maximum short-term erosion rate of -1.4 m/yr occurred at DeHaven Creek Beach (Table 9A), and the maximum short-term accretion rate of 3.3 m/y occurred just north of the Ten Mile River mouth (Figure 19).

The maximum long- and short-term erosion rates in the Navarro region are both found along isolated narrow beaches in the northern half of the region. These beaches are difficult to access and no development is threatened as a result of the higher erosion rates. Both long- and short-term maximum accretion rates were near the Ten Mile River mouth north of Fort Bragg. The high long- and short-term accretion rates were likely related to the large volumes of sand discharged by the Ten Mile River (Merritts and others, 2005).

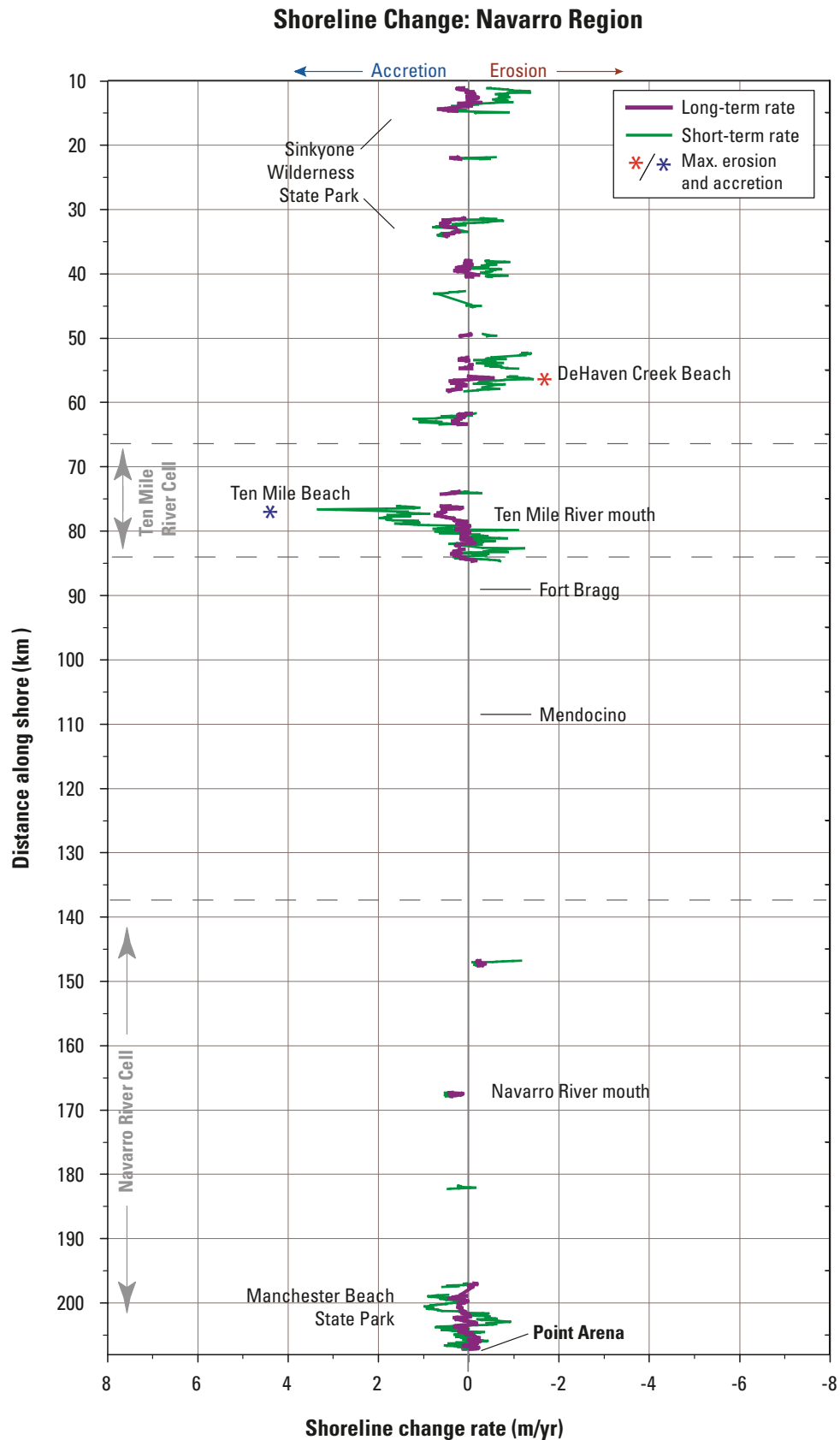


Figure 19. Shoreline change rates for the Navarro region. The maximum long-term erosion rate was -0.6 m/yr at DeHaven Creek Beach, and the maximum short-term erosion rate of 1.4 m/yr was also measured at DeHaven Creek Beach.

Russian River Region

The Russian River region begins 12 km south of Point Arena along a remote, rocky stretch of coastline that has

little development, and extends 155 km south to Tomales Point (Figures 14A and 21). Similar to the other regions in Northern California, there are few linear stretches of sandy shoreline, especially in the northern half of the region. The



Figure 20. Photographs from 1972 (top) and 2002 (bottom) show the widening of the spit beach at the Ten Mile River mouth. Also note the increased vegetation on the dunes. (photo: Copyright © 2002-2005 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.californiacoastline.org).

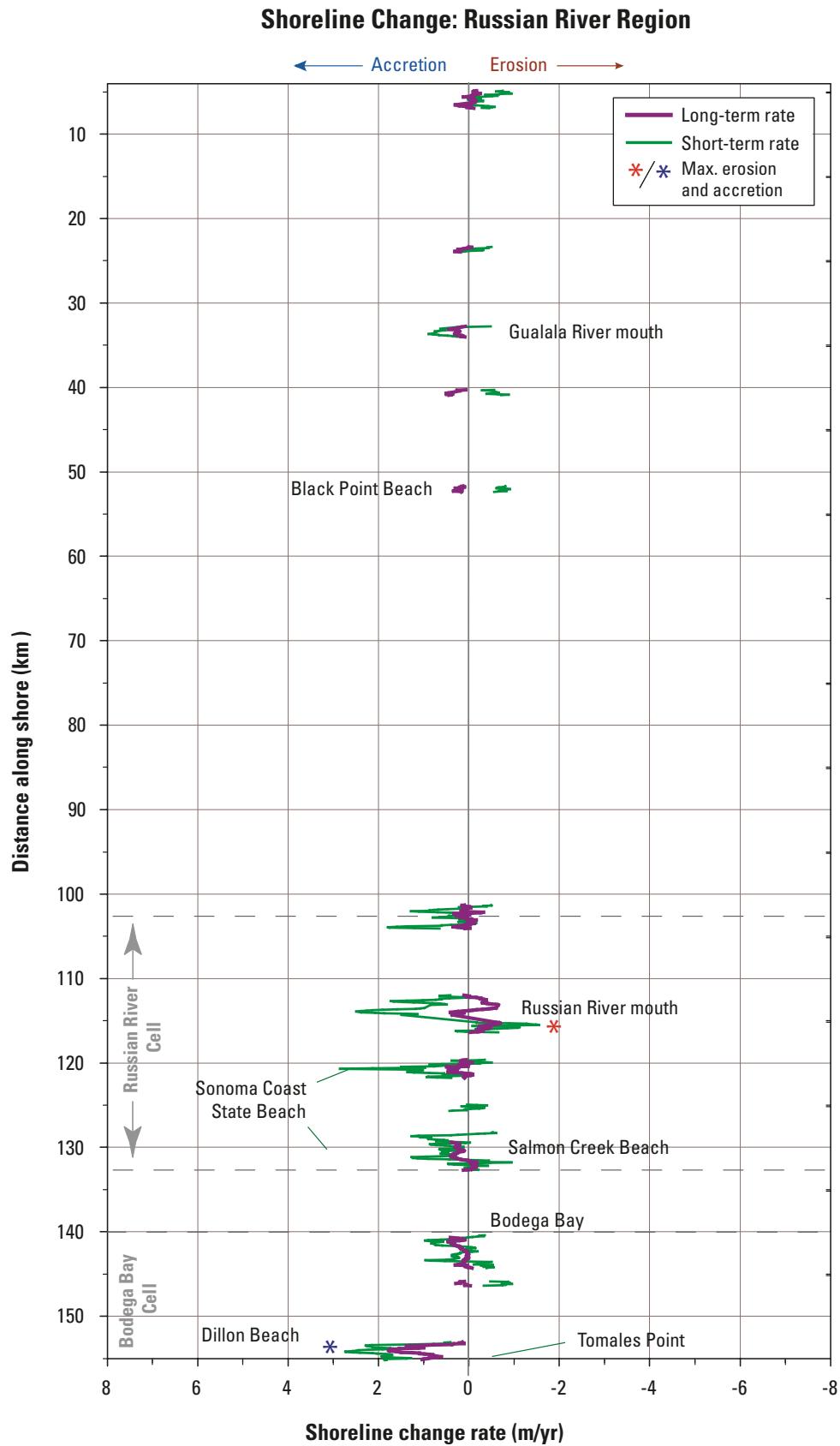


Figure 21. Shoreline change rates for the Russian River region. The maximum long-term erosion rate was -0.7 m/yr on Sonoma Coast State Beach, and the maximum short-term erosion rate of -1.6 m/yr was also measured along a remote beach along Sonoma Coast State Beach.

most extensive beaches are formed near large rivers such as the Gualala and the Russian Rivers (Figure 21). In addition, a wide sandy beach and dune system exist at Salmon Creek Beach just north of Bodega Head. The Russian River region contains both the Russian River and Bodega Bay littoral cells.

Of the 155 km of coast in this region, we were only able to measure *long-term* shoreline change along 21.8 km, primarily because of the lack of linear beaches; we did not measure shoreline change rates on pocket beaches smaller than 0.5 km in length. The average net *long-term* shoreline change rate for the Russian River region was 0.2 m/yr. Average long-term erosion was -0.2 m/yr and occurred over only 28% of the coast (Table 6A). Similar to the other regions in Northern California, a much higher percentage of the coast is accreting in the long-term than eroding. The average long-term accretion rate for the Russian River region was 0.3 m/yr and was observed along 72% of the coast. The maximum long-term accretion rate, 1.8 m/yr, was at Dillon Beach, and the maximum long-term erosion rate of -0.7 m/yr was along Sonoma Coast State Beach (Figure 22; Table 9A).

Net *short-term* shoreline change averaged 0.4 m/yr, measured along 24.1 km of the coast. Short-term erosion occurred along 35% of the coast, and the average rate was -0.4 m/yr (Table 6A). This is the lowest percentage of eroding coastline of the four Northern California regions. The average short-term accretion rate was 0.8 m/yr.

The maximum *short-term* accretion rate (3.5 m/yr) was at Dillon Beach (Figure 22; Table 9A) and the highest short-term erosion rate (-1.6 m/yr) occurred along Sonoma Coast State Beach ~1.5 km south of the Russian River mouth..

Sandy shorelines in the northern 100 km of this region are rare and occur only where small pocket beaches form at the mouths of rivers and creeks. Overall the shoreline change was accretional; the highest erosion rates were near the Russian River. This is the only region in the state in which the average rate of net shoreline change increased from the *long-term* to the *short-term*.

Central California

The Central California section begins approximately 5 km south of Tomales Point in Point Reyes National Seashore (PRNS) and extends south to El Capitan State Beach, just north of Santa Barbara, a total distance of approximately 740 km (Figure 14B). Central California is divided into six regions including San Francisco North, San Francisco South, Monterey Bay, Big Sur, Morro Bay and Santa Barbara North. The average net *long-term* shoreline change rate for Central California was found to be undetectable at the significant figures appropriate for this analysis and is reported as 0.0 m/yr. In the *short-term*, however, the average net rate is strongly erosional (-0.5 m/yr).

There are many gaps in our analysis along this coast, as much of the shoreline is rocky with isolated pocket beaches;



Figure 22. Many of the large rivers in Northern California have well-developed sandy spits such as this one extending across the mouth of the Russian River (photo: Copyright © 2002-2005 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.californiacoastline.org).

there are a few continuous linear beaches such as in the Monterey Bay region. Coastal engineering structures and nourishment projects are limited to small harbor construction (e.g. Port San Luis, Santa Cruz) and some harbor bypassing. Numerous seawalls and revetment exist along the coast but these are primarily related to issues of coastal cliff erosion mitigation, not to protect structures from erosion of the sandy shoreline.

San Francisco North Region

The San Francisco North region is 93 km long and includes the Point Reyes, Drakes Bay and Bolinas Bay littoral cells (Figure 9). This is primarily a rocky coastline, with narrow beaches backed by high coastal cliffs, small isolated pocket beaches between rocky headlands, and an expansive dune field at Point Reyes. There are two very small, developed sections of the coast in this region at Bolinas and Stinson Beach. Due to a data gap in the 1800s-era t-sheets we have no *long-term* shoreline change rates for either of these areas. Other than these two areas, the coast here is undeveloped and remote, and falls entirely within either PRNS or the Golden Gate National Recreation Area (GGNRA).

Net *long-term* shoreline change rates in this region, averaged along 45.1 km of coast, were low and averaged 0.1 m/yr (Table 6B). Forty-six percent of the shoreline was eroding in the long-term at an average rate of -0.2 m/yr. Long-term accretion rates of 0.3 m/yr occurred along 54% of the coast. The highest and lowest long-term rates occurred north of Point Reyes Headland where the long-term trend was largely accretional (Figure 23). However, the maximum long-term erosion rate for the San Francisco North region of -0.5 m/yr was at Limantour Beach, which is north of Point Reyes (Table 9B).

Net average *short-term* shoreline change rates were measured along 51.9 km of coastline, and the average change rate was -0.5 m/yr. Eighty-one percent of the coast was eroding (short-term) with the rate of erosion averaging -0.7 m/yr. Short-term accretion rates, averaging 0.5 m/yr, occurred along only 19% of the coast.

Short-term shoreline change trends north of Point Reyes Headland (Figure 23) were highly variable with accretion dominant in the north, changing to predominantly erosion in the south. The maximum short-term erosion rate of -3.1 m/yr was measured at Point Reyes Beach (Figure 23). This trend is driven by the position of the most recent (lidar) shoreline and may indicate a rotation of the beach during the 1997-98 El Nino where the dominant littoral transport changed directions from southward to northward in many local areas.

In the San Francisco North region, the *long-* and *short-term* shoreline change rates were significantly different; there was an overall shift from a net shoreline change trend that was 0.1 m/yr in the *long-term* to a net shoreline change rate that was strongly erosional (-0.5 m/yr) in the *short-term*. In addition, the percent of coastline along which

erosion was measured increased from 46% in the *long-term* to 81% of the *short-term*.

As demonstrated in Figure 23, from Point Reyes headland to Point Bonita, the sandy beaches were relatively stable in the *long-term*. In the *short-term*, this section of beach as primarily erosional, with a few localized exceptions (i.e south of Drakes Estero). The *short-term* erosion rates at Stinson Beach were the highest of those measured in the southern portion of the San Francisco North region. Winter storm waves frequently inundate Stinson Beach, moving large volumes of sand, and threatening homes built on the sand spit. Figure 24 shows a house buried by sand that had been eroded from a location further north. Riprap has been emplaced in many areas to protect the houses from beach erosion (Savoy and others, 2005).

San Francisco South Region

The San Francisco South region is 115 km long and extends from the mouth of San Francisco Bay to Davenport (Figures 14B and 25). The northern coast in this region is urban and includes San Francisco, Pacifica and Half Moon Bay; the southern half is largely undeveloped and agricultural. The San Francisco littoral cell is within this region (Figure 9). The geomorphology of the coastline is variable, with linear beaches backed by dunes, steep cliffs with narrow fronting beaches, rocky coast with small pocket beaches, and steep, high-relief coast with no sandy shoreline. There are no known beach nourishment projects in this region, although a dredge spoil deposit offshore may be contributing material to the beach (Barnard and Hanes, 2006). Additionally, wind-blown sand is regularly removed from the inland side of the dunes and from the adjacent highway and added to the south end of the beach (Wiegel, 2002). The most notable coastal engineering structures are the O'Shaughnessy and Great Highway seawalls along Ocean Beach in San Francisco and the Pillar Point Harbor at Half Moon Bay.

For this analysis we calculated net average *long-term* shoreline change rates for 56.3 km of coastline, and the average rate was -0.2 m/yr. Long-term erosion occurred along 76% of the coast at an average long-term rate of -0.4 m/yr. For the 24% of the coast along which accretion occurred, the long-term average accretion rate was 0.1 m/yr. The maximum long-term accretion rate (0.4 m/yr) in this region was located 0.25 km south of Mussel Rock, and the maximum long-term erosion rate of -1.8 m/yr occurred on the north side of Point Año Nuevo (Figure 25; Table 9B).

Net *short-term* shoreline change, with an average rate of -0.5 m/yr, was measured along 57.5 km of coast in the San Francisco South region. Along the portions of coast where the short-term shoreline change was erosional, the rate was -0.7 m/yr, averaged over 81% of the coast. The average short-term accretion rate was 0.5 m/yr.

Short-term change trends in the central portion of this region are more variable than the *long-term* trends; erosion

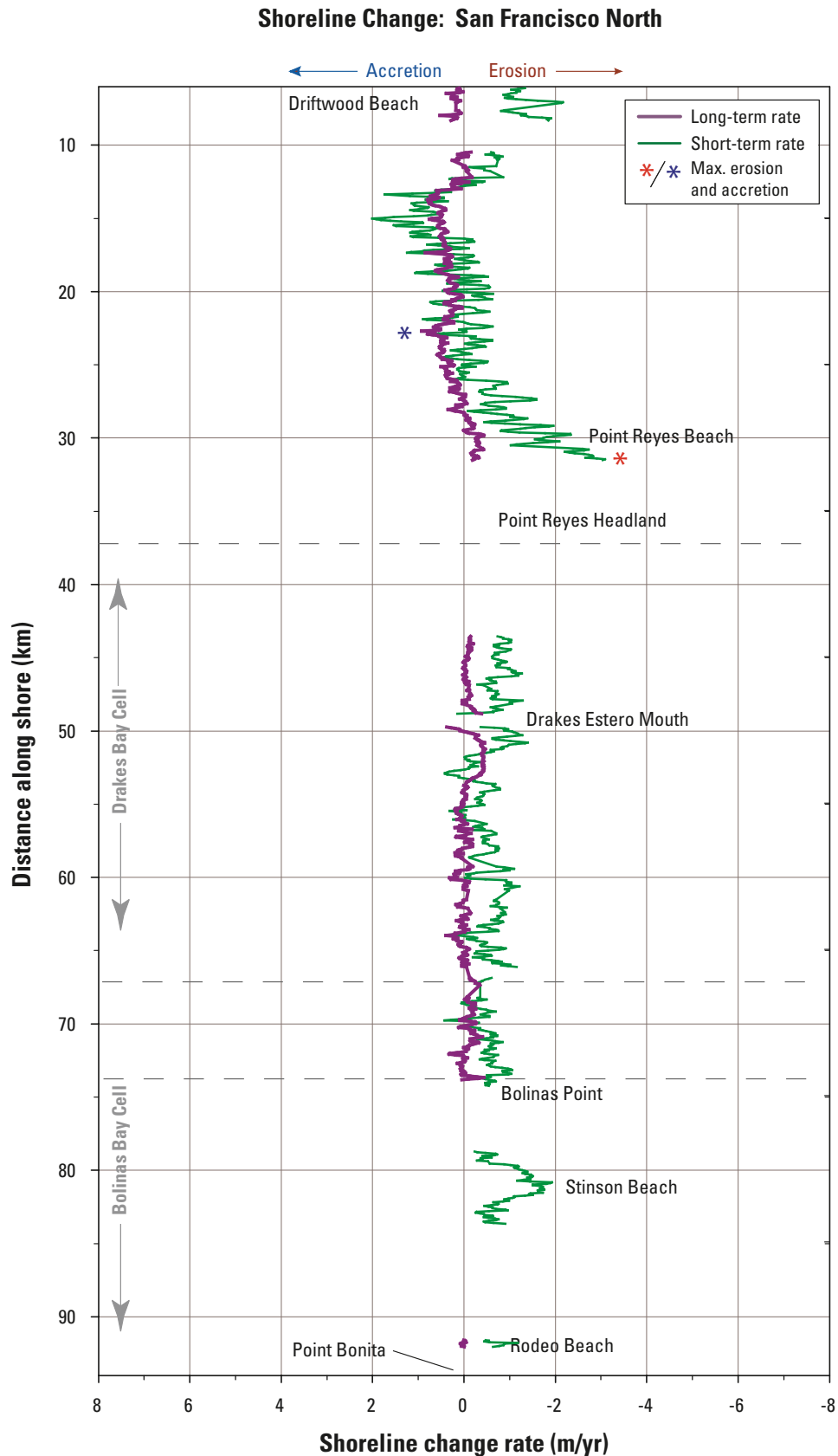


Figure 23. Shoreline change rates for the San Francisco North region. The maximum long-term erosion rate was -0.5 m/yr on Limantour Beach east of Drakes Estero; the maximum short-term erosion rate of -3.1 m/yr was measured at Point Reyes Beach just north of Point Reyes.

Table 9B. Maximum and minimum shoreline change rates: Central California

Region	Long-term (m/yr)	Location	Short-term (m/yr)	Location
San Francisco N				
Max. erosion	-0.5	Limantour Beach, 2.5 km east of Drakes Estero	-3.1	Pt Reyes Beach, immed. north of Pt Reyes
Max. accretion	1.0	Pt Reyes Beach, 9 km north of Pt Reyes	0.9	Pt Reyes Beach, 12 km south of Tomales Pt.
San Francisco S				
Max. erosion	-1.8	North side of Pt. Año Nuevo	-2.6	North side of Pt. Año Nuevo
Max. accretion	0.4	0.25 km south of Mussel Rock	2.2	Tunitas Beach
Monterey Bay				
Max. erosion	-1.3	Indian Head Beach, Marina	-2.4	Seaside, 3 km north of Laguna Del Ray
Max. accretion	1.2	Salinas River State Beach	1.8	Twin Lakes Beach, 0.3 km east of harbor
Big Sur				
Max. erosion	-0.8	North end of Carmel River State Beach	-1.7	Carmel City Beach
Max. accretion	0.7	JP Burns Landslide, Big Sur Coast	2.4	Pfeiffer Beach
Morro Bay				
Max. erosion	-0.6	South of Ragged Pt. – narrow pocket beach	-3.4	Montana De Oro State Park
Max. accretion	1.5	Immed. north of Morro Rock	1.2	Morro Bay, 800 m south of breakwater
Santa Barbara N				
Max. erosion	-1.1	Guadalupe Dunes, SLO Co.	-6.7	Guadalupe Dunes, SLO Co.
Max. accretion	1.1	Vandenberg Air Force Base	4.7	Vandenberg Air Force Base

was relatively high north and south of Pillar Point Harbor (Figure 26) where the breakwater disrupts the natural transport of sand and focuses wave energy at the south end of the breakwater. The maximum *short-term* accretion rates were found along the central area, where they reach a maximum of 2.2 m/yr at Tunitas Beach (Figure 25). The maximum *short-term* erosion rate, -2.6 m/yr, was along the north side of Point Año Nuevo.

Both the long-term and short-term net trends were erosional, and the rates more than doubled from the long-term to the short-term. The percents of coast eroding and accreting were similar in both the long-term and the short-term (Table 6B). Along Ocean Beach, both were relatively stable

at the very northern end of the beach adjacent to the mouth of San Francisco Bay. However, both long-term and short-term rates became strongly erosional to the south except immediately north and south of Mussel Rock.

The long- and short-term maximum erosion rates (-1.8 m/yr and -2.6 m/yr, respectively; Table 9B) were observed immediately north of Point Año Nuevo. This area of rapid erosion was adjacent to a former sand spit that connected Año Nuevo Island to the mainland (Griggs and others, 2005). The spit was breached sometime in the late 1800s, providing a path for the transport of sand to the south.



Figure 24. Houses on the spit at Stinson Beach are partially buried by sand during an El Niño winter storm in 1983 (photo: Gary Griggs, UCSC).

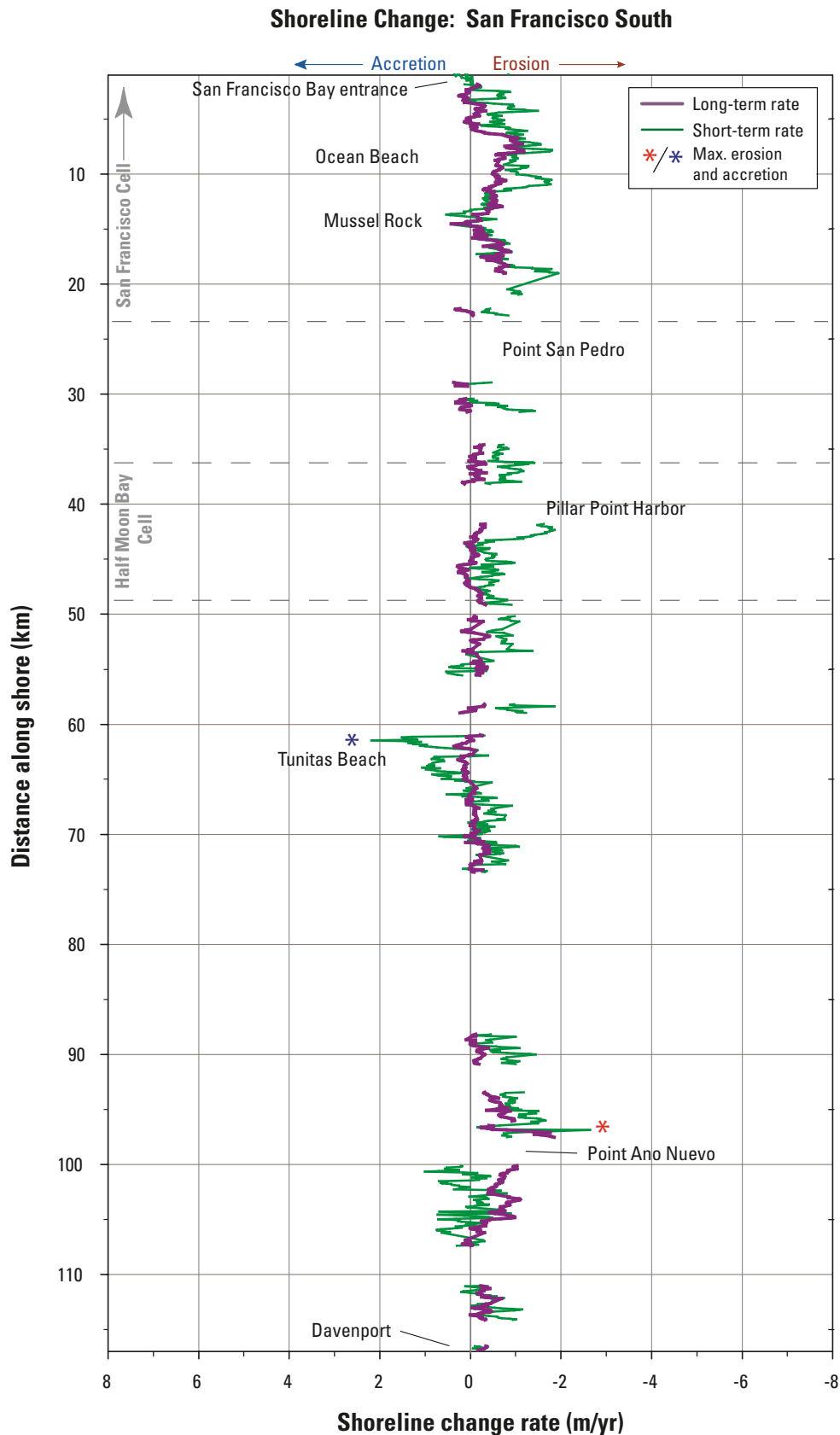


Figure 25. Shoreline change rates for the San Francisco South region. The maximum long-term erosion rate was -1.8 m/yr on the north side of Point Año Nuevo; the maximum short-term erosion rate of -2.6 m/yr was also measured on the north side of Point Año Nuevo.



Figure 26. A riprap revetment protects an apartment building that overlooks a narrow beach near Pillar Point Harbor in a photograph taken in February, 2002. Note that the beach (background) with no revetment is much wider (photo: Gary Griggs, UCSC).

Monterey Bay Region

The Monterey Bay region begins approximately 2 km north of Davenport in Santa Cruz County and extends 75 km to Del Monte State Beach in Monterey (Figures 14B and 27). This region includes the Santa Cruz and Southern Monterey Bay littoral cells, and is characterized by a variable coast that includes rocky points and pocket beaches, cliffed coastline with narrow fronting beaches, and linear beach and dune systems. Development varies from urban (city of Santa Cruz and environs) to rural/agricultural. The Santa Cruz Small Craft Harbor, built in the early 1960s, currently has an active entrance channel dredging programs and the sand is placed downcoast from the harbor mouth. One beach in this region, Capitola, is down-coast from the Yacht Harbor and has been nourished.

The total length of sandy shoreline along which *long-term* change was measured in the Monterey Bay region is 50.7 km. The average net long-term shoreline change rate was -0.2 m/yr. Along the 41% of the coast that had a long-term erosional trend, the average rate was -0.6 m/yr. Long-term accretion occurred along 59% of the sandy shoreline, and had an average rate of 0.4 m/yr (Table 6B).

Long-term shoreline change throughout the central portion of the Monterey Bay was accretional. However, in the northern portion of the bay near the Santa Cruz Yacht Harbor, the shoreline change trend shifts from accretional west of the harbor to erosional east of the harbor (Figure 27). The effects of the harbor appear to diminish south of Capitola State Beach, where the change rates are strikingly uniform. In the southern part of Monterey Bay there was a noticeable shift in the long-term shoreline change trend from strongly accretional in the north to erosional in the south (Figure 27). Both the maximum long-term accretion and erosion rates were measured in the southern area (Table 9B). The maximum long-term erosion rate of -1.3 m/yr occurred at Indian Head Beach, and the maximum accretion rate (1.2 m/yr) occurred further south at Salinas River State Beach (Figure 27).

The net *short-term* shoreline change rate in the Monterey Bay region was -0.6 m/yr, measured over 51.5 km of coast. Along those portions of the coast that had an erosional trend, the average rate was -0.8 m/yr, and occurred along 77% of the coast. The average *short-term* accretion rate, 0.3 m/yr, is the lowest in the Central California region.

The maximum *short-term* accretion rate (1.8 m/yr) was measured just south of the harbor on Twin Lakes State Beach (Figure 27; Table 9B). This maximum is likely due to material that was dredged from the harbor channel every winter and spring and placed on or just offshore of this beach (Griggs and Johnson, 1976; Wiegand, 1994). In the northern part of the Bay, the large pulse of *short-term* accretion near Capitola Beach was the result of beach nourishment projects. This project was implemented shortly after the harbor jetties were built to compensate for the disrupted downcoast transport of sand (Griggs and Johnson, 1976; Clayton, 1991).

The northernmost portion of the Monterey Bay region is primarily a rocky coastline with scattered small pocket beaches; therefore, there is little sandy shoreline along which to measure change. The first continuous stretches of beach in this region are associated with the San Lorenzo River mouth at Main Beach in Santa Cruz (Figure 27). The net average rates of change in the Monterey region were significantly different, and there were distinct trends in the rates of change from the *long-term* to the *short-term*. The net average change rate more than doubles from the *long-term* (-0.2 m/yr) to *short-term* net change of -0.6 m/yr. In addition, the percent of coast experiencing erosion increased by 36%. This trend suggests that the Monterey Bay region is undergoing a shift to overall increased erosion in the more recent time period.

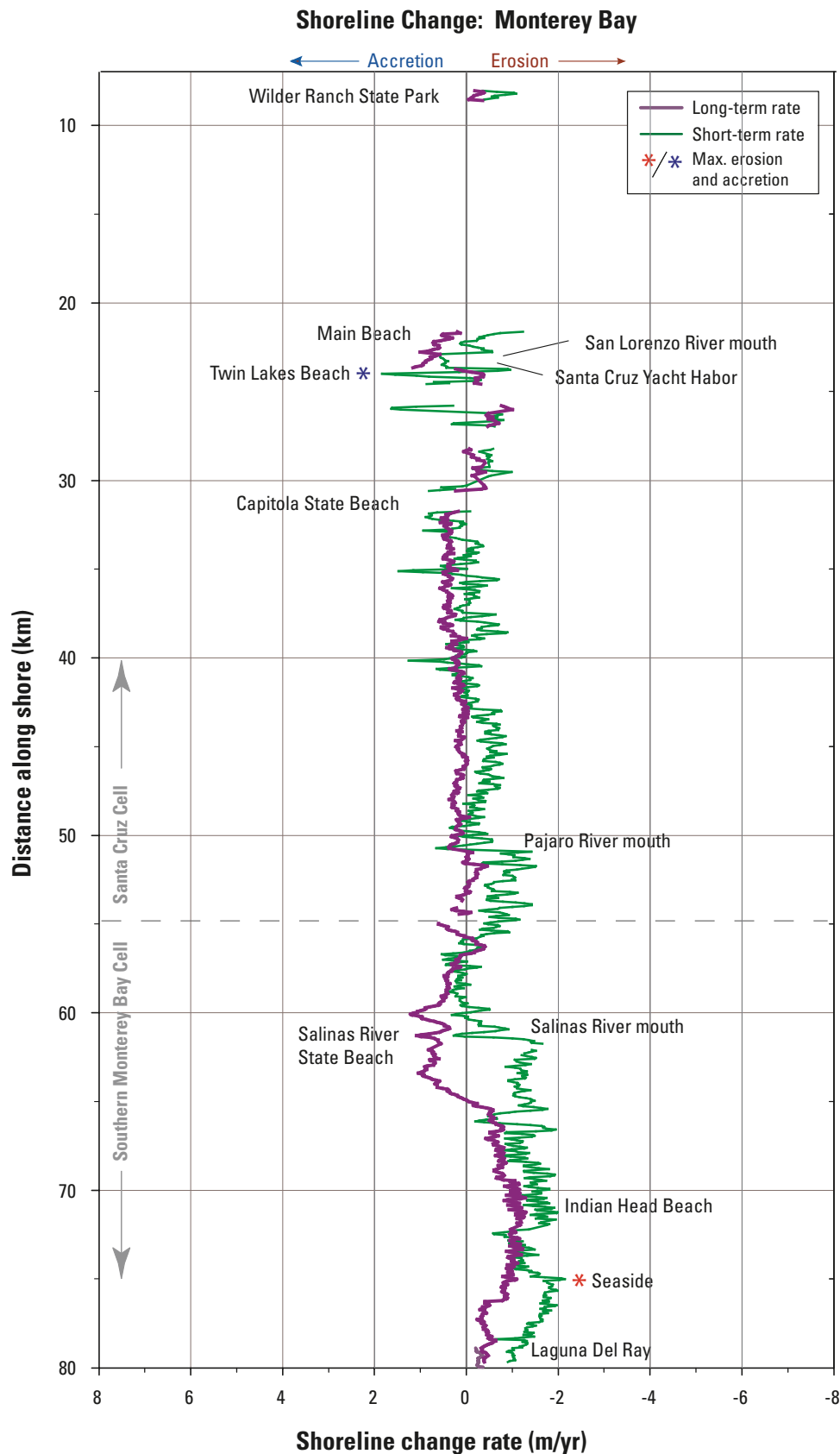


Figure 27. Shoreline change rates for the Monterey Bay region. The maximum long-term erosion rate was -1.3 m/yr on Indian Head Beach near Marina. The maximum short-term erosion rate of -2.4 m/yr was measured near Seaside.



Figure 28. Aerial photographs of the Santa Cruz Yacht Harbor show the impoundment of sand against the constructed jetties. The top photo is from 1963, one year after the jetties were constructed. The bottom photo is from 1987, and shows a now wide, sandy beach (Seabright Beach) on the upcoast side of the jetty (photos: Santa Cruz Harbor Master's Office).

In general, in the northern portion of the bay, the *long-term* and *short-term* trends of accretion gradually increased to the southeast where sand is impounded against the northwestern Yacht Harbor jetty (Figure 28). In the Southern Monterey Bay, accretional trends to the north gradually

shifted to erosional trends to the south. The general area where erosion becomes more predominant corresponds to the portion of coast where sand mining practices throughout the 20th century removed large volumes of sand from the

beach and dunes (Griggs and Patsch, 2005; Thornton and others, 2006).

Big Sur Region

The Big Sur region extends along 165 km of largely remote and rugged coastline from Point Piños in the north to near Cape San Martin in the south (Figures 14B and 29). The littoral cells within this region are the Carmel River cell and the Point Sur cell (Figure 9). This region includes the development associated with Monterey and Carmel in the north; the remainder of the coast is essentially undeveloped. The primary hazards along this coast are large landslides that threaten roads and small development. The only sandy shorelines are along small pocket beaches and the extensive beach and dune system at the mouth of the Little Sur River extending to Point Sur. There are no known coastal engineering structures or beach nourishment projects. Due to the lack of linear stretches of sandy shoreline, we were able to measure shoreline change along only 27 km of the Big Sur region.

The net *long-term* average shoreline change rate was found to be undetectable at the significant figures appropriate for this analysis and is reported as 0.0 m/yr in Table 6B. The average long-term erosion and accretion rates were both low (-0.1 and 0.2 m/yr, respectively), but accretion occurred over a much higher percent of the shoreline, 61% versus 39% for the eroded areas. The maximum long-term erosion rate (-0.8 m/yr) was measured in the northern portion of the region at the southern end of Carmel River State Beach (Figure 29).

In the *short-term*, the net average shoreline change rate is was -0.2 m/yr. Short-term erosion occurred along 65% of the coast, with rates averaging -0.5 m/yr. Short-term accretion rates averaged 0.4 m/yr. Similar to the maximum *long-term* erosion rate, the maximum short-term erosion rate was in the northern portion of the region at Carmel River State Beach and Carmel City Beach (Figure 29) where the maximum short-term erosion rate was -1.7 m/yr (Table 9B). Pfeiffer Beach, which is approximately 13 km south of Point Sur, had the maximum short-term accretion rate (2.4 m/yr) in this region.

Beaches along the Big Sur region are widely scattered and typically occur only at or near the mouths of rivers and creeks. The longest continuous stretches of beach are near the Little Sur River mouth and the dune system at Point Sur (Figure 29) where there is adequate sand supply. The highest *long-term* accretion rate was at the site of the Julia Pfeiffer-Burns landslide, which occurred in 1983. As a result of the landslide, a small beach was created where none had existed before (Hapke, 2005; Figure 30). Overall, the net shoreline change rate for the Big Sur region became more erosional from the long-term to the short-term.

Morro Bay Region

The Morro Bay region is 105 km long, includes the section of coast from San Carpoforo Creek in the north to Point Bachon in the south (Figures 14B and 31) and falls within the Morro Bay littoral cell. This is a lower relief coast than the Big Sur region to the north, with stretches of rocky coastline with no beaches, low cliffs backing narrow beaches, as well as several linear beach and dune systems. The largest dunes are in the southern part of the region at Morro Strand State Beach and Montana De Oro State Park (Figure 14B). Shoreline change (both *long-term* and *short-term*) was measured along only 22.3 and 22.9 km of coast respectively, partly due to the rocky nature of the coastline, and partly due to gaps in the lidar data. The Morro Bay region is moderately developed with the developed sections of coast concentrated in the southern areas. The towns of San Simeon, Cambria, Cayucas and Morro Bay are within this region.

In the Morro Bay region, the net average *long-term* shoreline change rate of 0.1 m/yr was the one of the highest (most accretional) in Central California (the San Francisco North region also had a net long-term rate of 0.1 m/yr) (Table 6B). Accretion was measured along 65% of the coast, and the average rate of the accreting sections was 0.3 m/yr. Where the beach was eroding, the rates averaged -0.1 m/yr. The maximum long-term erosion rate (-0.6 m/yr; Table 9B) was measured in the northern part of the region along a small, unnamed pocket beach.

The average *short-term* shoreline change rate, -0.7 m/yr, was the most erosional net change rate in Central California. Where the beach was eroding (80% of the coast), the short-term erosion rates averaged -1.0 m/yr, the highest in Central California. The short-term accretion rates averaged 0.4 m/yr.

Shoreline change rates in the Morro Bay region were highly variable in both the long-term and short-term (Figure 31). Beaches in the southern portion of the region were largely stable in the *long-term*, but becoming highly erosional in the *short-term*, suggesting a more recent disruption of the sand supply in this area. Figure 32 shows an area of *long-term* beach accretion at Morro Rock, which is the site of the highest accretion rate (1.5 m/yr) in the Morro Bay region. This high accretion was related to the trapping of sand up coast from the Morro Bay harbor breakwater and the Morro Rock causeway, which was built during the 1930s – 1940s. The maximum *short-term* accretion rate was located just downcoast of the breakwater (1.2 m/yr) (Figure 31; Table 9B). For the *long-term* period, beaches along the Montana De Oro shoreline were stable; however in the *short-term*, this area eroded rapidly, and included the maximum *short-term* erosion rate of -3.4 m/yr.

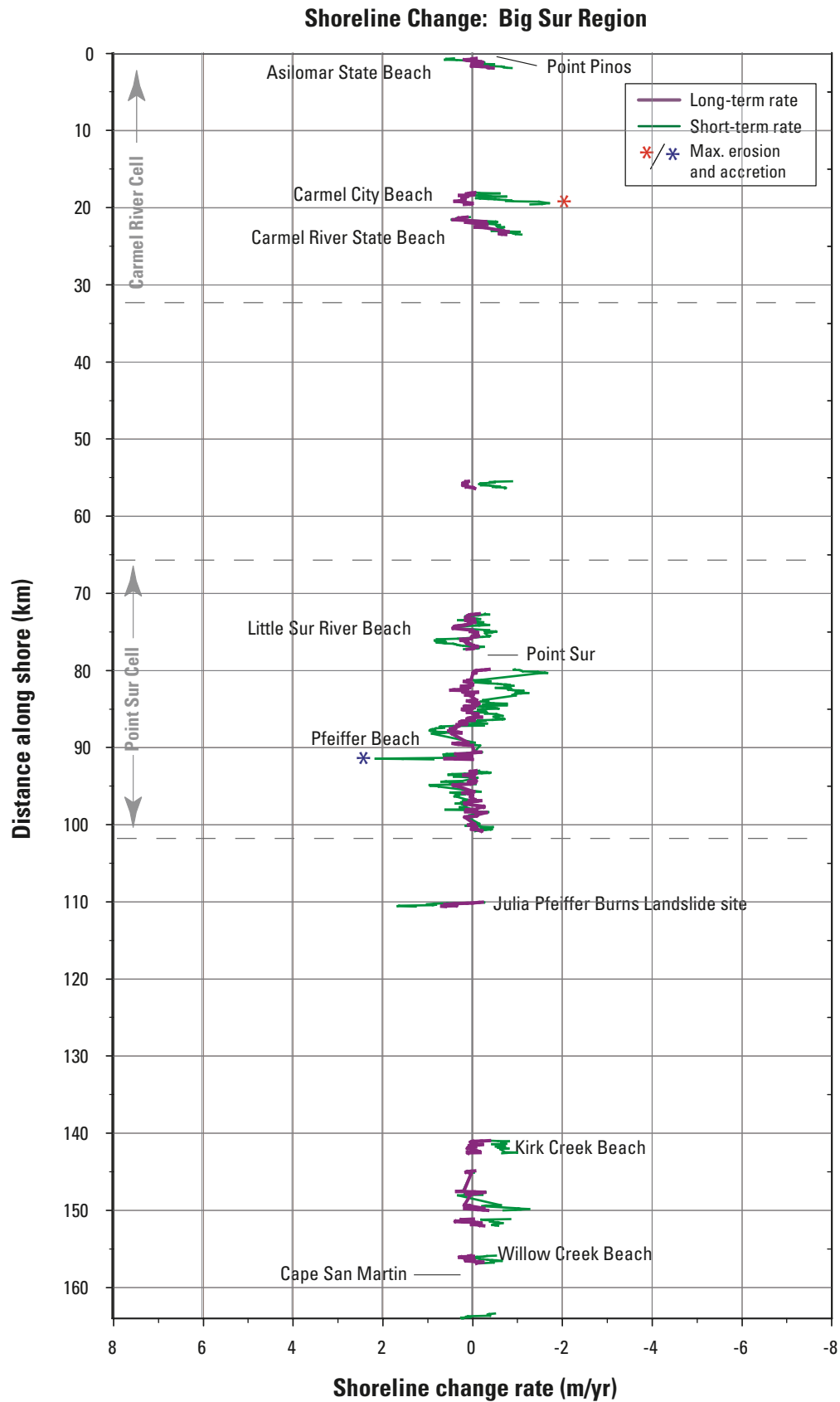


Figure 29. Shoreline change rates for the Big Sur region. The maximum long-term erosion rate was -0.8 m/yr on the north end of Carmel River State Beach. The maximum short-term erosion rate of -1.7 m/yr was measured at Carmel City Beach.

A



B



Figure 30. JP Burns waterfall shows the beach that formed as a result of the sediment added to the system from the 1983 landslide. a) photo taken July 10, 1963 shows waterfall pouring directly into the ocean (from photo archives, Caltrans), b) photo taken June 10, 2003 shows water now pouring on to a beach (photo: Cheryl Hapke, USGS).

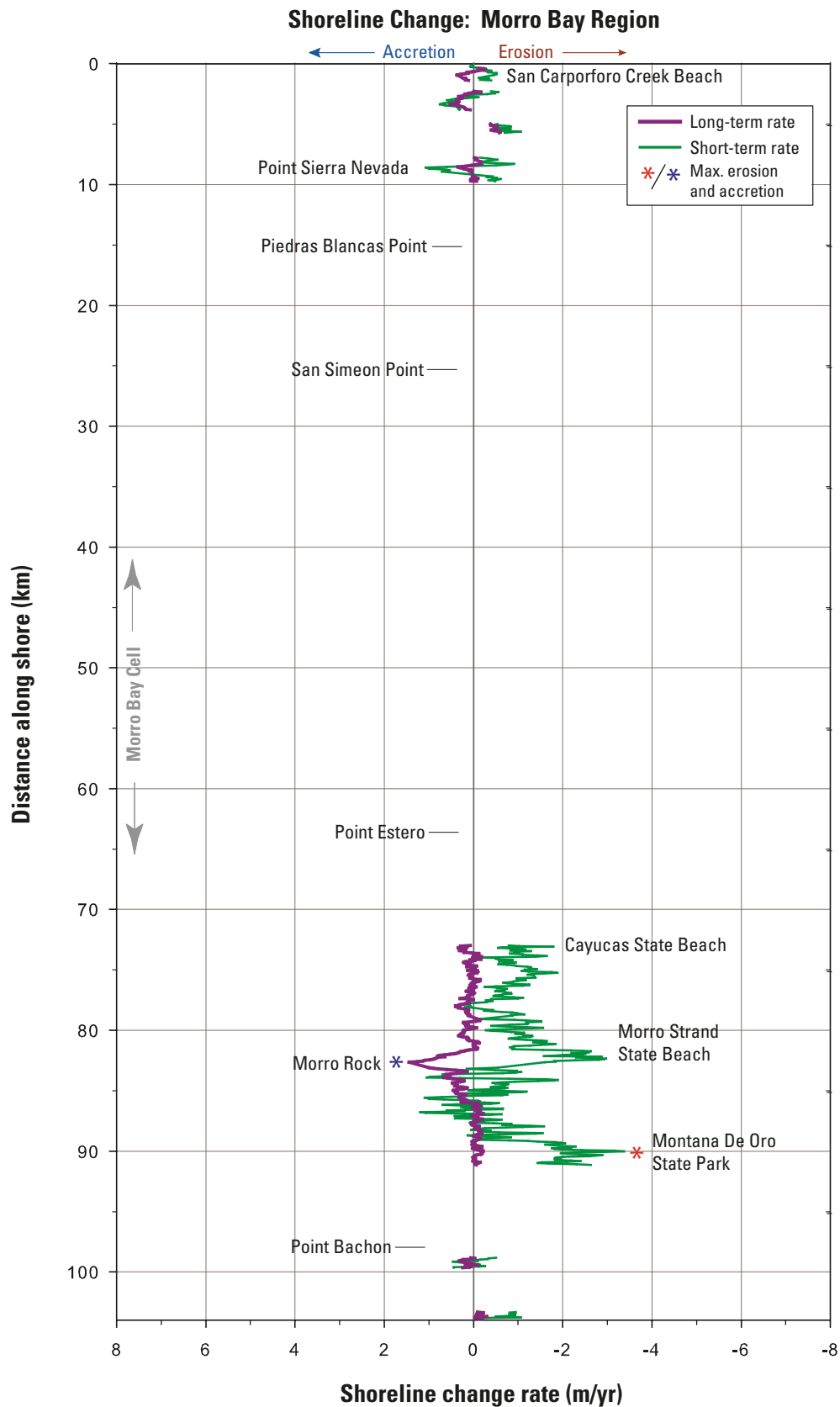


Figure 31. Shoreline change rates for the Morro Bay region. The maximum long-term erosion rate was -0.6 m/yr along a narrow pocket beach south of Ragged Point. The maximum short-term erosion rate of -3.4 m/yr was measured at Montana De Oro State Park.



Figure 32. Development of a tombolo at Morro Rock after a causeway was built in the 1930s. Top photo was taken in 1936 just after the completion of the causeway. The postcard (lower image) is from the 1950s and shows a sandy tombolo leading out to Morro Rock (photos: <http://morro-bay.com/morro-rock/>).

Santa Barbara North

The Santa Barbara North region extends for 186 km from Point San Luis in the north to El Capitan State Beach in the south (Figures 14B and 33). The division between the Santa Barbara North and South regions is the transition from UTM Zone 10 (northwest) to UTM Zone 11 (southeast), and was necessitated by our analysis techniques. The Santa Barbara North region contains the Santa Maria River and Santa Ynez River littoral cells along with the northern half of the Santa Barbara cell (Figure 14B). Much of the coast is rugged and remote, and not highly developed. An exception is the area extending from Avila Beach to Pismo State Beach where some seawalls and riprap have been emplaced to protect coastal roads and buildings from cliff erosion. In

addition there is a small harbor and breakwater at Port San Luis. The coast is predominantly cliffed with small pockets beaches or narrow linear beaches. However, linear stretches of wide beaches are present from Pismo State Beach south through the expansive beach and dune systems at Oceano and Guadalupe Dunes (Figure 34) and within Vandenberg Air Force Base, which occupies more than 60 km of coastline in the region. There are no known beach nourishment projects in this region (Clayton, 1991; Wiegel, 1994).

Ninety-nine point two kilometers of shoreline were measured in this region and the *long-term* net shoreline change rate was found to be undetectable at the significant figures appropriate for this analysis and is reported as 0.0 m/yr in Table 6B. Long-term erosion was measured along

Shoreline Change: Santa Barbara North Region

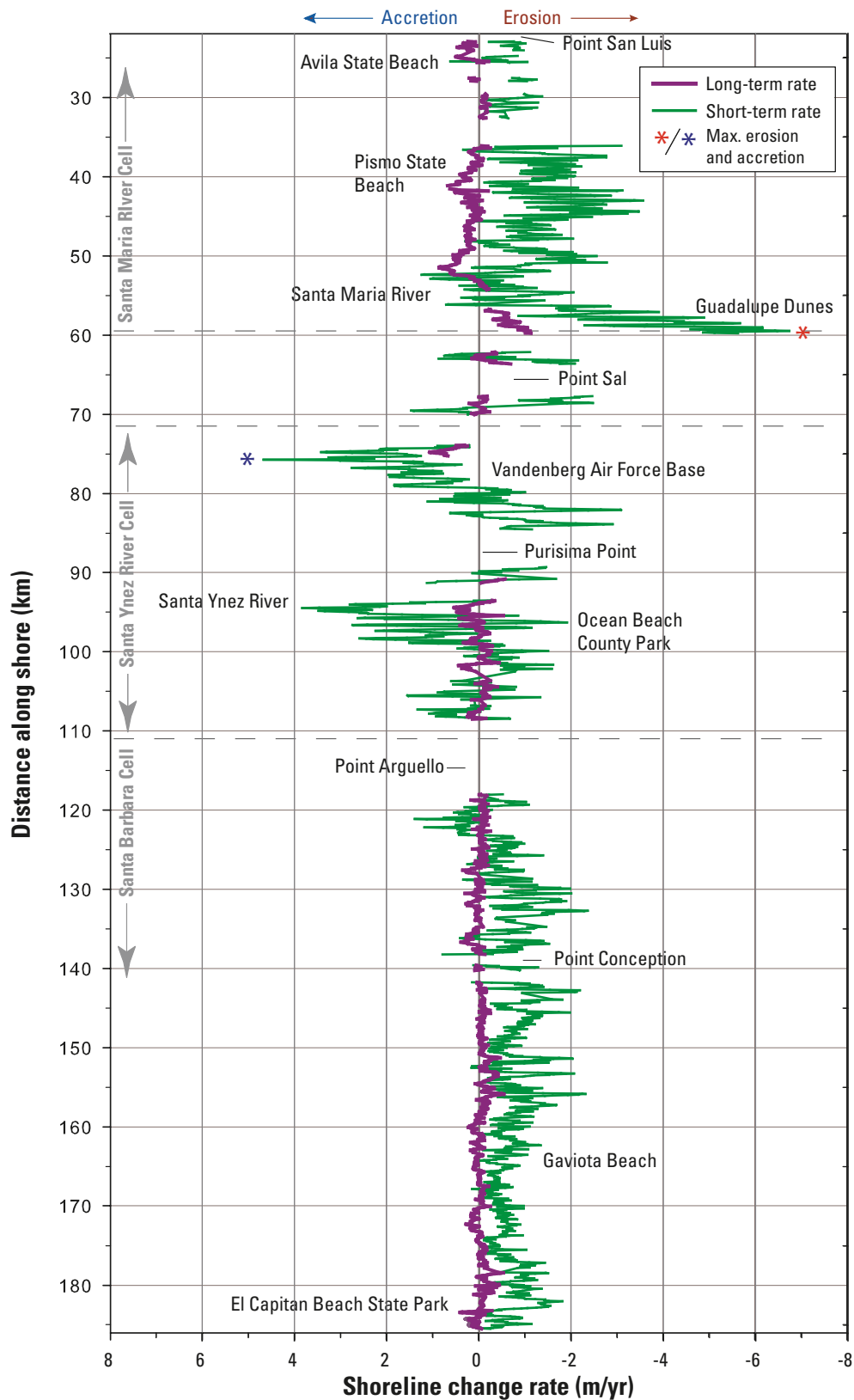


Figure 33. Shoreline change rates for the Santa Barbara North region. The maximum long-term erosion rate was -1.1 m/yr at Guadalupe Dunes; the maximum short-term erosion rate of -6.7 m/yr was also measured at Guadalupe Dunes, and was the highest short-term rate measured in the state.



Figure 34. Photographs from January 1989 shows the well-developed dune field at Guadalupe Dunes; the beach in this area has the highest short-term erosion rates in the State (photo: Copyright © 2002-2005 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.californiacoastline.org).

56% of the coast and the average long-term rate was -0.2 m/yr (Table 6B). Long-term accretion rates averaged 0.2 m/yr.

The *short-term* net average shoreline change rate was -0.6 m/yr, as averaged over 113.3 km of coastline. The short-term average accretion rate of 0.9 m/yr was the highest in Central California and occurred along 20% of the coast. The short-term average erosion rate of -1.0 m/yr, was the same as the rate observed in the Morro Bay region.

The *long-term* and *short-term* shoreline change rates were significantly different. The net average shoreline change shifted to a more erosional trend from the *long-term* (0.0 m/yr) to the *short-term* (-0.6 m/yr). There were distinct changes in the patterns and magnitudes of shoreline change from north of Point Arguello to the southern limit of this region. To the north, the magnitudes of change, especially in the *short-term*, were highly variable and oscillated from erosion to accretion (Figure 33). North of Point Sal, *long-term* accretion shifted to high rates of *short-term* erosion, with rates increasing dramatically from north to south. The highly (spatially) variable change rates also occurred in the central portion of this region between Point Sal and Point Arguello. South of Point Arguello, the coastline was stable during the *long-term* period, however, the *short-term* trend is strongly erosional along this undeveloped coast. In the northern part of this region, *short-term* erosion rates were high along the central part of Pismo State Beach and exceeded -2.0 m/yr in some areas. In general, along the

Pismo State Beach coast the *long-term* trend was stable with the exception of the southern segment where *long-term* change went from dominantly accretion to the most rapid erosion in this section, which was at Guadalupe Dunes (Figure 33; Table 9B). This dominant trend of erosion, just south of the Santa Maria River, is likely related to flood control projects on the Santa Maria River. The highest *short-term* erosion rates (-6.7 m/yr) were the highest in the state for a non-nourished system. The highest accretion rates both in the long- and *short-term* were within Vandenberg Air Force Base, approximately 10 km north of Purisima Point.

Southern California

The Southern California section extends from El Capitan State Beach north of Santa Barbara to the Mexico border (Figure 1), approximately 420 km of coastline. The shoreline change data for this section of the California coast is divided into five regions: Santa Barbara South, Santa Monica, San Pedro, Oceanside and San Diego (Figure 14C).

This section of coastline has the longest stretches of continuous, linear beaches in the state, although there are many areas where the beaches are narrow and are backed by coastal cliffs or bluffs. This is also the most engineered coastline in the state, consisting of numerous harbors, ports, breakwaters, jetties and groins. There are only a few small

data gaps for Southern California: in the Point Fermin area, and in the San Clemente - Laguna Beach region. Both of these gaps are due to lack of 1800s-era t-sheets.

A total of 280.7 km of coastline was included in our *long-term* Southern California analysis, whereas the *short-term* analysis covered 315.0 km of coast. The net *long-term* shoreline change rate for the section was accretional, with an average rate of 0.3 m/yr and the net average *short-term* rate was -0.1 m/yr.

Santa Barbara South Region

The Santa Barbara South region begins within the Santa Barbara littoral cell, at El Capitan Beach State Park, approximately 15 km north of Goleta Point and the University of California Santa Barbara campus (Figures 14C and 35). This region includes the beach communities of Santa Barbara, Ventura and Oxnard among others. With the exception of the coast north of Santa Barbara, this is a highly developed to urbanized coastline and numerous engineering structures and nourishment projects have greatly altered the natural patterns of shoreline change. The beaches along this stretch of coast are narrow, and undergo large seasonal fluctuations in beach volume (Norris, 1964; Thompson, 1987; Flick, 1993).

Long-term shoreline change trends were measured along 84.6 km of the Santa Barbara South region. The net average long-term shoreline change rate was 0.1 m/yr (Table 6C), and of the measured coast, 44% accreted and 56% eroded. The average long-term accretion rate was higher than the erosion rate, 0.5 m/yr versus -0.2 m/yr. The maximum long-term accretion rate (2.0 m/yr) was located at West Beach, Santa Barbara, immediately adjacent to the harbor breakwater.

Between the 1970s and 1990s the net average shoreline change rate was -0.5 m/yr, measured along 88.0 km of the coast. The *short-term* erosion rate, which averaged -1.2 m/yr, occurred along 72% of the coast. The short-term average accretion rate, 1.1 m/yr, was the highest in Southern California, and was observed along 28% percent of the region.

North of Santa Barbara, most of the coastline had little measurable change in the *long-term* (Figure 35). In the *short-term*, however, the area at and just north of Isla Vista experienced high *short-term* erosion rates, exceeding -2.0 m/yr. In Santa Barbara, shoreline change was strongly influenced by the breakwater construction and subsequent extensive sand-bypassing (Figure 36) at Santa Barbara Harbor (Clayton, 1991; Wiegel, 1994). Relatively high *long-term* erosion south of Santa Barbara at Sandyland and Carpinteria beaches (-0.2 to -0.4 m/yr) changed to a strong trend of accretion in the *short-term* (Figure 35). Recent anecdotal evidence suggests this area is currently undergoing rapid erosion; the *short-term* accretion likely was an artifact of disrupted or reversed transport directions during the 1997-98 El Niño. This analysis only utilizes data through

1998, and shoreline change trends may have become more erosional since then.

South of Rincon Point, there is an increase in the spatial density of harbors, marinas and ports, such as at Ventura, Channel Islands and Port Hueneme. These structures substantially affect the shoreline change rates. Emplacement of groin fields along Buenaventura Beach in the 1960s produced a *long-term* accretion rate of 2.0 m/yr; however, the wide beaches that developed on the north side of the groins eroded rapidly from the 1970s to the 1990s, when erosion rates exceeded -2.0 m/yr. The highest erosion rates in both the *long-term* (-0.7 m/yr) and *short-term* (-5.5 m/yr) were located at Ormond Beach, approximately 6 km south of Port Hueneme Harbor. The maximum short-term accretion rate of 6.0 m/yr was measured at South Beach in Ventura (Table 9C). Overall, the net shoreline change rate changed from slightly accretional to strongly erosional from the long-term to the short-term.

Santa Monica Region

The Santa Monica region is approximately 85 km long and extends from Point Dume to Point Vicente (Palos Verdes) (Figures 14C and 37). This region is within the Santa Monica littoral cell and the Point Dume subcell (Inman and Frautschy, 1966). The coastline, which is extensively developed, includes the well-known beach communities of Los Angeles County (including Malibu, Manhattan Beach, Redondo Beach and Santa Monica). The coast has been highly engineered, including beach nourishment projects, shoreline armoring, construction of jetties, groin fields and offshore breakwaters (California Dept. of Navigation and Ocean Development, 1977; Clayton, 1991; Flick, 1993; Wiegel, 1994). Prior to the 1920s, the beaches within Santa Monica Bay were relatively narrow. The first beach nourishment began in 1938 and continued into the 1990s, although the volumes decreased substantially in the more recent time period (Clayton, 1991; Flick, 1993; Leidersdorf and others, 1994).

The net average *long-term* shoreline change rate, measured along 66.0 km of coast, was 0.4 m/yr. The average long-term erosion rate was -0.1 m/yr (Table 6C) and occurred along 31% of the coast. The average long-term accretion rate was 0.7 m/yr.

During the more recent time period, the net *short-term* shoreline change rate, averaged over 75.2 km of coast, was -0.1 m/yr. Where the short-term rate was erosional, the average rate was -0.5 m/yr; this occurred along 60% of the beaches. The average accretion rate, 0.9 m/yr, occurred along 40% of the beach.

The highest *short-term* erosion rates (-2.2m/yr) in the Santa Monica region were observed at Trancas Beach north of Point Dume, within the Dume subcell. Additionally the highest *short-term* accretion rates (4.0 m/yr) were also measured in the northern portion of the region, at Amarillo State Beach north of Malibu Point (Figure 37; Table 9C).

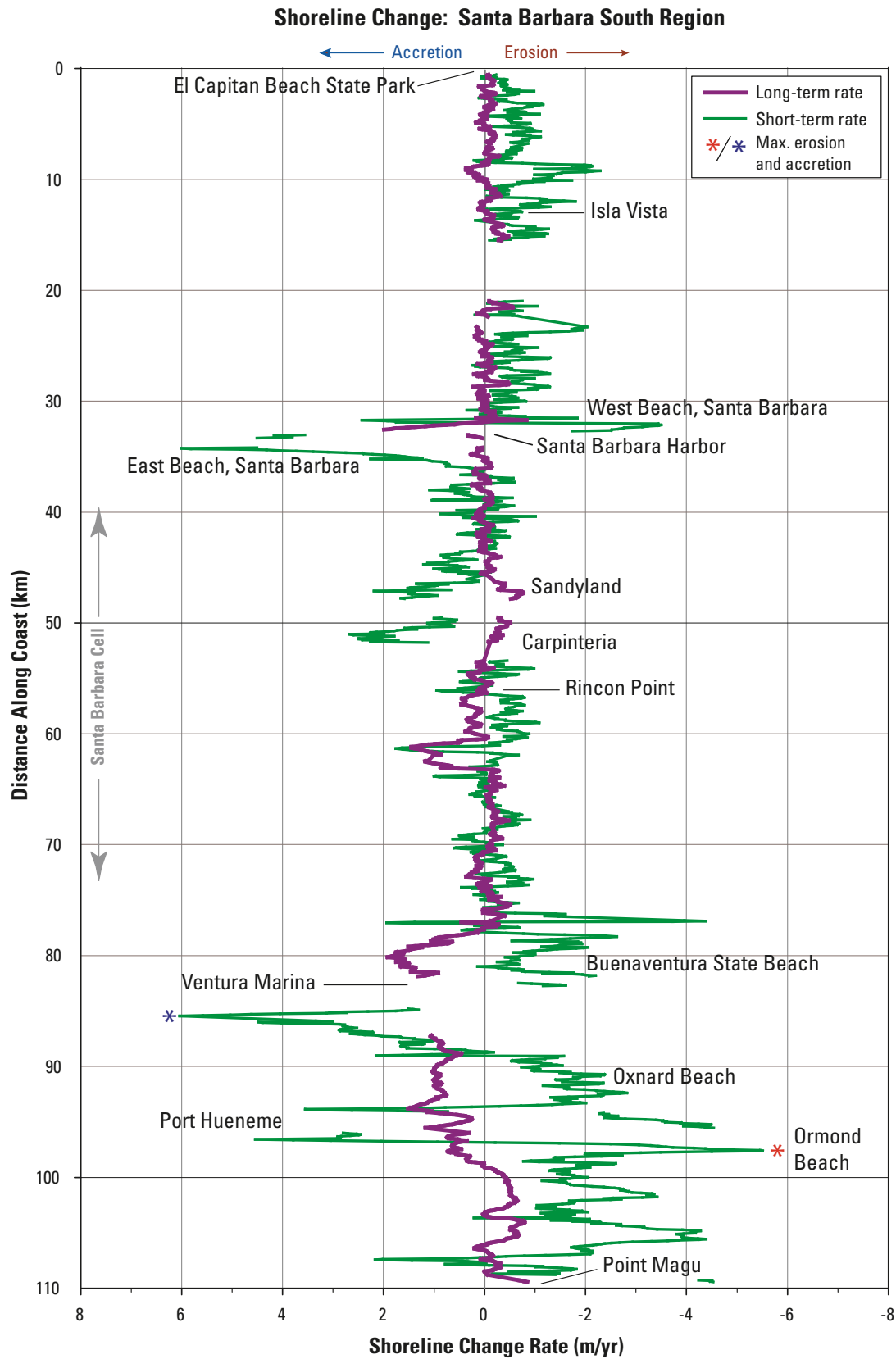


Figure 35. Shoreline change rates for the Santa Barbara South region. The analysis begins at El Capitan Beach State Park in the north, and extends 110 km southeast to Point Magu. The maximum long-term erosion rate was -0.7 m/yr at Ormond Beach and the maximum short-term erosion rates was -5.5 m/yr, also at Ormond Beach.



Figure 36. Dredging of spit at Santa Barbara Harbor. Dredged material is placed down-drift of the harbor where it replenishes East Beach, which accreted more than 6.0 m/yr from the 1970s to 1990s. (photo: Copyright © 2002-2005 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.californiacoastline.org).

The average erosion rate in this region increased five-fold from the *long-term* to the *short-term* (Table 6C). Accretion rates remained nearly consistent from one time period to the next. Widespread accretion was related to the construction of coastal facilities. According to Flick (1993) an average of 800,000 m³/yr of sand was placed on Santa Monica beaches between the 1940s and the 1960s. This

material was primarily from two projects, construction of the Hyperion sewage facility and dredging of Marina del Rey.

In the *long-term*, much of the northern Santa Monica littoral cell was stable with little or no measurable change (Figure 37). The *short-term* trends along the northern portion of the littoral cell are more variable. Beginning at

Table 9C. Maximum and minimum shoreline change rates: Southern California

Region	Long-term (m/yr)	Location	Short-term (m/yr)	Location
Santa Barbara S				
Max. erosion	-0.7	Ormond Beach, 6 km south of Port Hueneme Harbor	-5.5	Ormond Beach, 1.7 km south of Port Hueneme Harbor
Max. accretion	2.0	West Beach, Santa Barbara, north of harbor	6.0	Ventura South Beach, at Santa Clara River flood control channel
Santa Monica				
Max. erosion	-0.3	Leo Carillo State Beach	-2.2	Trancas Beach, 6 km north of Pt Dume
Max. accretion	0.3	Trancas Beach, 4.5 km north of Pt Dume	4.0	Amarillo State Beach, 2 km north of Malibu Pt
San Pedro				
Max. erosion	-2.4	1.5 km south of Newport Bay Harbor	-2.2	Newport Beach
Max. accretion	2.0	Huntington State Beach, north of jetty	2.8	Huntington State Beach, 0.6 km north of jetty
Oceanside				
Max. erosion	-0.3	Cardiff State Beach	-3.5	Del Mar Beach
Max. accretion	1.9	Oceanside Harbor (north side)	6.8	Doheny State Beach, south of Dana Point Harbor
San Diego				
Max. erosion	0.0	---	-3.6	Mission Beach Park, north of jetty
Max. accretion	3.3	Silver Strand State Beach	1.6	Silver Strand State Beach

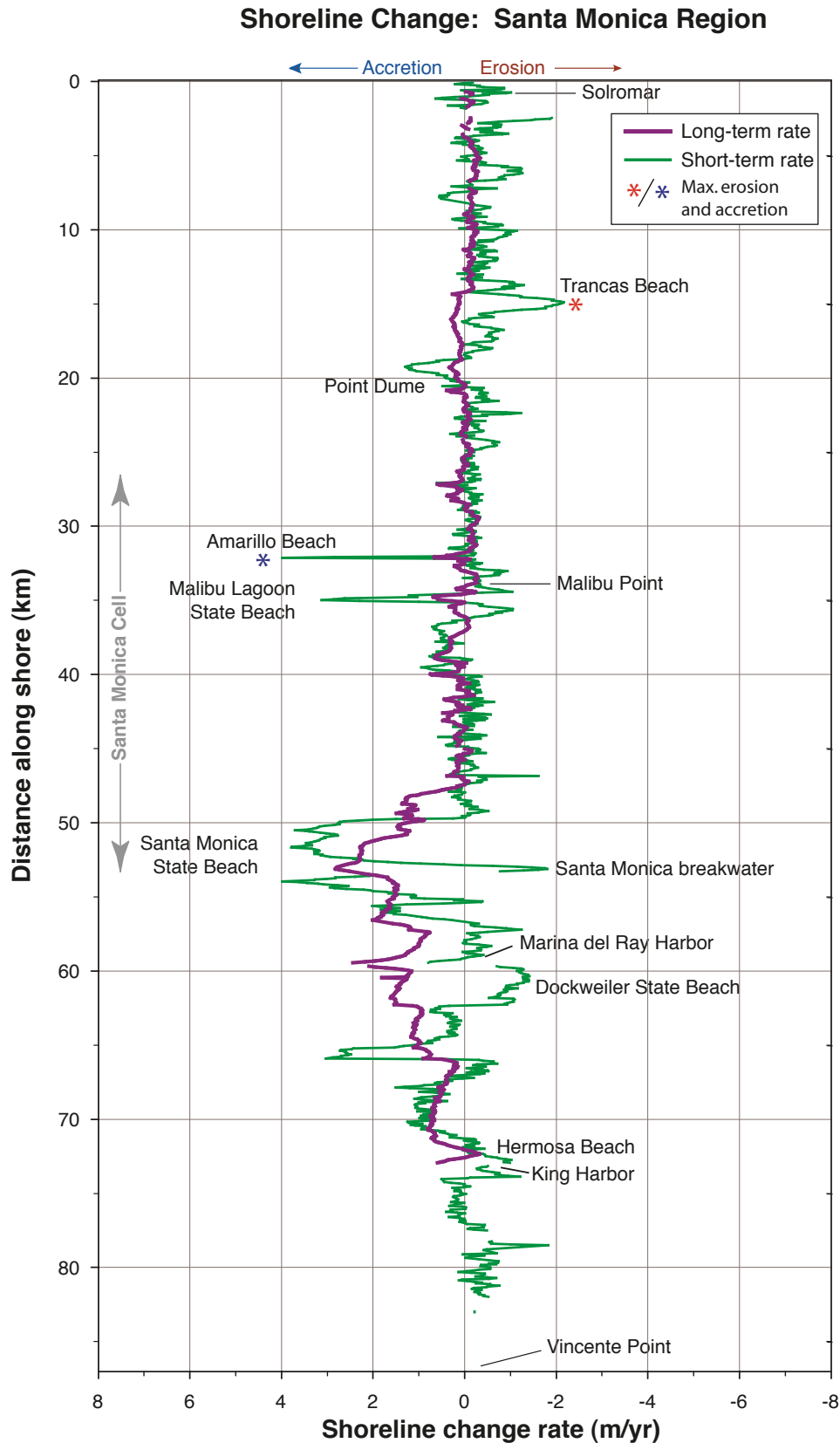


Figure 37. Shoreline change rates for the Santa Monica region. The analysis begins within the Dume subcell to the north near Solromar and extends to Vincente Point. The maximum long-term erosion rate was -0.3 m/yr at Leo Carillo State Beach and the maximum short-term erosion was -2.2 m/yr at Trancas Beach.

the interior of Santa Monica Bay, where groin fields exist along Santa Monica State Beach, the *long-term* change trend became predominantly accretional to Hermosa Beach (Figure 37). According to Coastal Frontiers (1992), as of the early 1990s, this approximately 32-km section of coast had 5 breakwaters, 3 jetties, 19 groins, 5 revetments and 6 piers (Figure 38).

The *short-term* trend showed primarily erosion throughout the northern half of the region except north and south of Malibu. From the interior beaches of Santa Monica Bay to the southern end of the region, the *short-term* change trend, while highly variable, shifts to erosional (Figure 38). From the 1970s to the 1990s, the 2.5 km stretch of beach at Dockweiler State Beach eroded at a maximum rates of over 1.9 m/yr (Figure 37), despite the extensive groin fields and nourishment projects. The *long-term* change at Dockweiler State Beach was accretional, due primarily to massive nourishment projects. The distinct shift to erosion began sometime after 1970, when artificial material was no longer placed on these beaches (Flick, 1993; Wiegel, 1994).

San Pedro Region

This region includes both the San Pedro littoral cell and the Laguna subcells to the south (Figure 9). The small (~14 km long) Palos Verdes subcell to the north of Point Fermin was not covered by this report because the coastline here is rocky with occasional narrow pocket beaches, and thus has little sandy shoreline. The San Pedro region extends approximately 67 km from Point Fermin to Dana Point (Figures 14C and 39). The massive Los Angeles Harbor complex and breakwater west of Long Beach (Figure 40) occupy the northern 14 km of the region. The communities of Long Beach, Huntington Beach and Newport Beach (Figure 14C) are all located within the San Pedro region. The Laguna littoral subcells begin at Newport Bay and extend south approximately 22 km to Dana Point. Due to a data gap in the 1800s-era t-sheets we were not able to calculate long-term shoreline change rates along a large portion of the southern half of this region, although we do have more data for the short-term analysis.

Net *long-term* shoreline change rates in the San Pedro region averaged 0.5 m/yr. The average long-term erosion rate, which was -0.3 m/yr, was the highest in Southern California. However, long-term erosion was observed along



Figure 38. Oblique aerial photograph of a breakwater along the highly engineered Santa Monica coastline (Copyright © 2002-2005 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.californiacoastline.org).

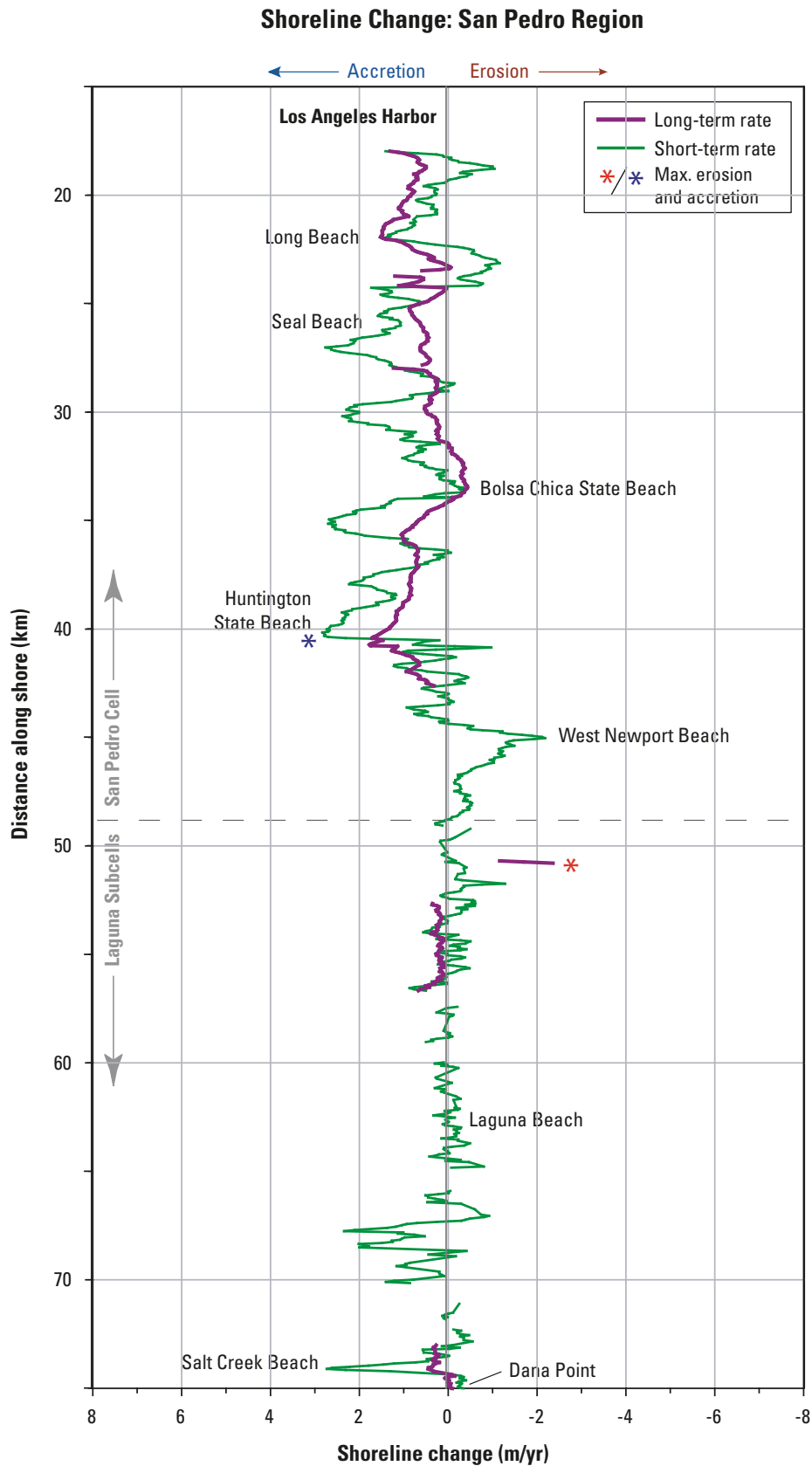


Figure 39. Shoreline change rates for the San Pedro region. The analysis extends from Los Angeles Harbor to Dana Point. The maximum long-term erosion rate was -2.4 m/yr south of Newport Bay Harbor and the maximum short-term erosion was -2.2 m/yr at Newport Beach.



Figure 40. Oblique aerial photograph of the Los Angeles Harbor (photo: Cheryl Hapke, USGS).

only 12% of the 30.3 km of shoreline analyzed. The average rate of long-term accretion was 0.6 m/yr (Table 6C).

The net *short-term* change rate, averaged along 46.3 km of coastline, is 0.5 m/yr, the highest rate in of all California regions, and the only net accretional short-term trend in Southern California. For the short-term period, erosion in the San Pedro region was observed along 35% of the coast and averaged -0.5 m/yr. The average accretion rate was 1.0 m/yr.

Beach nourishment and coastal construction projects greatly influenced the shoreline change patterns within the San Pedro region (Herron, 1987; Clayton, 1991; Flick, 1993; Wiegel, 1994). There was a dominantly accretional trend throughout the northern half of the San Pedro region (Figure 39). The accretion is a result of ongoing nourishment programs that were designed to counteract a loss in natural sediment input from the Los Angeles, San Gabriel and Santa Ana Rivers where major flood control structures trap natural sediment (Clayton, 1991; Flick, 1993; Wiegel, 1994). Accretion rates from Seal Beach to Huntington State Beach (Figure 39) were substantially higher in the *short-term* than the *long-term*. Low rates of *long-term* erosion at Bolsa Chica State Beach make this the only section of coast in the San Pedro littoral cell to have measurable *long-term* erosion, with a maximum of -0.4 m/yr. The area of maximum *short-term* erosion was on Newport Beach where the *short-term* rates reached -2.2 m/yr (Table 9C). There were very few areas of measurable *long-term* erosion throughout the southern portion of the San Pedro region, with the exception of a small stretch of beach south of Newport Bay Harbor where the long-term erosion rate was -2.4 m/yr. The pattern of *short-term* rates in the southern half of the San

Pedro region indicated that this section of coast was stable (Figure 39).

Oceanside Region

The Oceanside region is within the Oceanside littoral cell, which is the second largest of the Southern California cells (Figure 9). This region extends approximately 90 km from Dana Point to Point La Jolla in the south (Figures 14C and 41). The many beach communities in this region include Carlsbad, Solana Beach, Encinitas, San Clemente, Oceanside and Del Mar. Nearly 15 km of shoreline north of the Oceanside Harbor is within the Camp Pendleton Marine Corps Base. Much of the shoreline consists of narrow beaches backed by cliffs and many of the beaches have been nourished (Flick, 1993). According to the U.S. Army Corps of Engineers (1991), nearly 26 million m^3 of sand were placed on beaches in the Oceanside littoral cell from 1954 to 1988, and the earliest nourishment began in the late 1920s on Doheny State Beach (Clayton, 1991).

The net *long-term* shoreline change rate for the Oceanside region, averaged over 78.0 km, was 0.2 m/yr. Average long-term erosion was -0.1 m/yr, and occurred along 31% of the coast. Average long-term accretion was 0.3 m/yr, the lowest average long-term accretion rate of the Southern California regions (Table 6C).

The net *short-term* average shoreline change rate for the Oceanside region was -0.1 m/yr and was assessed over 79.3 km of coastline. The average short-term erosion rate, -0.6 m/yr, occurred along 67% of the coast. The average short-term accretion rate was 0.9 m/yr, and the highest short-term accretion rate, 6.8 m/yr, was measured at Doheny State Beach (Table 9C), where sand-fill was placed north

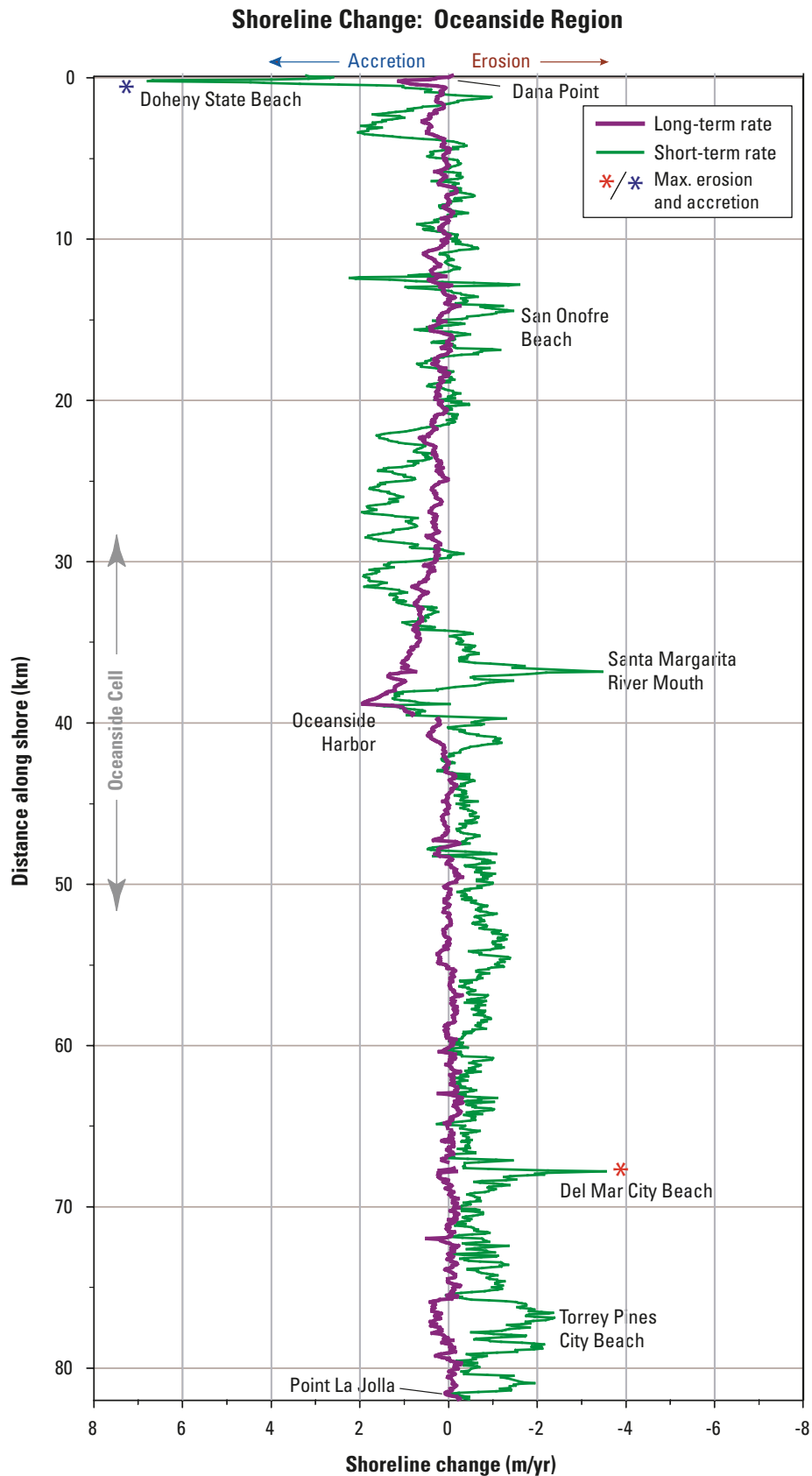


Figure 41. Shoreline change rates for the Oceanside region. The analysis extends from Dana Point to Point La Jolla. The maximum long-term erosion rate was -0.3 m/yr at Cardiff State Beach and the maximum short-term erosion rate was -3.5 m/yr at Del Mar Beach.

of the San Juan Creek jetty in 1964 (Price, 1966; Wiegel, 1994).

There is a clear differentiation in shoreline change trends between the northern and southern parts of the Oceanside region. Most of the beach north of Oceanside Harbor (Figure 41) was stable or accreting, except immediately adjacent to the Harbor where the maximum *long-term* accretion rate of 1.9 m/yr was recorded. This accretion was related to the construction of the harbor jetties which, when completed in 1968, began to trap vast amounts of sand moving downcoast (Flick 1993). The *short-term* change north of the harbor was predominantly accretion, except for the areas around San Onofre State Beach and the Santa Margarita River mouth. South of the Oceanside Harbor, the shoreline was relatively stable in the *long-term*; however, the *short-term* trend was dominantly erosion, and erosion rates increased to the south. The maximum *short-term* erosion rates, which were measured at Del Mar City Beach (-3.5 m/yr), also were high at Torrey Pines Beach (-2.2 m/yr) (Figure 42) as well. According to Flick (1993), the north jetty at Oceanside Harbor either has trapped sand or deflected it offshore (or both), leading to an increasingly starved system in the southern part of the region.

San Diego Region

The San Diego region includes both the Mission Bay and Silver Strand littoral cells that together extend for approximately 45 km from Point La Jolla to the Mexico border (Figures 14C and 43). The coastline in this region consists of rocky coast with small pocket beaches, low-relief linear beaches, and narrow beaches backed by cliffs. The

shoreline is highly engineered, with large coastal facilities such as the flood control jetties at Mission Bay and the 2300-m-long Zuniga Jetty at the entrance to San Diego Bay (Figure 44). In addition, many beaches have been nourished, principally the result of coastal construction projects, beginning as early as the 1930s (Clayton, 1991). As a result of data gaps in the 1800s-era t-sheets in this area, our *long-term* analysis within the San Diego region is limited to the linear beaches of Pacific Beach and Mission Beach Parks in the northern half of the region.

Long-term shoreline change rates for the San Diego region were measured along 21.9 km of sandy shoreline. The net average long-term rate was 0.9 m/yr, the highest net change rate in the state. Average long-term erosion is -0.1 m/yr, and occurred along 21% (Table 6C) of the shoreline. The average long-term accretion rate was 1.2 m/yr, the highest average long-term accretion rate in the state.

The net average *short-term* shoreline change rate, measured along 26.2 km of coastline, was -0.8 m/yr and occurred along 90% of the measured shoreline. Both the net shoreline change and the percent of eroding beaches changed substantially from the long- to the *short-term* (Table 6C). This suggests that the region became increasingly unstable in the latter part of the 20th century.

Although the *long-term* shoreline change trend was accretional in the San Diego region, both the rate of erosion and the percentage of eroding coast increased significantly in the short-term period (Figure 43; Table 6C). *Short-term* erosion was measured over large stretches of coastline, such as along Mission Beach Park just north of the northern Mission Bay jetty, as well as along the southern portion of Silver Strand State Beach. The highest *short-term* erosion



Figure 42. Narrow beach fronting tall coastal bluffs at Torrey Pines City Beach. The short-term beach erosion rates are high in this area (photo: Gary Griggs, UCSC).

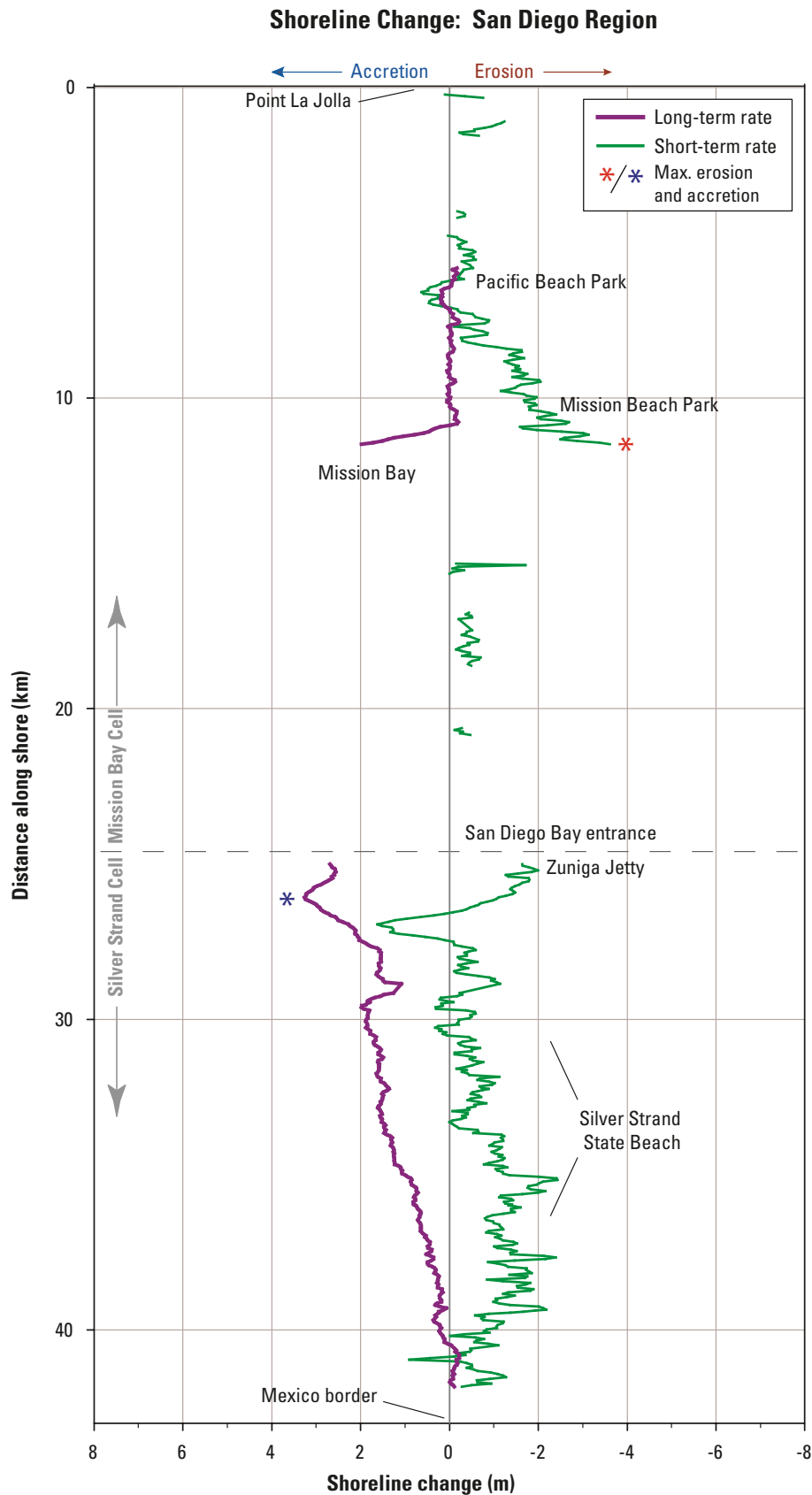


Figure 43. Shoreline change rates for the San Diego region. The analysis extends from Dana Point to the Mexico border. There is no measurable long-term erosion rate in this region; the maximum short-term rate was -3.6 m/y at Mission Beach Park.



Figure 44. Oblique aerial photograph of Zuniga Point and breakwater at the entrance to the San Diego Harbor (photo: Cheryl Hapke, USGS).

rate (-3.6 m/yr) was observed at Mission Beach Park (Table 9C). Other than just north of the Mission Bay jetty, the Mission Bay littoral cell showed little *long-term* change. In the southern half of the San Diego region, there was rapid *long-term* accretion (3.3 m/yr) adjacent to Zuniga Point and breakwater (Figure 44) on Coronado Island. The effect of this structure diminished to the south. The highest *long-term* accretion rates were directly related to the entrapment of sand against an along-shore barrier (USACE, 1986; Wiegel, 1994). *Short-term* shoreline change in the southern half of the region shifted from accretion in the north (with the exception of immediately adjacent to the breakwater) to erosion in the south. The highest erosion rates along this section of coast were over -2.0 m/yr.

DISCUSSION AND FURTHER CONSIDERATIONS

Summary of Shoreline Changes

According to a recent study by the California Department of Boating and Waterways and the California State Coastal Conservancy (2002) the state of California has 1,860 km of open ocean coastline. Of this, 1,188 km has some type of fronting beach. In many cases, especially in Northern and Central California, the beaches are narrow strips of sand fronting coastal cliffs or bluffs and may only be exposed during lower tides. Shoreline change analyses were not conducted for the approximately 36% of the total length of the California coastline that is characterized as

rocky. In this report, *long-term* rates of shoreline change are provided for 728.1 km of the total length of sandy shore, and *short-term* rates are provided for 807.1 km. Of the sandy shorelines, gaps in either the lidar data or T-sheets resulted in a lack of four shorelines along 27% of the coast characterized as beach. Therefore, in this report we present *long-term* shoreline change rates for 40% of the total California coast and *short-term* rates for 44% of the total length of coastline.

Of the California shoreline where *long-term* rates of change were quantified 40% were eroding; the highest regionally-averaged *long-term* erosion rate, -0.2 m/yr, occurred in the Monterey Bay and San Francisco South regions. This rate is high due to the artificially high erosion in the southern portion of the Monterey Bay caused by *long-term* sand mining operations (Griggs and others 2005; Thornton and others, 2006). Average *long-term* erosion rates for California were highest in the San Pedro region in Southern California (-0.3 m/yr), the Monterey Bay region in Central California (-0.6 m/yr) and the Klamath region in Northern California (-0.4 m/yr). The San Francisco South region experienced erosion along the most coastline (76%). One of the highest specific areas of *long-term* erosion in the state (-1.8 m/yr) was on the north side of Point Año Nuevo in the San Francisco South region (Table 9B) where a spit was breached in the late 1800s and large volumes of sand were mobilized and transported down coast. In Southern California, the highest measured *long-term* erosion rate, -2.4 m/yr, was south of Newport Bay Harbor. In Northern California, the maximum *long-term* erosion rate (-1.2 m/yr)

was adjacent to the Klamath River mouth where a dynamic spit shifts spatially through time.

Overall the highest *long-term* accretion rates were associated with coastal engineering structures and beach nourishment sites (Southern and Central California) and where there is high sediment supply from large rivers (Northern California). The highest rate of *long-term* accretion (4.8 m/yr) occurred 10 km south of the Klamath River mouth, and appeared to be a natural rate, likely associated with sediment influx from the soft bluff and gullies that are incised in the bluffs.

In general, there was a statewide increase in the percent of sandy shoreline that eroded from the *long-term* (40%) to the *short-term* (66%). This trend implies that erosion hazards have increased in California, especially from the 1950s-70s to the late 1990s. This may be related to the climatic shift that began in the mid-1970s when California's climate entered a period of more frequent and stronger storms, including two of the most intense, and damaging El Niño winters of the last century. It must also be remembered that our analysis only extends up to 1998 (or 2002 in some areas) and does not include trends that may have developed since.

Planned Updates and Related Research

The USGS plans to revise and report on rates of shoreline change for California every 5 to 10 years, and thus this report and associated data should be considered a work in progress. The revision interval will depend on new information and technological advances that will allow relatively rapid shoreline position acquisition, processing, and dissemination. Future revisions will also incorporate the results of ongoing shoreline research. For example, we plan to continue to refine the methodology that we applied to quantify the effects of using different shoreline proxies on the shoreline change rates. We will also explore other approaches to reduce shoreline positioning uncertainty (spatial errors) and shoreline sampling uncertainty (temporal variability). GPS technology has greatly reduced positioning errors so that they are no longer a significant component of the uncertainty analysis. GPS and lidar also eliminate the need for digitization and introduction of associated positioning errors. The dynamics of sandy beaches ensure that short-term shoreline fluctuations will not be eliminated entirely from future shoreline positions, but data being collected in various coastal regions as part of the USGS regional studies will provide quantitative assessments of seasonal and inter-annual changes in shoreline position. These assessments will provide a means to determine if the detected shoreline change is within the expected range of movement and allow us to further constrain the uncertainties.

Influence of Human Activities

As coastal communities continue to grow along the California Coast, potential conflicts may arise between preservation of property (typically privately owned) and conservation of the beach (typically publicly owned). Past social responses indicate that these conflicts most likely will be resolved through a combination of beach nourishment projects and shoreline protection structures. Both of these engineering responses to erosion alter the natural beach processes and eventually lead to artificial shoreline positions.

Adding sand to eroding beaches is a common method to mitigate storm damage and to maintain a recreational beach. Beach nourishment alters the rates of retreat by causing rapid artificial accretion of the shoreline. In those areas where nourishment is frequent, the trends of shoreline change will be biased toward accretion or stability. Additionally, the proposed removal of dams in some of the watersheds in California may alter the shoreline change trends, as previously impounded sediment begins to make its way into the littoral system. Passive erosion of the beach by emplacement of seawalls or revetments may initially lead to an increase in the rate of erosion, but the rate will slow to zero if the beach erodes away in front of the structure. Because many beaches are already altered by shoreline protection projects and more will be altered in the future, the methods of analyzing shoreline movement have to take shoreline stabilization activities into account so that the documented trends and derived rates of change can be expressed in their proper context.

Distinguishing between natural rates of shoreline movement and those influenced directly by human activities is crucial when historical rates of change are used for planning and to project future shoreline positions. Improved methods of analyzing shoreline movement will be needed to document the natural rates of shoreline change.

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Erosion Along An "Equilibrium Coastline",
Southern Monterey Bay, California

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Abstract

A number of lines of evidence indicate that, in the past, all of inner Monterey Bay, from New Brighton Beach at the north to Del Monte Beach at the south, has been an equilibrium coastline with sediment input and output being essentially in balance. The existence of wide sandy beaches throughout this area as well as the flanking sand dunes indicate sand supply in the past was in excess of sand loss. The log spiral or arcuate shape of both ends of the bay is also evidence of this equilibrium condition, meaning that overall coastal configuration remains approximately the same overtime, with periods of erosion being balanced by subsequent accretion.

Field observations as well as comparative measurements from early surveys (dating back 70 years) and aerial photographs, (dating back 45 years) however, indicate that the coastline of southern Monterey Bay has been retreating for a number of years. Average annual erosion rates for the southern bay (Municipal Wharf to Holiday Inn) range from about one to two feet. From Sand City to Marina, erosion has progressed more rapidly at rates of 2.5 to over 10 feet/year on the average. Highest rates occur in the Ft. Ord area where, at one location, 173 feet of bluffs consisting of loose dune sand were eroded between 1962 and 1982.

A partial reduction in the sand supplied by the Salinas River due to reservoir impoundments, continued removal of large quantities of beach sand (300,000 yds./year) by sand mining operations, and the more frequent occurrence of severe storms have all contributed to this coastal retreat and disequilibrium. Coastal erosion has now begun to threaten developments such that major protective works are now being emplaced.

INTRODUCTION

Monterey Bay on the central California coast has a unique semicircular shape open to the west. The combination of resistant rocky headlands at Point Santa Cruz on the north and Point Pinos on the south, the low lying structural depression between the two, and the effects of wave refraction have produced an embayment which is spiral or arcuate shaped at both ends (Figure 1). Although California's coastline has a number of hooked or spiral shaped bays (Drakes Bay, Half Moon Bay, San Diego Bay, for example), these are all formed to the south of resistant headlands. This coastline configuration is one of equilibrium, with the log spiral or hooked shape of the coast being the end result or response to a dominant wave approach from the northwest.

Swells which approach the central California are dominated by waves from the quadrant between northwest and west, with occasional but large storm waves

coming from the southwest or west. The configuration of inner Monterey Bay is thus the long term geologic response to the prevailing wave conditions as can be seen on wave refraction diagrams. Wave fronts bend to a shape closely approximating that of the inner bay shoreline (Figure 2).

By definition, an equilibrium coastline, or beach, is in balance such that over the long term it is neither advancing nor retreating. On the basis of overall coastline morphology, then, Monterey Bay from New Brighton Beach on the north to Del Monte Beach on the south should be in equilibrium (Figure 1). In other words, sand input should be essentially in balance with sand output over time. The presence of a broad dune field flanking the bay from north of the Pajaro River to Monterey, however, indicates that at least in the recent geologic past, excess sand was available and was being transported inland by the predominant winds from the northwest.

COASTAL EROSION ALONG SOUTHERN MONTEREY BAY

Despite the apparent equilibrium configuration of the bay's coastline, it has been apparent from field observations, as well as measurements from early surveys (dating back 70 years) and aerial photographs (dating back 45 years) that the shoreline of southern Monterey has been retreating. Although the beaches narrow and widen seasonally due to changing wave conditions, and the dunes undergo periods of erosion during major storms followed by slow accretion, the overall pattern for at least the past 70 years has been progressive shoreline retreat.

A series of eight severe storms struck the California coastline in early 1983. Wave damage to coastal structures as well as beach, dune, and cliff erosion were exaggerated by the simultaneous occurrence of extreme high tides as well as elevated sea levels due to storm surge. Sea levels at San Francisco were 2 feet above those predicted and the highest measured in 128 years of record keeping. The overall effect on the entire California coast of these storms was devastating with damage in excess of \$100,000,000. Erosion throughout southern Monterey Bay was severe and brought attention to the short and long term erosion issues as did the beach and dune erosion during the preceding five years.

It is clear to those who study coastal erosion that the retreat of the shoreline, whether, dune, beach, or bluff, is an episodic or irregular process. Thus, although long or short term erosion rates are usually expressed in feet/year, this is simply an average value based on the total amount of erosion over some time span between aerial photos or surveys. It is the infrequent but large storms usually aided by high astronomical tides, such as those of 1978 and 1983 which produce the major erosion. For the most part, then, the lifespan of any particular shoreline structure could be approximated by utilizing the average erosion rate at the site in question, but more realistically, the controlling factor is how soon the next severe coastal storm will occur.

A number of studies have investigated shoreline erosion along southern Monterey Bay. The methods utilized most commonly involve measurements from sequential aerial photographs or comparative ground surveys. The accuracy and reliability of average erosion rates determined from stereo aerial photographs are based on many factors, including dates, scale and resolution of the photographs, measurement techniques and availability of reference points for

repeat measurements, and the skill and experience of the interpreter. Despite these apparent limitations, erosion measurements around southern Monterey Bay show remarkably consistent patterns.

Some of the earliest indications of long term retreat was presented by Cooper (1967) who cited the narrowing of the southern Monterey Bay dune belt during the past 3000 to 5000 years opposite Fort Ord as evidence of long term coastal and dune erosion. The height of the dunes here, virtually adjacent to the beach, indicated that a much broader dune belt should have existed, but had been gradually eroded.

Continued erosion in the Sand City area (Figure 1) and interest in building a state beach led to a Department of Navigation and Ocean Development study (1972) which showed average shoreline recession between 1946 and 1967 at about five feet per year. Arnal, Dittmer and Shumaker (1973) reported an increase in shoreline erosion rates in the Fort Ord area from about 1.5-2.0 ft/year in the 1920's to about 3.0 ft/yr in the 1950's to 5.0 ft/yr in the 1960's.

The severe erosion along this coastline within the past 6 years led to a number of erosion studies, often directed towards specific sites where either existing buildings were being threatened (Griggs, 1983; Smith, 1983), new construction was proposed (Thompson, 1981; Thornton, 1984), or a general interest in the coastline existed (Leighton and Associates, 1982; Jones, 1983) (Table 1). It has now become clear that the shoreline from the Monterey breakwater to the Salinas River mouth is retreating and has been for some time.

These data, which span differing time periods, indicate that average erosion rates are the lowest at the extreme southern end of the bay (Monterey breakwater to Del Monte Beach - 1.0 to 1.8 ft/year) and increase to maximum values at Ft. Ord where retreat at some locations averaged over the last 15-25 years amounts to 12-15 feet/year (Figure 3). Further north at Marina the rates decrease somewhat but are still very high (5.6 to 6.8 ft/yr).

The erosion has advanced far enough and is occurring rapidly enough that major structures are now threatened with collapse. This has even become a problem in the Del Monte Beach area. An 84 unit apartment complex constructed on the dunes about 15 years ago provides a clear example of the erosion problem. Retreat of the dunes within recent years had come to within 14 feet of the apartments by spring 1983 (Figure 4). Although emergency rip rap was emplaced along 585 feet of eroding dune and public beach to protect the structures (Figure 5), the city of Monterey has denied a request to build a permanent structure. The apartment complex is built right to the property line requiring any rip rap or revetment structure to be built on public beach. The aerial photographic record for the site shows an average retreat rate of the dunes of 1.2 ft/year between 1956 and 1983. On the basis of original subdivision maps and subsequent surveys for the adjacent property to the southwest, approximately 140 to 150 feet of dunes have been eroded since 1912-14 (McIntyre, 1984). This "long-term" average amounts to two feet of retreat per year. An entire row of "lots" and a road shown on original surveys now lie beneath the waves. A thorough investigation of erosion rates prior to apartment construction would have avoided the serious problem faced at the apartment complex today. Two hundred and twenty thousand dollars has already been spent on temporary protection and a permit request for a protective structure

on city property denied. It is only a matter of time until the arrival of the next major storm waves when destruction of the outer apartments will begin as their pilings are undermined.

In this area all of the public utilities are buried in the dunes directly behind the beach. Erosion in 1983 broke the waterline, which had to be rerouted, and threatened the sewer and electrical lines as well.

A large Holiday Inn was constructed on the beach just upcoast in the Sand City area in 1968. In order to protect the hotel a concrete sheet pile seawall was constructed which extends across the front and north side of the building (Figure 6). Overtopping seawater during the 1983 storms led to piping through joints between the panels and several large areas of collapse behind the wall. Long term (1956-1983) erosion rates in this area average about 2-5 ft/yr. (Figure 3) and will eventually outflank the seawall.

Erosion at Ft. Ord is the most severe in the entire Monterey Bay area, and as elsewhere, is dramatically episodic. The army has just completed a study of the area (Smith, 1984) due to continued erosion threats to Stillwell Hall Recreational Center and the Fort Ord Ammo supply point. Smith concludes on the basis of observations of longtime Fort Ord employees that average retreat rates of 6-7ft/year characterize the area. Measurements along specific transects across aerial photos of the military base and field surveys by Jones (1983) yield rates average and retreat of 11.7 to 15 feet/year for unprotected sites (1956-83.)

An awareness of the continuing erosion of the bluffs (which consist of unconsolidated dune sand) and threats to structures in the 1960's and 1970's led to some stabilization efforts by the Army. Loose rock and broken concrete rubble dumped over the bluff provided some protection during the generally quiescent period of the 1960's to early 1970's. Dune erosion to either side of the "protected" area in front of Stillwell Hall had proceeded 50 to 100 feet inland, however, by 1982. Storm waves in 1983 broke over the unmaintained rock to undermine the toe of the bluff. Large scale sliding and slumping of the dunes occurred which advanced rapidly to within 15-20 feet of the hall. By early 1984 an additional protection project was underway as rock was being dumped at the foot of the eroding bluff (Figure 7). Conclusions of the Army study of the erosion problem indicate a cost of \$4 million to demolish and replace Stillwell Hall, but a cost in excess of \$7 million for reliable shore protection with maintenance expenses and eventual extension being a certainty.

Perhaps the most spectacular erosion in the Fort Ord area is at one of the sewer outfall lines. This large diameter pipe was initially placed atop massive concrete piers (set 35 feet apart) and buried below sand level in 1962. The outfall line is now 20 feet above beach level and six piers are exposed, indicating a loss of 175 feet of bluff in 21 years (Figure 8). As much as 40 feet of bluff was lost in the first 3 months of 1983 alone (Jones, 1983).

Is there a logical reason for the greater erosion rates at this particular locality? It appears that the refraction of waves within the bay and over Monterey Submarine Canyon in particular produces a convergence or increase in wave energy in the Ft. Ord area. Storm waves from the west and northwest are known locally to have the worse consequences, and the Ft. Ord coastline has been observed to have the highest breakers anywhere in Monterey Bay under

these conditions (Smith, 1984, Thornton, 1984).

FACTORS PRODUCING COASTLINE DISEQUILIBRIUM

Although the configuration of southern Monterey Bay is one of apparent equilibrium, it is clear that coastline retreat has been taking place for some time. This retreat has accelerated within the past 5 or 6 years due to more severe storm conditions since 1978 which may or may not be associated with a climatic change. If this type of weather persists as coastal geologists at Scripps Institute of Oceanography have predicted, the high recent erosion rates will continue. Although this is difficult to quantify, it is clear that the relatively moderate weather conditions of the 1950's to late 1970's produced much less coastline erosion than did the severe winters since 1978.

A more significant long term factor is the apparent deficiency in the littoral sand budget. Two evaluations of sand budgets in southern Monterey Bay have been carried out (Dorman, 1968, Arnal, Dittmer, and Shumaker, 1973) and summarized by Allyaud (1978) and Thornton (1983). Major sediment inputs to the beaches of southern Monterey Bay include the Salinas River, longshore drift from the north, wave transport from offshore and dune or bluff erosion. Output or losses include transport down Monterey Submarine Canyon, wind losses into the dunes and sand mining (Figure 9). Although there are limitations and difficulties involved in calculating budgets of this sort, Monterey Bay has been well studied and measurements and reasonable approximations can be made for the various inputs and outputs. Although the 1968 and 1973 studies produce somewhat different values for individual components of the budget, both conclude that sand output exceeds input resulting in continuing erosion of the beaches and flanking dunes.

It seems clear that recent historical events have clearly affected the sand budget of area. The Salinas River is one of the major sand suppliers for southern Monterey Bay. The Nacimiento Dam built in 1957 and the San Antonio Dam built in 1965 have impounded about 15% of the watershed. The effect is to 1) trap all of the sand which formerly would have been delivered to the coast from these sub-basins, and 2) reduce peak flood flows which are responsible for transporting the bulk of the fluvial sediment which ultimately reaches the beach.

Another major loss which has been difficult to quantify precisely is the removal of beach and dune sand through sand mining. Four active operators take in excess of 300,000 cubic yards of sand annually directly from the beaches through draglines (Figure 10). Sand mining began as early as 1906 and has increased over time. The annual volume removed represents a significant loss which has to be considered as detrimental. If the 300,000 cubic yards of beach sand removed each year required a comparable amount of dune erosion in order to replenish the beach, it would require the removal of 5 feet annually from the entire 10 miles of dune front from the Monterey breakwater to Marina (assuming an average dune height of 30 feet).

The shoreline of southern Monterey Bay will continue to erode unless there is some major change in the sand budget. The structures now existing at the bluff edge can only be protected temporarily and at great cost. As the economic assessment of Ft. Ord shows, it is less costly in the long run to demolish and rebuild than to attempt to halt the ongoing erosion at this location. Any protective structure will eventually create a peninsula as the

flank areas continue to retreat, and the structure itself should be considered temporary. A termination of sand mining may be one of the only ways to reduce the rate of retreat, although with the existing data the impact of such an action is difficult to quantify.

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Table 1. Shoreline Erosion Rates Along the Coastline of Southern Monterey Bay

<u>Location</u>	<u>Time Span</u>	<u>Average Rate (Feet/Year)</u>	<u>Source</u>
Marina	1937-83	5.6-6.0	Jones (1983)
Fort Ord	1956-83	11.7-15.0	Jones (1983)
Fort Ord	1920's	approx. 3.0	Arnal, Dittmer, Shumaker (1973)
Fort Ord	1950's	~ 3.0	"
Fort Ord	1960's	5.0	"
Fort Ord	"long term"	6.0-7.0	Smith (1983)
Sand City	1956-83	4.0-6.2	Jones (1983)
Sand City	1932-70	1.3-2.6	Welday (1972)
Sand City	1946-67	5.0	DNOD (1972)
Sand City	1932-70	1.4-3.3	Thompson (1981)
Sand City	1945-81	2.4-5.2	Leighton and Assoc. (1982)
Monterey State Beach	1956-83	1.0-1.7	Jones (1983)
Monterey State Beach to Del Monte Beach	1939-78	1.0-1.8	Thompson (1981)
Del Monte Beach	1956-84	1.2	Griggs (1983)

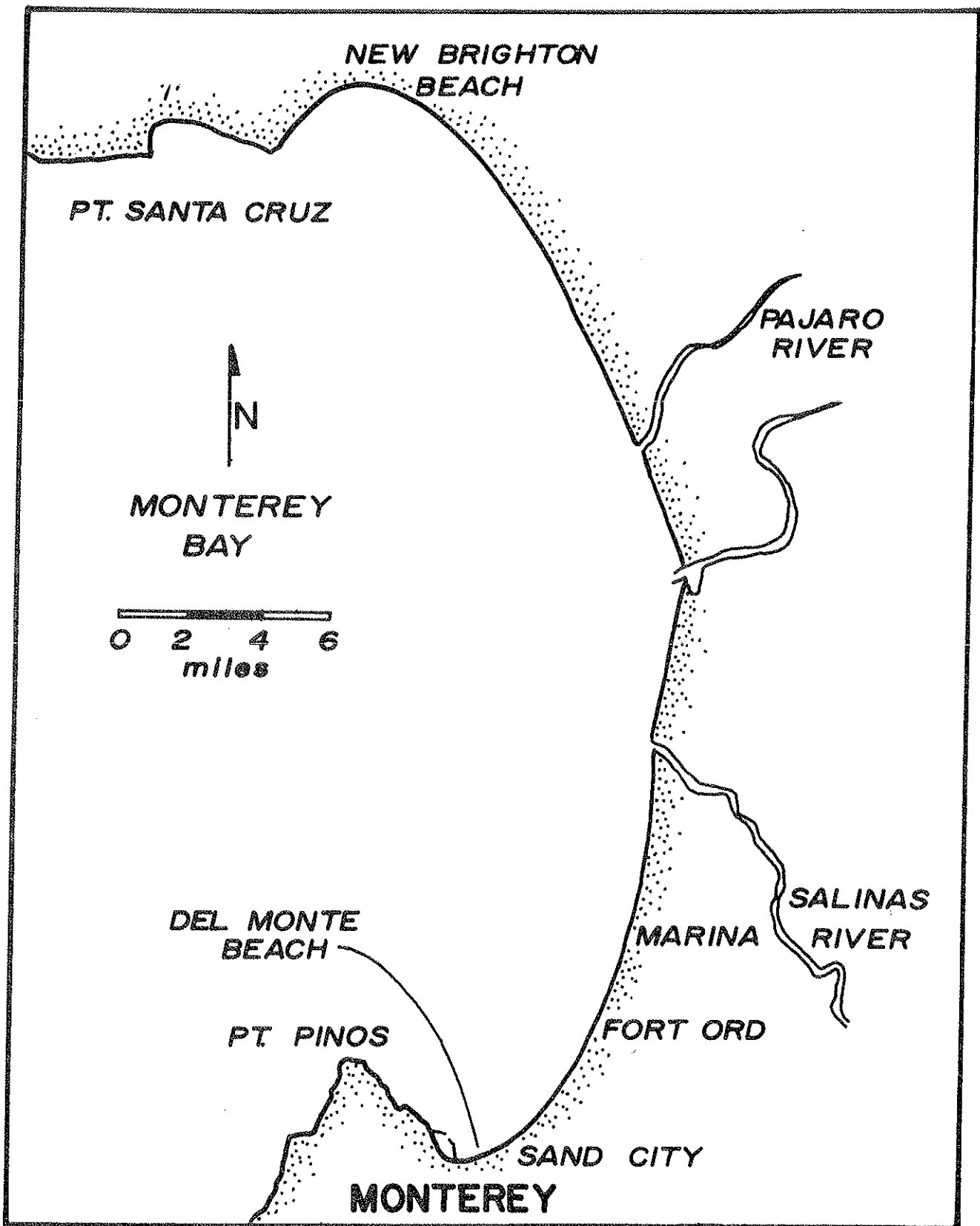


Figure 1. Location Map for Monterey Bay.

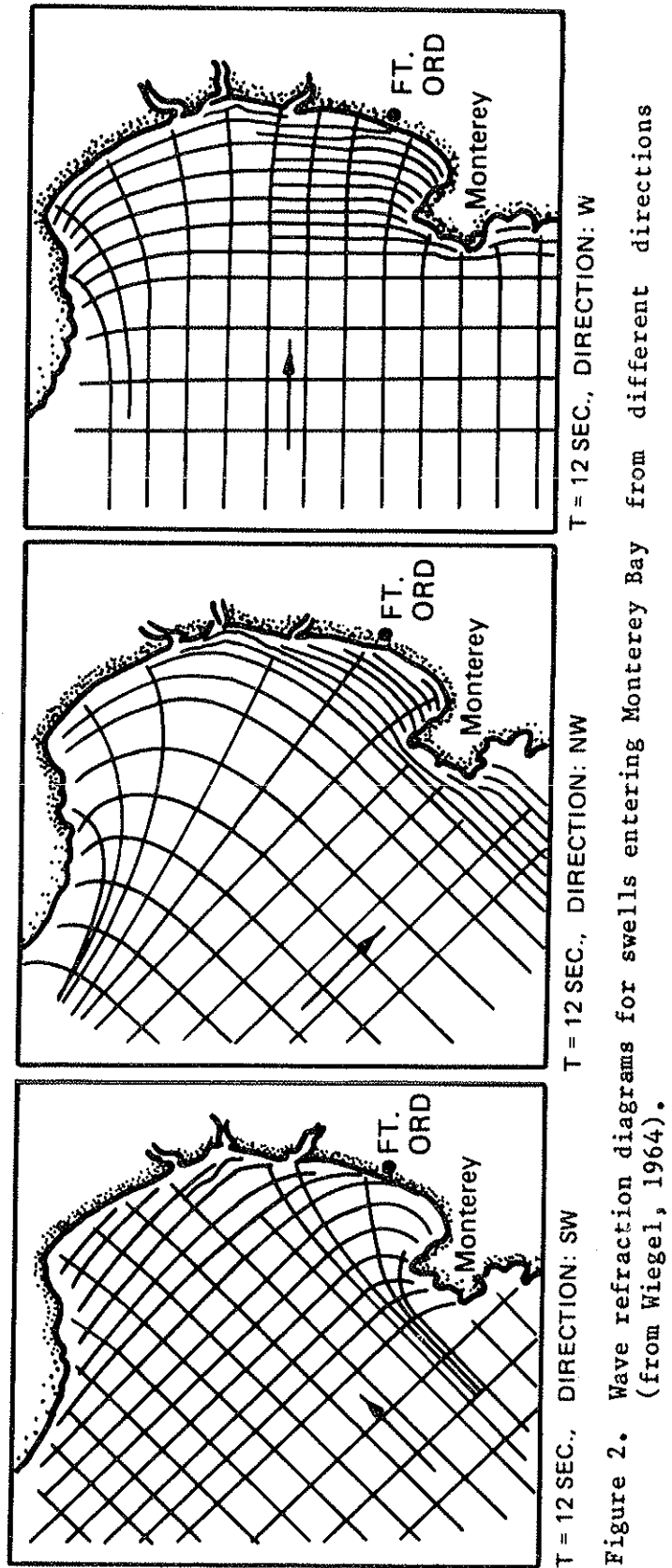


Figure 2. Wave refraction diagrams for swells entering Monterey Bay from different directions (from Wiegel, 1964).

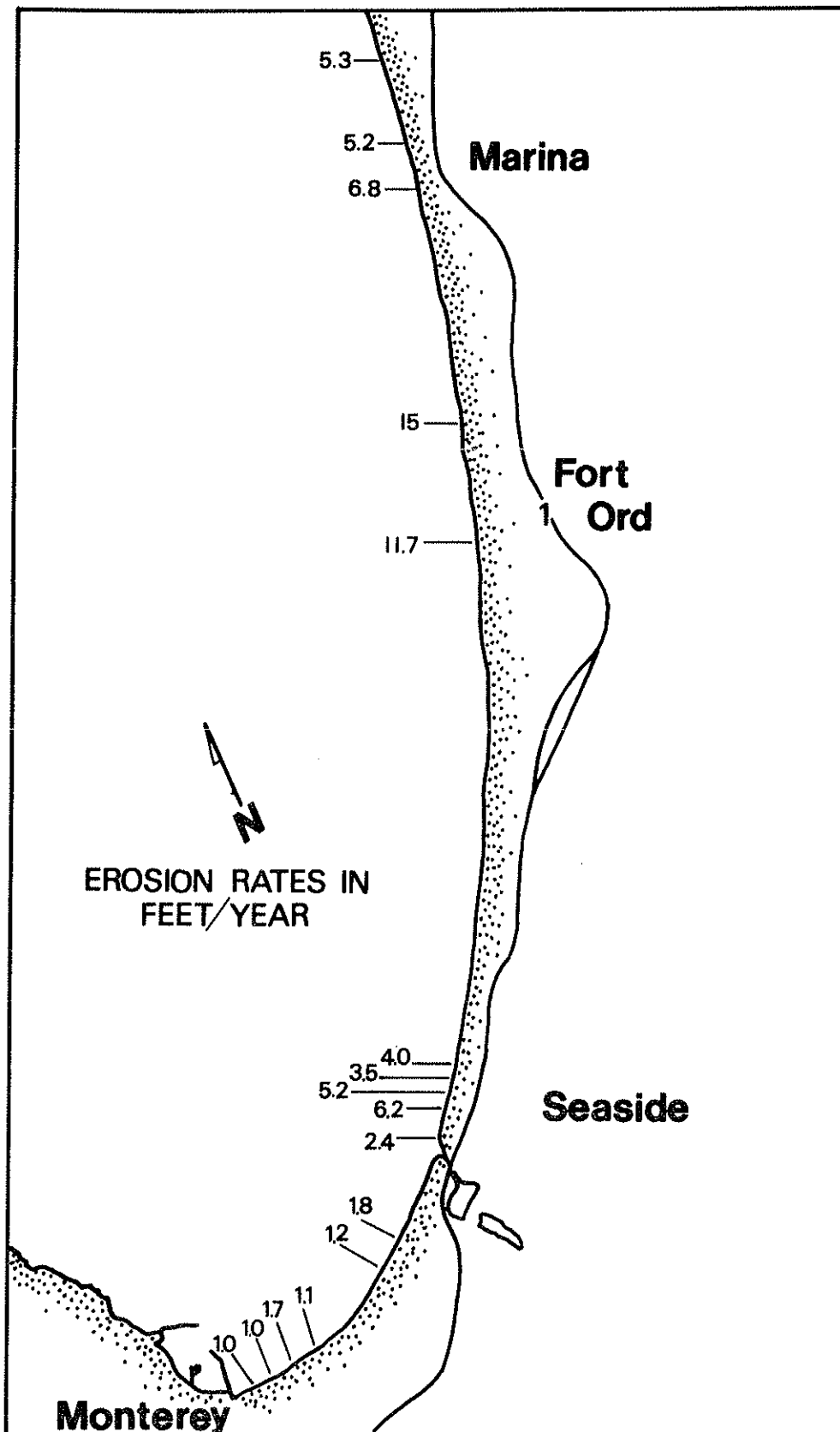


Figure 3. Average annual shoreline erosion rates for southern Monterey Bay (see Table 1 for references)

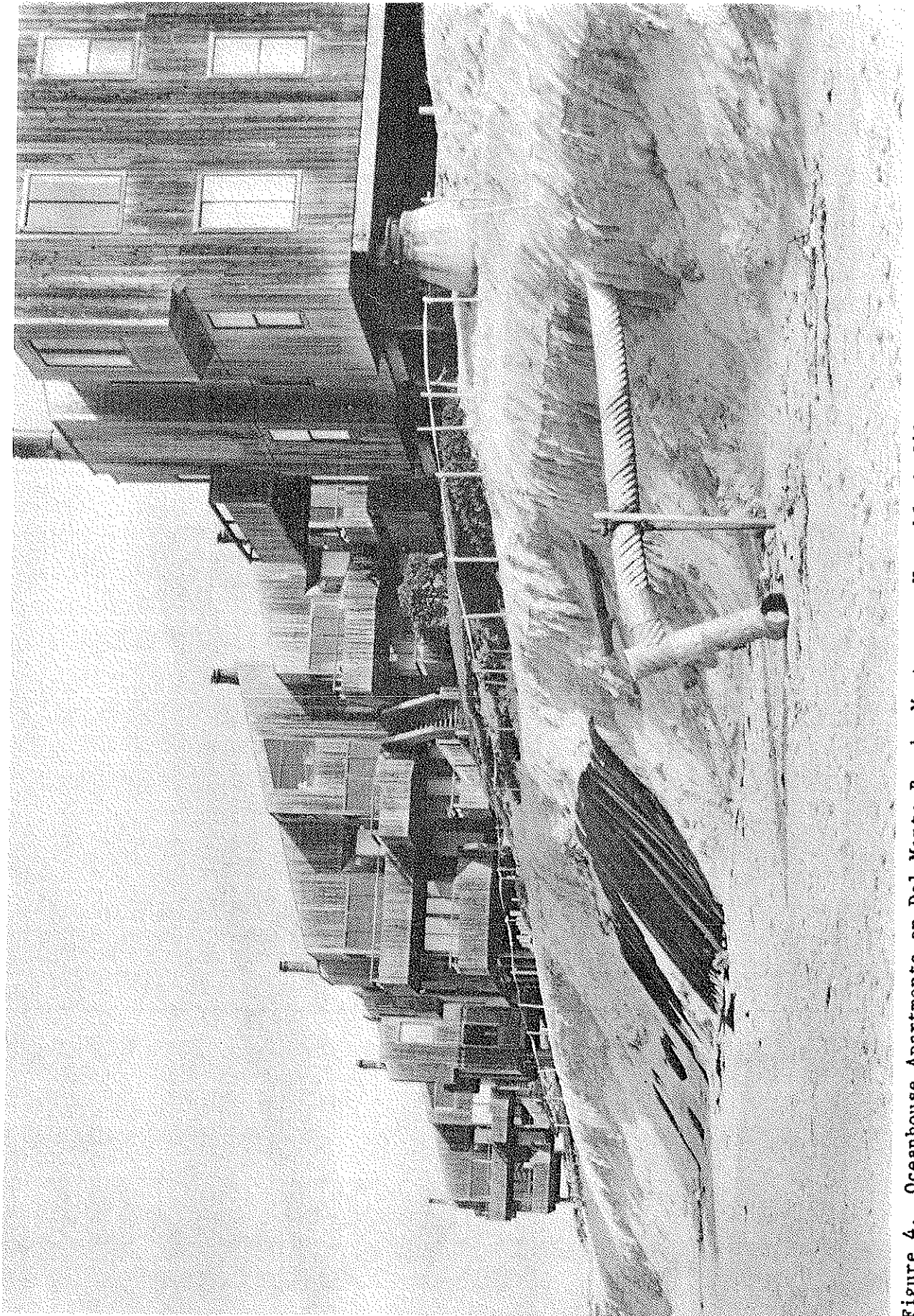


Figure 4. Oceanhouse Apartments on Del Monte Beach, Monterey. Note black filter cloth exposed (January 1984).



Figure 5. Oceanhouse Apartments after emplacement of "emergency" rip rap (May 1984).



Figure 6. Holiday Inn at Sand City showing protective seawall (May 1984).



Figure 7. Stillwell Hall at Ft. Ord showing protective rip rap and rubble. Note erosion and failure of loose bluffs behind and at flanks of rubble (May 1984).

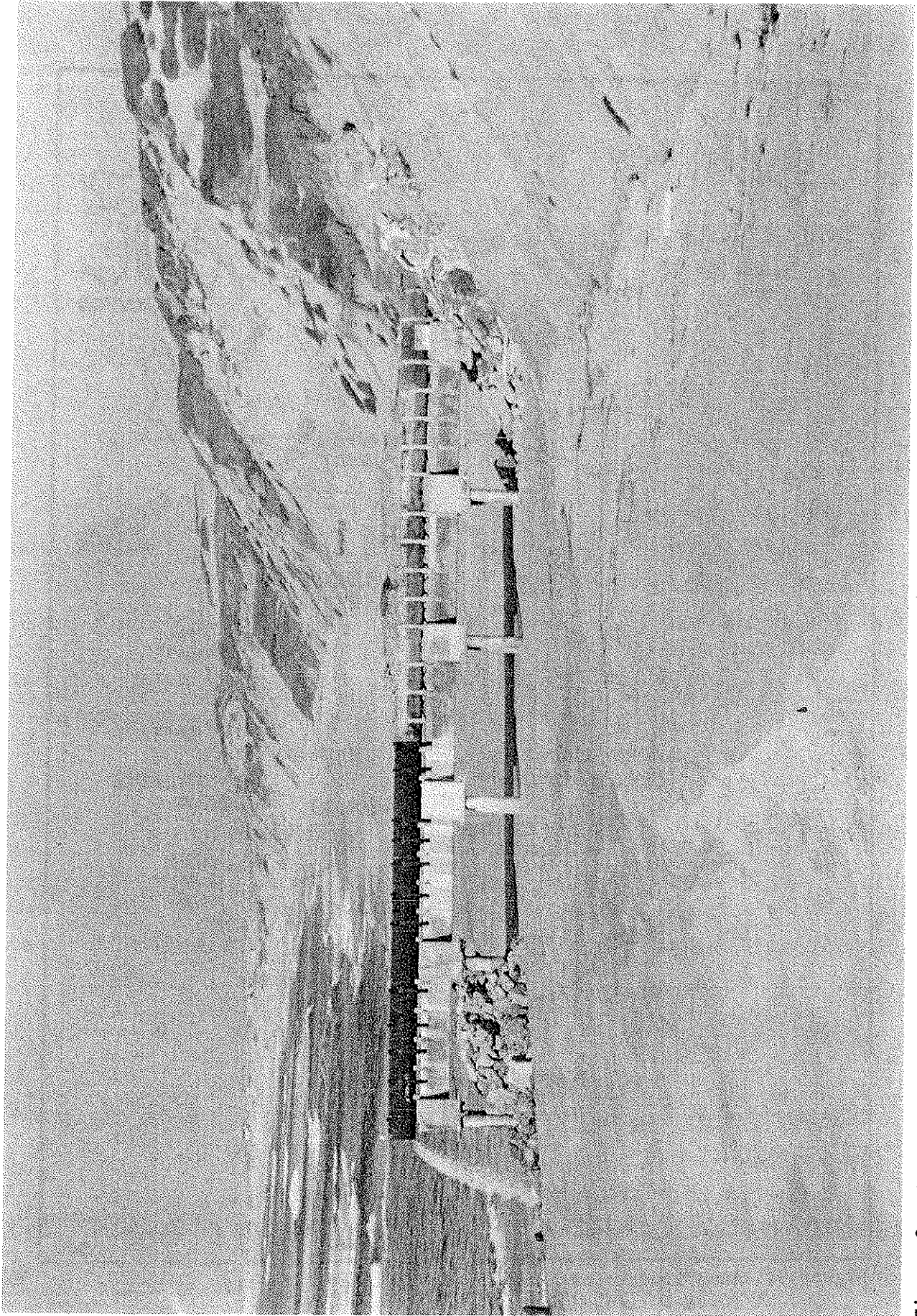


Figure 8. Sewer outfall line exposed by continued erosion at Ft. Ord. In 21 years, 175 feet of retreat has taken place (Jan. 1984).

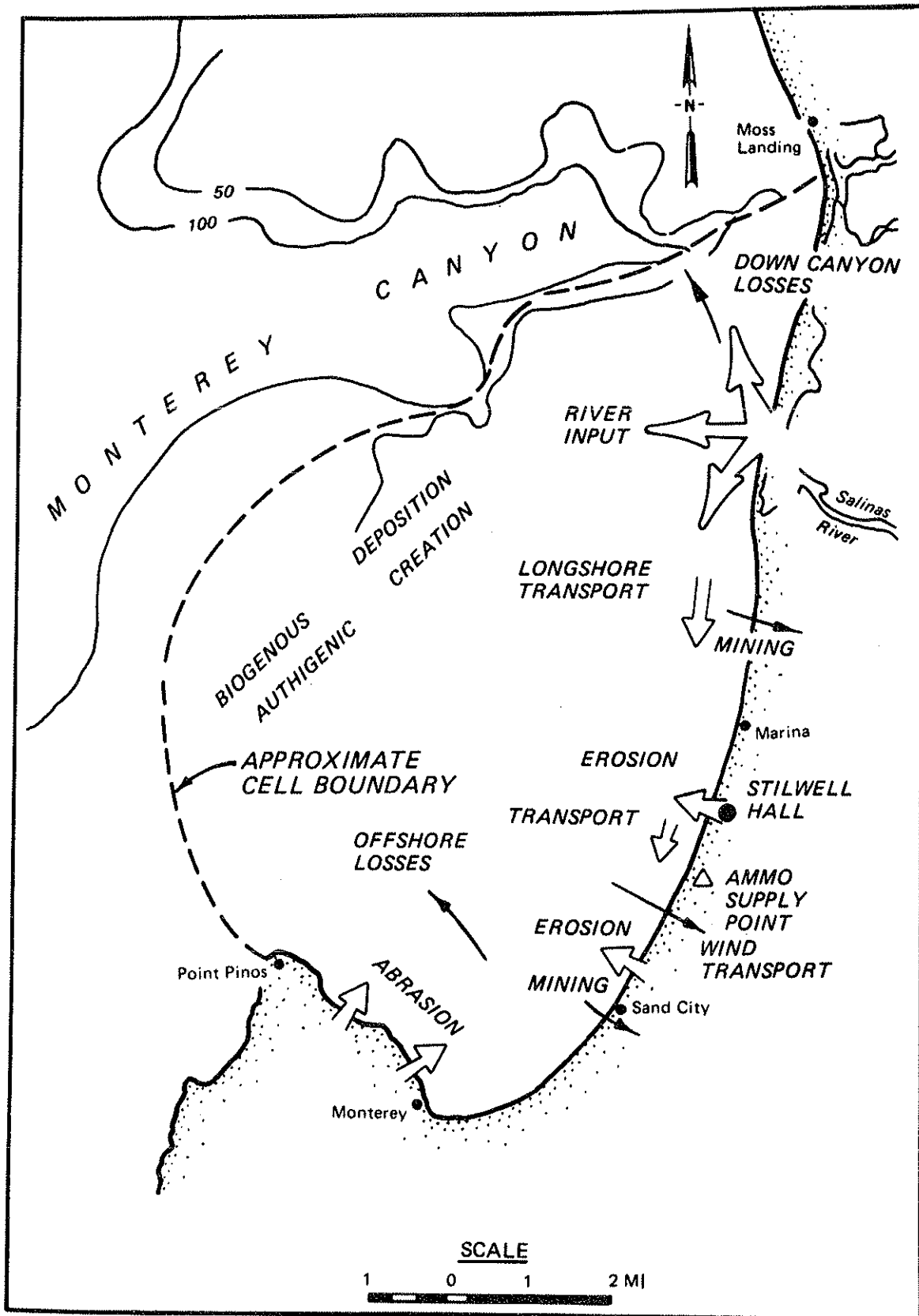


Figure 9. Sand sources and losses for southern Monterey Bay (from Dorman, 1968).

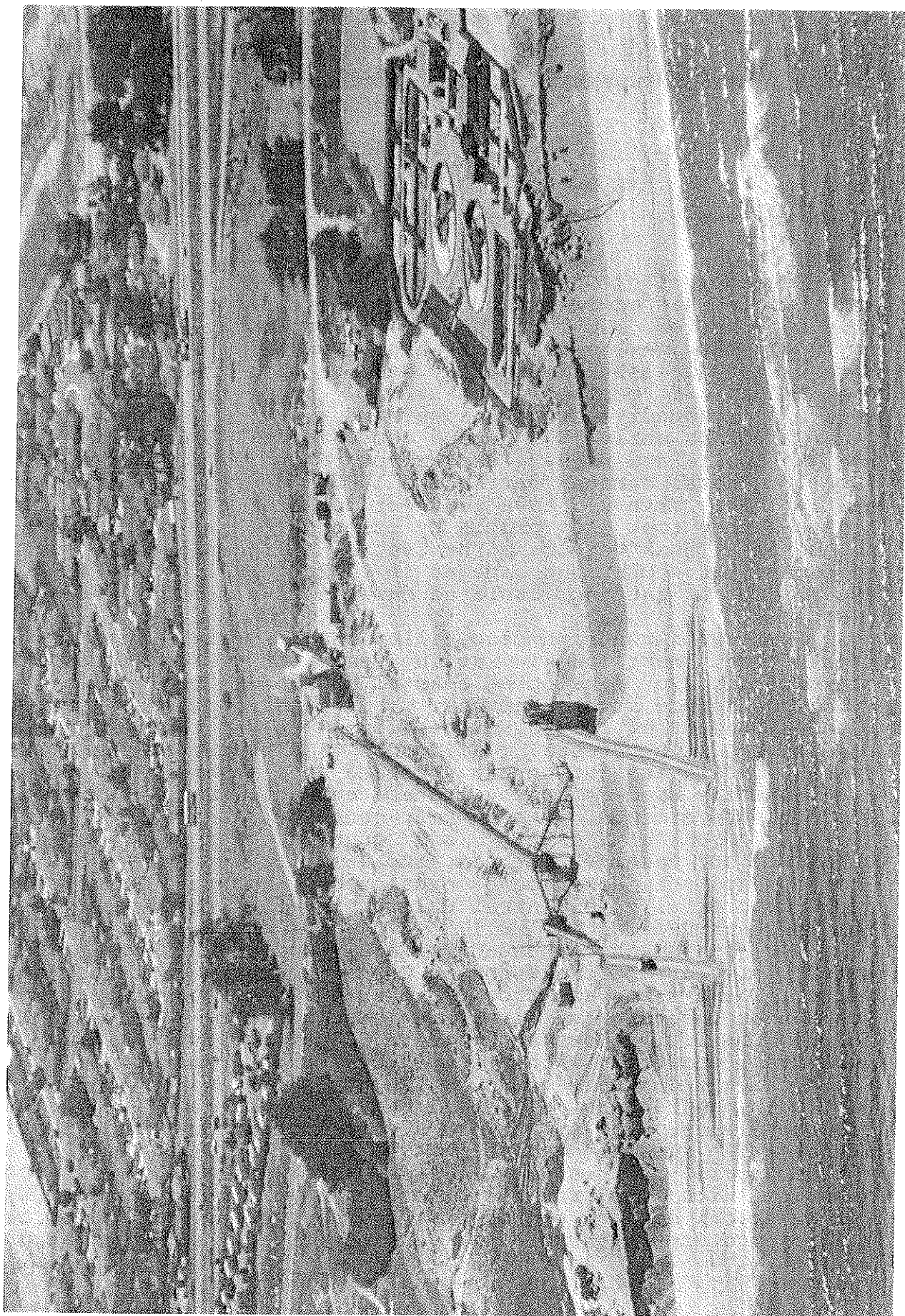
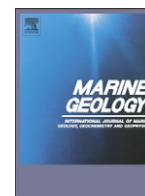


Figure 10. Dragline removal of beach sand at Marina (May, 1984).



Alongshore rip channel migration and sediment transport

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ABSTRACT

The relationship between alongshore rip channel migration and sediment transport is investigated using time-averaged video images to identify the positions of rip channels at three sites along southern Monterey Bay, California, over 1–3 year periods. Daily migration rates are calculated for each site. The basic Coastal Engineering Research Center (CERC) formula for bulk alongshore sediment transport is used to estimate alongshore transport rates at each site, based on hourly input of directional wave spectra measured at an offshore buoy and shoaled and refracted to the nearshore. The wave transformation model is validated by comparison with measured nearshore directional wave spectra in 13 m water depth. An expanded CERC formulation that accounts for the additional forcing of alongshore wave height gradients is also tested but rejected. Correlation coefficients between daily rates of calculated alongshore transport and rip channel migration are low: 0.01, 0.44, and 0.38 at the Sand City, Stilwell, and Marina sites, respectively. The problem of digitization noise, associated with video-based rip channel identification, is discussed and several filtering methods are used to increase the signal to noise ratio and obtain improved correlations. Results indicate that higher frequency migration events (on time scales shorter than 8 days) will likely be obscured below the digitization “noise floor”, but that longer period oscillations (such as tidal and seasonal cycles) show up clearly in both rip migration and sediment transport datasets. Daily rates are cumulatively summed to generate time series of representative overall rip migration distance and net alongshore transport, and the cumulative summing procedure is shown to be similar to applying a low-pass filter. Mean migration is demonstrated to lag behind net transport in the summertime, suggesting that a minimum level of alongshore forcing is required to generate detectable rip migration. Rip channel migration and net alongshore transport have correlation coefficients that range from 0.76 to 0.94 at the three sites.

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1. Introduction

The causal relationship between nearshore flow processes and alongshore migration of rip channels is highly complex. Small-scale changes in rip channel morphologies that occur on hourly or daily timescales are too complicated to be well simulated at this time. At timescales of months to years, however, a quasi-linear relationship may develop in which seasonal variations in climatology become dominant and generate large scale, proportional shifts of rip channels. The subsequent analysis demonstrates this relationship by measuring rip migration and estimating concurrent alongshore sediment transport, exploring both shorter (tidal) and longer (seasonal) timescale trends and examining correlations. Rip channel migrations are measured with time-averaged video imaging techniques, while alongshore transport is estimated by transforming measured deep water wave spectra to shallow water using a spectral wave propagation model and then applying a standard bulk transport

formulation. The analysis focuses on three sites in southern Monterey Bay, California (Fig. 1).

1.1. Rip channel migration

When incoming waves approach a barred beach from a near shore-normal direction, offshore-directed rip currents can develop and cut channels through the sandbar (Aagaard et al., 1997; Brander and Short, 2001; MacMahan et al., 2006). Shoreward of the bar, feeder currents converge into the rip from both sides, propelled by wave radiation stresses and alongshore setup gradients (Bowen, 1969). Offshore, channel flow diverges and weakens, forming a rip head that can extend beyond the outer surf zone. Rip channels on open coasts tend to occur simultaneously over relatively long stretches of beach with quasi-regular spacing. Herein, a grouping of similarly spaced rip channels over an alongshore distance of 1 to 2 km will be designated a “rip field”.

For the past two decades, rip channel location, width, and behavior have been measured using video imaging techniques introduced by Lippmann and Holman (1989). Because nearshore wave breaking is depth-dependent (Thornton and Guza, 1983), it tends to be

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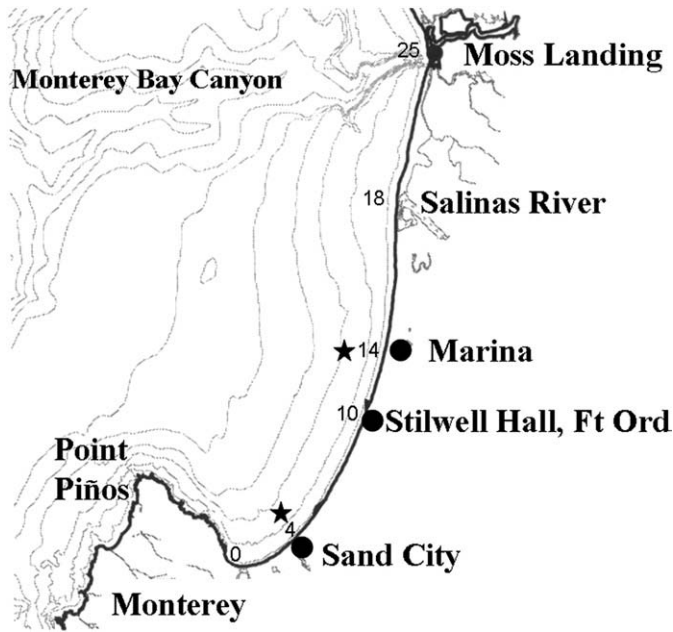


Fig. 1. Three video sites (circles) and two nearshore (13-m depth) ADCP sites (stars) along southern Monterey Bay, California, which were used in the study. Alongshore distance (km) from the southern end of the bay is indicated for each site and various other landmarks. Real-time data from these instruments are available online at <http://www.oc.nps.edu/stanton/miso>. (The Marina site was shut down in 2009.)

concentrated over shallow-water shoals in the surf zone. In rectified, time-averaged (timex) surf zone images, the regions of persistent wave breaking over shallow sandbars appear as white bands of surface foam. When rip channels are present, the white bands are interrupted by darker patches with little or no wave breaking, a consequence of the channels' greater depths. This makes it possible to trace the rip channels' subsurface locations by tracking variations in the intensity of image pixels (Lippmann and Holman, 1989; van Enckevort and Ruessink, 2001). The alongshore locations of intensity minima in the bar have been shown to correspond well with those of the underlying rip channels (Ranasinghe et al., 1999, 2004).

Most rip channel research has focused on the wave conditions under which rips develop, while less has been done to analyze and model the alongshore motion of existing channels. Several studies have directly or indirectly monitored longer term rip motion in the field. Short (1985) described visual observations of rip locations for nineteen months along Narrabeen Beach, Australia. Ruessink et al. (2000) measured the cross-shore and alongshore motion of crescentic bar systems on an open coast with rectified video images and cross-shore bathymetry profiles over a six-week period at Egmond, the Netherlands. They found that migration rates approached 100 m/day owing to large incident wave angles and that the rates were proportional to the alongshore component of the deep-water energy flux. Bogle et al. (2001) used rectified video images to track rip channel formation and evolution for 11 months at the 2 km pocket beach at Tairua, New Zealand and found a mean migration rate of 14 m/day averaged over selected storms. Rip channel migration speeds ranging from 2 to 20 m/day were measured using a four-year video data set at the 2.5 km embayed Palm Beach, Australia (Ranasinghe et al., 1999; Holman et al., 2006). These authors noted that periods of high wave energy occasionally caused the rip channel bathymetry to "reset" itself, with all channels disappearing for a period of hours to days and then re-emerging at different locations. The individual rip channels were found to persist an average of 46 days. In contrast, along the nearby, relatively long, straight Surfers Paradise Beach, rip channels migrated 5–50 m/day and persisted only 8 days on average (Turner et al., 2007).

Larger wave heights and more oblique angles of incidence, from either swell or locally generated wind waves, result in greater alongshore currents and rates of sediment transport (e.g. Komar, 1998). The relationship with rip channel migration appears to be more complex, particularly on hourly to daily timescales. Once a rip channel has been established, the morphology and flow dynamics tend to positively reinforce each other, leading to a relatively stable channel in a fixed location (Murray, 2004). Holman et al. (2006) find that eight-day average rip channel migration rates can be linearly related to predicted alongshore current velocities with an $r^2 = 0.78$.

Few modelers have focused specifically on the propagation of rip channels and its dependence on alongshore sediment transport. Smit et al. (2003) found a direct relationship between wave incidence angle and rip migration direction using a process-based model with an idealized bathymetry. However, no attempt was made to physically verify this relationship with field data. Ruessink et al. (2000) used complex empirical orthogonal function analysis (CEOF) to calculate crescentic bar migration during six weeks at the Egmond site, but noted that such a procedure only works for relatively uniform wave conditions with regularly spaced rip channels. Klein and Schuttelaars (2006) modeled crescentic bar systems and found that rip migration rates correlated with the alongshore wavelength of the crescentic bars.

Herein it is hypothesized that the alongshore migration rate of rip channels may be expressed as a linear function of the local alongshore sediment transport rate over longer timescales. Measuring this correlation requires accurate estimates of both migration rates and alongshore transport rates.

1.2. Alongshore sediment transport

Alongshore sediment transport has been analyzed and modeled for decades, and a variety of formulations have been developed to predict it. The bulk transport formula developed by the Coastal Engineering Research Center (CERC; USACE, 2002) is among the earliest and most widely used. It provides a cross-shore- and depth-integrated estimate of the total alongshore sediment transport rate, q_s , based on alongshore wave energy flux and requires only the cross-shore component of the alongshore wave-induced momentum flux (radiation stress), S_{yx} , and phase speed at breaking, C_b , as input parameters.

$$q_{s,CERC} = K S_{yx} C_b \quad (1)$$

where K is an empirical, dimensional constant.

In estimating alongshore sediment transport, most formulations assume that wave heights are constant in the alongshore direction ($\partial H / \partial y = 0$). This assumption implicitly neglects forcing by alongshore gradients of wave setup $\bar{\eta}$ (alongshore pressure gradient) and radiation stress component S_{yy} , which oppose and balance each other outside the surf zone but combine in shallower water to modify the alongshore flow (Bowen, 1969; Keeley and Bowen, 1977). While appropriate for many coastal locations, the assumption is not generally applicable to southern Monterey Bay, where strong refraction and sheltering by Point Piños (Fig. 1) usually result in a nonzero $\partial H / \partial y$ (Fig. 2). In an extended version of the CERC formula (Ozasa and Brampton, 1980; List et al., 2007), a second term is added to account for transport forced by alongshore wave height gradients:

$$q_{s,CERCex} = K S_{yx} C_b + \frac{K_2 H_{rms,b}^{5/2}}{\beta} \cos(\alpha_b) \left(-\frac{\partial H_{rms,b}}{\partial y} \right) \quad (2)$$

where K_2 is a semi-empirical function of sediment density and porosity, $H_{rms,b}$ is root-mean-square (RMS) wave height at breaking, β is the average beach slope across the surf zone, and α_b is the wave incident angle at breaking.

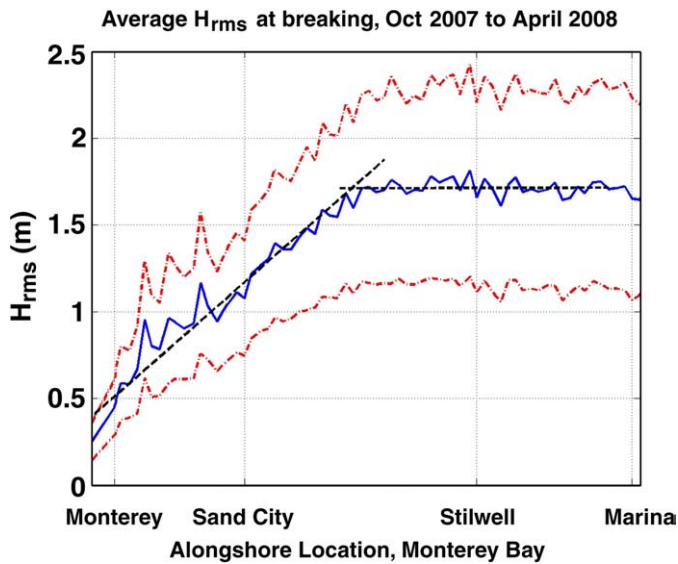


Fig. 2. Model-predicted RMS wave heights at breaking along the shoreline of southern Monterey Bay, averaged over six months. Data spread ($\pm$ one standard deviation) is shown by dash-dot lines. Dashed lines on top of the main curve indicate mean alongshore slopes of wave heights on southern and northern sections of the shoreline between Monterey and Marina. While wave heights remain relatively constant over the northern half of this range, there is a wave height gradient ($\sim 1/4000$) further south, indicating that alongshore variations in radiation stress component S_{yy} and setup $\bar{\eta}$ will have a stronger effect on alongshore transport for that section of coastline.

In the following sections, the study site and methods are described, then results and correlations are presented and significant findings are discussed in greater detail. An error analysis is included in Appendix A.

2. Study site and instrumentation

Monterey Bay, California, is an ideal location for the study of rip channels and associated beach processes (Thornton et al., 2007). Waves refract over the Monterey Bay submarine canyon (Fig. 1) and consistently approach the shoreline from near shore-normal, resulting in year-round rip fields and relatively weak alongshore currents (typically <0.5 m/s). For most of the year, deep water swell waves generally approach the Monterey Bay from the northwest, generated by the energy of western Pacific tropical cyclones in the summer and fall and northern Pacific storms in the winter. This pattern is episodically interrupted during the winter months, when larger tropical weather systems approach the California coast directly from the west. The one-year-return-period RMS wave height at breaking is approximately 3.5 m. There is an order of magnitude variation in wave energy along the shoreline, owing to wave refraction and sheltering by Pt. Piños headland. Mean RMS breaking wave heights range from under 1 m at Monterey in the south to over 2 m near mid-bay. This creates a concomitant variation in alongshore morphodynamic length scale, with rip channel spacing increasing from south to north (Thornton et al., 2007).

Along much of the shoreline, a steep (approximately 1:10) beach gradually curves out to a 1:100 low tide terrace, then steepens to about 1:20 offshore of the bar (MacMahan et al., 2005). Maximum tidal range is about ± 1.5 m. Following the classification of Wright and Short (1984), the alongshore morphology is characterized as transverse-barred with regular incisions by rip channels. Alongshore rip spacing varies from approximately 100 to 500 m, and large-scale beach megacusps have comparable alongshore lengths. Mean grain size increases from 0.1 mm at the Monterey wharf to 0.4 mm north of Marina, with an additional ± 0.05 to 0.1 mm variation across the surf zone at any given location.

Since 2001, the Naval Postgraduate School (NPS) has maintained several video camera towers continuously recording surf zone images along the southern half of the Monterey Bay shoreline. The present study will analyze video data from sites at Sand City, the former Stilwell Hall (on Fort Ord), and Marina (Fig. 1). At each site, 5-image datasets are produced every 20 min by Eltec “MiniHypercam” b/w video cameras, which internally process 800×600 pixel images at approximately 10 Hz to generate a time-exposure pixel intensity mean, a standard deviation, and a single snapshot, as well as images of maximum and minimum pixel intensity. Camera calibration, ground truthing, and image rectification procedures follow those outlined for Argus camera systems by Holland et al. (1997). At Sand City, cross- and alongshore pixel resolution are about 0.5 and 11 m per pixel, respectively, at mid-range (400 m) from the camera tower and 1.0 and 19.8 m, respectively, at the alongshore edges of the view fields (750 m). At Stilwell and Marina, mid-range (500 m) resolution values are about 0.6 and 9.1 m, and long-range (1000 m) values are 1.3 and 29 m, respectively. The beach and nearshore topography along southern Monterey Bay has been extensively measured, providing detailed records that can be used to validate video-based morphology estimates.

Spectral wave data are available from several offshore buoys (NOAA, 2010a). NPS also operates acoustic Doppler current profilers (ADCPs) along the 13 m depth contour offshore of the Sand City and Marina video towers. Each ADCP returns continuous 1 Hz time series of velocities over the water column and pressure.

3. Methods

3.1. Tracking rip migration

Video images from three NPS cameras at Sand City, Stilwell, and Marina, are used to identify and track rip channel locations. The Sand City and Stilwell video datasets encompass three years (Nov 2004–Nov 2007), while the Marina images cover a single year (Jan 2007–Jan 2008). The measurement procedure followed here parallels that as described by Holman et al. (2006). Rip locations are manually identified by visually selecting and marking off intensity minima on alongshore transects through the daily rectified timex images (see, for example, Fig. 3). The subjective error of this procedure was first estimated by having a 110-day section of video record (Stilwell, 2004–5) analyzed independently in this manner by co-authors Orzech and Thornton along with two graduate students (Table 1). The average user-associated RMS digitization error for rip locations marked by all four subjects ranged from 10.1 m near the cameras to 12.1 m near the far edges of the rectified images. Overall user-associated digitization error is estimated to be 11.5 m, which is essentially the same error found by Holman et al. (2006).

By recording channel positions from sequential, daily-averaged images, a timestack database is compiled for each site, tracking the development, migration, and extinction of rips in the field of view of the video cameras (Fig. 4). A representative migration rate for each date is obtained from each timestack by computing three-point slopes of each continuous rip location timeline on that date, then taking the ensemble average across the rip field of these rates of change. The alongshore averaging technique allows the varied motions of multiple rips to be represented by a single time series and also contributes to reducing subjective errors inherent in the rip-marking process (see Appendix A).

Resets are identified in rip location time series when rip channels disappear and then reappear at different location and are attributed to the occurrence of high waves, large incident angles and strong alongshore currents. Resets are relatively rare in Monterey Bay compared with previous investigations, occurring 1–2 times per year. As marked on the time series plots of Fig. 4, these resets appear as clear discontinuities in rip location timelines that stretch along most or all of a rip field. Identification of resets with video is not always

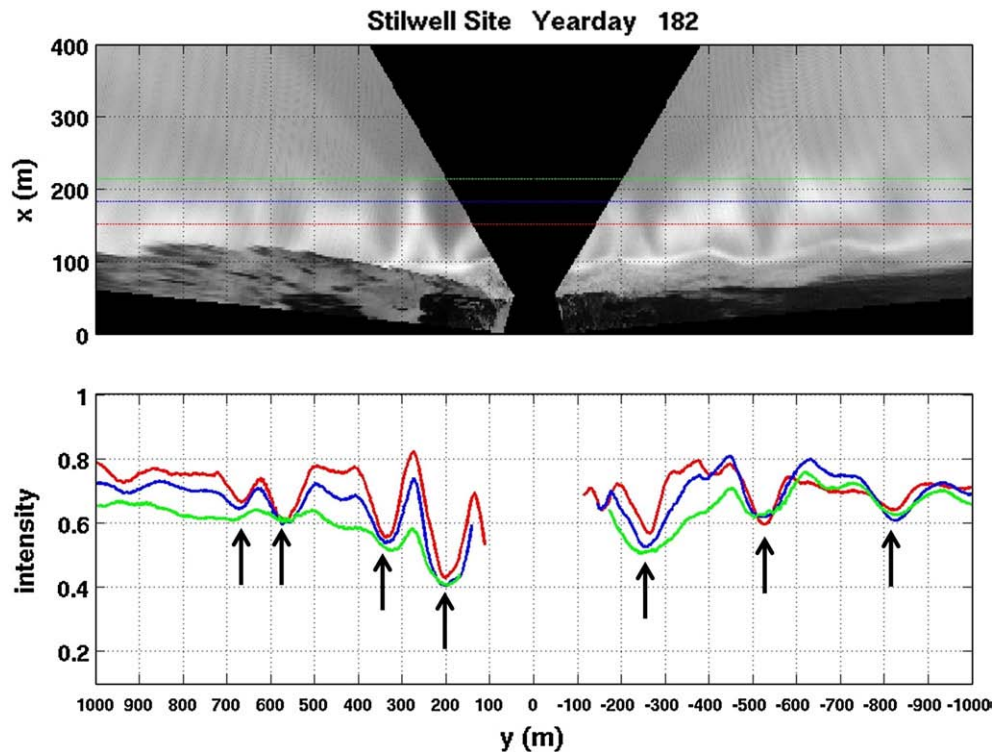


Fig. 3. Example of intensity image and transects used for visually marking alongshore rip channel locations. Top panel shows time-averaged image from Stilwell site, transformed to an overhead perspective. White regions correspond to surf zone areas of consistent wave breaking, while offshore-directed, darker regions between them delineate rip channels. Bottom panel plots image intensity versus alongshore location for the three colored alongshore transects of the rectified image (red: 150 m; blue: 180 m; and green: 210 m). Selected intensity minima corresponding to rip locations are indicated with vertical arrows.

reliable, as reset periods tend to be associated with inclement conditions and more frequent video “whiteouts” due to heavy fog, rains and larger waves that break across the entire surf zone and obliterate the images of rip channels. An examination of offshore swell and local wind wave data for each reset period identified in Fig. 4 does not reveal any consistent conditions that might have led to the shifts. Relatively high, long-period waves ($H_{rms} = 1.5\text{--}3.5\text{ m}$; $T_p > 15\text{ s}$) do appear to be present during each reset. However, wave directions are inconsistent: three resets have wave approach angles from 0 to 3° south of shore normal, while one (Marina in December 2007) sees mean angles exceeding 7° south, and another (the Stilwell site in September 2007) has swell approaching from 3° north. Estimated alongshore transport forcing due to local wind waves is less than ten percent of that due to swell in all cases. The infrequent occurrence of resets in southern Monterey Bay likely results from the region's consistently small wave incident angles and associated weak alongshore currents, which are rarely strong enough to obliterate rip channels.

Table 1

Comparison of rip location statistics. Summary of subjective differences in rip locations, which were selected on 110 daily rectified video images from Jan to Apr 2005 by four investigators. MO is M. Orzech and ET is E. Thornton, while alternates 1 and 2 are graduate students somewhat less experienced with the problem. Statistics calculated are the same as those in Holman et al. (2006). Space and time averages (subscripts y and t) are presented for the location differences dy_i , their standard deviation, and their RMS value. The final two columns show the time-averaged number of rip locations matched and missed between each pair of investigators.

Digitizer	$\langle\langle dy_i \rangle\rangle_y$	$\langle\langle std(dy_i) \rangle\rangle_y$	$\langle\langle rms(dy_i) \rangle\rangle_y$	$\langle N_{match} \rangle_t$	$\langle N_{miss} \rangle_t$
MO–ET	0.3	11.5	11.5	6.1	2.1
MO–alt 1	1.8	10.4	10.6	5.3	2.3
MO–alt 2	−0.8	12.3	12.3	5.9	2.4

Alongshore flow in the surf zone may also include contributions driven by the shear of currents in deeper water, which are not included in the present analysis. Notably, mean alongshore velocities measured outside the surf zone by the Sand City ADCP can flow in the opposite direction of the predicted wave-induced alongshore current. Results from the one-month 2007 Rip Current EXperiment (RCEX) at Sand City indicate that alongshore flow in the surf zone can be composed of both wave-induced currents and contributions from other coastal circulations and eddies (Brown, 2009). The rip field reset observed at Sand City in December 2006 may have been partly due to unusually strong circulation patterns and higher transport rates resulting from these additional factors. Over the five days surrounding this reset event, ADCP-measured alongshore currents in 13 m water depth at the site were strongly southward and up to an order of magnitude larger than model-predicted surf zone flows.

3.2. Modeling alongshore sediment transport

Alongshore sediment transport rates are computed with the CERC formula (Eq. (1)), using wave spectra measured at offshore wave buoys and transformed to shallow water with a wave refraction model. Before transport is computed, model wave output is first verified by comparison with in situ ADCP data over a shorter time period.

3.2.1. Wave inputs

Because available ADCP wave data do not extend over the entire video measurement period, continuous time series are obtained at each site from a spectral wave refraction model (O'Reilly and Guza, 1993) operated by the Coastal Data Information Program (CDIP) at U.C. San Diego. Initialized by directional wave spectra measured at multiple offshore buoys, the CDIP model generates hourly estimates of nearshore wave frequency spectra and directional moments together with

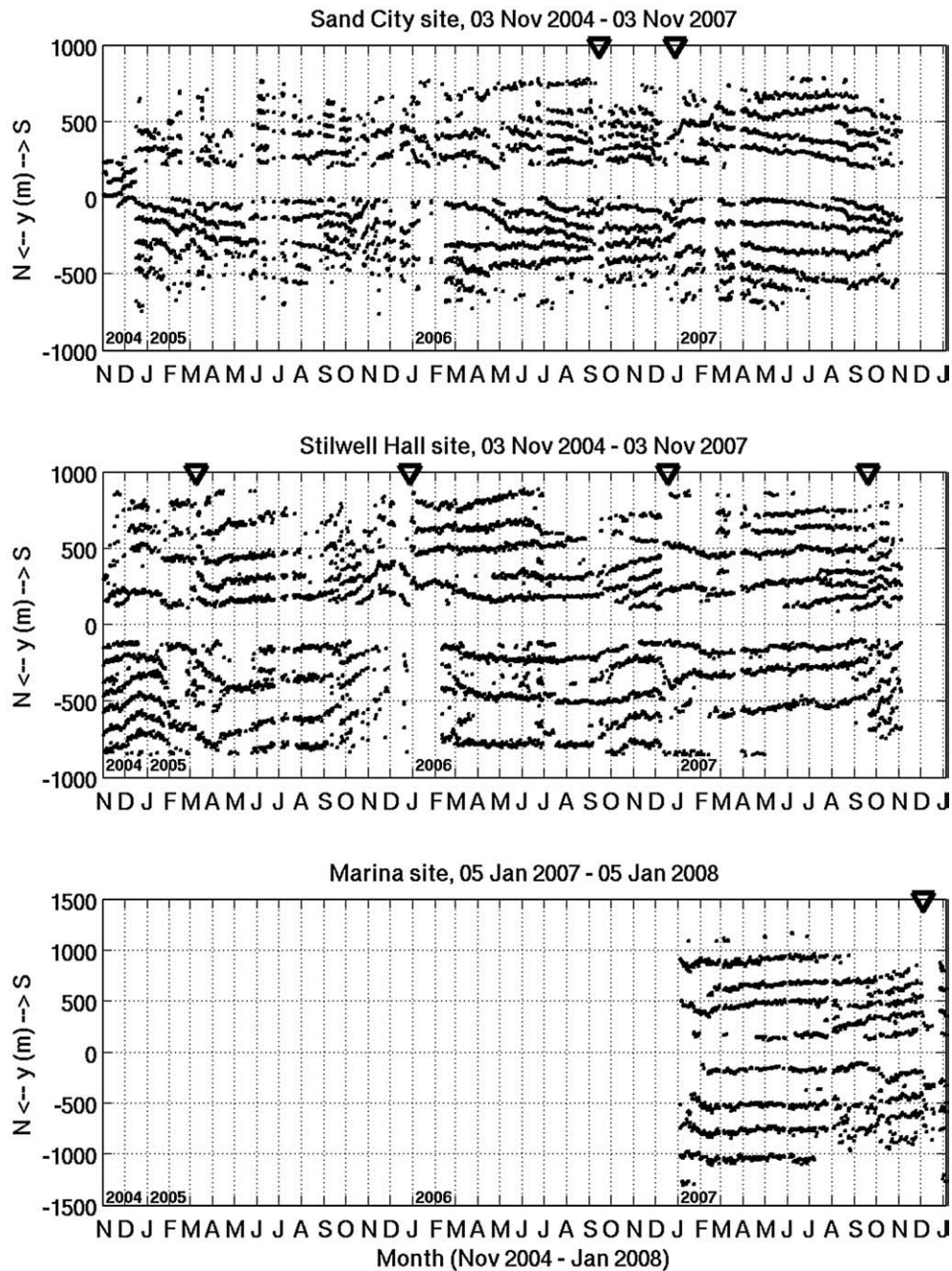


Fig. 4. Timestacks of rip channel locations at Sand City (top panel), Stilwell (middle), and Marina (bottom) camera sites. In each panel, individual selected rip locations are plotted as single points for each day, with alongshore location on the y-axis (positive southward) and time on the x-axis. Three years of video data are available for the Sand City and Stilwell sites; only one year is available for Marina. Approximate times of full or partial resets are marked with arrows along the top of each panel.

significant wave height ($H_s = \sqrt{2}H_{rms}$) and both peak and mean values of wave period and direction (CDIP, 2010). Because of the nearly shore-normal wave approach along the Monterey Bay shoreline, small errors in estimated shoreline orientation can significantly affect the magnitude and direction of calculated alongshore transport (see Appendix A). In this analysis, CDIP-predicted wave information is used in the transport computations, and shore-normal angles are estimated from the orientations of beach contours measured in recent shoreline surveys conducted using an all-terrain vehicle (ATV) equipped with a global positioning system (GPS) (Thornton et al, 2007).

Sixteen months of data from the Sand City ADCP, deployed in approximately 13 m depth, are used to assess the accuracy of wave model predictions. Processed ADCP output includes hourly frequency-directional spectra from which S_{yx} , wave height, period, and direction

can be extracted. CDIP model wave output in 15 m water depth is further shoaled and refracted to 13 m where the ADCPs are located, assuming alongshore uniform bathymetry. The CDIP model comparisons with in situ ADCP wave data at Sand City are summarized in Fig. 5. Correlation of wave heights is good, with an almost 1:1 ratio between predicted and measured values. In contrast, predicted mean directions correlate less well with ADCP values. This is not unexpected, because the (measured and modeled) mean directions at Sand City only vary by about 10° , which is just slightly larger than the noise in the ADCP mean direction estimates. However, modeled radiation stress values, S_{yx} , used in the sediment transport predictions correlate well with ADCP-initialized predictions (Fig. 5, lower left), with a coefficient of 0.94. Comparisons with the ADCP at the Marina site (not shown) follow a similar pattern.

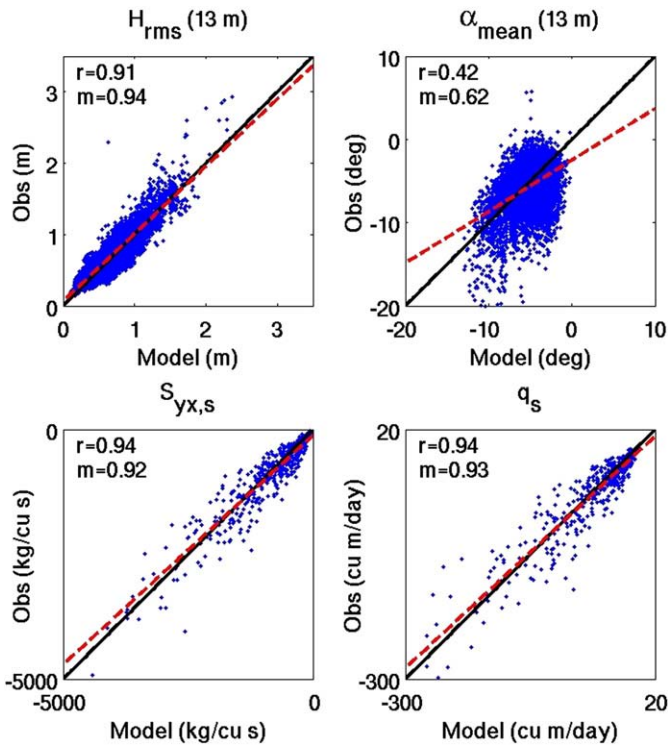


Fig. 5. Comparisons of model predictions with ADCP observations at Sand City between June 2006 and October 2007 with correlation coefficients (r) and slopes (m) in the upper left corner. While the correlation of CDIP- and ADCP-predicted RMS wave heights, H_{rms} , at 13 m depth is high (top left), mean direction α_{mean} , correlation is relatively poor (top right). The mismatch of directions is not surprising, as both modeled and measured directional spreads at Sand City are roughly of the same size as the estimated ADCP measurement error (i.e., about $\pm 5^\circ$). In spite of this, CDIP-model-based predictions of offshore radiation stress, $S_{yx,s}$, and sediment transport rates, q_s , in the surf zone correlate well with ADCP-based calculations (bottom). Positive is southward for α_{mean} , $S_{yx,s}$, and q_s .

3.2.2. CERC formula estimates

Alongshore sediment transport estimates are computed using the CERC formula (Eq. (1)), initialized at 15 m depth with CDIP wave data. S_{yx} is conserved from 15 m depth to breaking depth over assumed straight and parallel contours. The total S_{yx} is obtained as the sum over the sea-swell band of frequencies (0.04–0.25 Hz) of contributions at each frequency $S_{yx}(f)$, which are computed from the product of wave energy spectrum $E(f)$, second directional moment $b_2(f) = \int_0^{2\pi} S(f, \alpha) \sin 2\alpha d\alpha$ (where $S(f, \alpha)$ is the frequency-directional spectrum and α is the wave incident angle), and transmission coefficient $n(f)$ using linear wave theory:

$$q_{s,CERC} = K S_{yx} C_b = K \left[\frac{1}{4} \rho g \int_{0.04}^{0.25} E(f) b_2(f) n(f) df \right]_{15m} C_b. \quad (3)$$

The subscript “15 m” indicates that these quantities are evaluated offshore, at 15 m depth. Using shallow water wave theory, $C_b = \sqrt{gh_b}$, where breaking depth h_b is determined using the method of Dean and Dalrymple (1984) by iteratively shoaling and refracting input waves, assuming alongshore uniform bathymetry. Empirical coefficient K is set to 0.147 m³/h per J/(m s), as recommended by the Shore Protection Manual (USACE, 2002). Fixed, site-specific reduction factors of 0.5, 0.375, and 0.25 are applied to calculated transport rates at Sand City, Stilwell, and Marina, based on results from Zyserman and Fredsøe (1988) in which alongshore sediment transport is found to significantly decrease as the spacing between rip channels narrows. This alters transport magnitudes only and does not affect correlations

with rip migration rates. Hourly values are summed over each day to obtain daily transport rates. As might be expected from the earlier S_{yx} comparisons, the correlations of CERC-based sediment transport rates with ADCP-based values at Sand City are high ($r = 0.94$; Fig. 5, lower right panel).

4. Results and discussion

Daily RMS rip migration rates are calculated for the entire rip field at each of the three sites (Table 2, column 1). Rip channels at Sand City have a three-year-mean RMS migration of 5.8 m/day, while those at Stilwell average 6.7 m/day over the same period. Marina's rips have the largest mean RMS migration rate, 9.0 m/day, over their single recorded year. Modal daily RMS migration rates at Sand City, Stilwell, and Marina were 4.5, 4.5, and 7.5 m/day, and maximum RMS rates were 18, 22, and 30 m/day, respectively. Migration rates are mostly northward at Sand City and southward at Stilwell and Marina.

The ranges of absolute sediment transport rates predicted by the CERC formulation at each site are shown in Table 2, column 2. Trends seen in transport magnitudes among the sites are similar to those seen with RMS migration rates and are a result of the variations in wave energy and shoreline orientation along the coast of southern Monterey Bay. Sheltered Sand City in the south has the lowest estimated mean transport magnitude of 68 m³/day as well as the lowest maximum transport, and transport is skewed heavily northward owing to the shoreline orientation relative to typical westerly wave approach. The middle site, Stilwell, has a maximum estimated transport rate 9 times larger than Sand City and a mean transport magnitude of 200 m³/day. The greatest single-day transport rate, nearly 23,000 m³/day, occurred at the northernmost site, Marina, which has a predicted mean transport magnitude more than double that of Stilwell. While overall transport at Stilwell trends slightly southward, at Marina the north-south sediment balance is almost zero.

Because the mean RMS migration values are smaller than the digitization error of 11.5 m, an analysis is performed to determine whether daily migration rates are distinguishable above the noise floor resulting from the rip identification process (similar to Holman

Table 2

Rates and filtered correlations. Summary of measured rip migration and modeled sediment transport rates and filtered correlations. Column 1 lists RMS rip migration rate data at each site, determined by the methods described in Section 3. Column 2 shows absolute sediment transport rate statistics as predicted by the CERC formulation. Remaining columns contain correlation coefficients (excluding resets) for original daily rip migration and alongshore transport rates (column 3), using 8-day-average rates (column 4), using daily rates from only the highest 10% of transport days (column 5), using daily rates to which a 4th-order low-pass filter with cutoff of 1/8 days^{−1} has been applied (column 6), and using cumulatively summed mean migration distance and net sediment transport (column 7).

	RMS rip migration (m/day)	Sediment transport magnitude (m ³ /day)	Migration–transport correlation				
			Daily		Filtered		
			8-day		Low-pass	High 10%	Cumulative sums
	1	2	3	4	5	6	7
Sand City							
Max	18.0	500					
Mean	5.8	68	0.01	0.06	0.07	0.23	0.94
Mode	4.5	26					
Stilwell							
Max	22.0	4500					
Mean	6.7	206	0.44	0.60	0.66	0.66	0.76
Mode	4.5	2					
Marina							
Max	30.0	22700					
Mean	9.0	462	0.38	0.58	0.60	0.54	0.87
Mode	7.5	175					

et al., 2006). Using the methods of Section 3.1, daily RMS migration rates are computed from 10 synthetic Gaussian noise time series with zero mean and RMS values equal to our digitization error. The mean RMS migration rate for the synthetic data is roughly 8.5 m/day, which is of the same order as the measured RMS daily rates given above. One-day migration rates will thus generally be difficult to distinguish from digitization noise at all three sites. As would be expected, correlations with CERC formula daily sediment transport rates are consequently poor: daily correlation coefficients are $r = 0.01$, 0.44, and 0.38 at Sand City, Stilwell, and Marina, respectively (Table 2, column 3).

As Sand City features significant alongshore wave height gradients, the expanded CERC formulation (Eq. (2)) is applied at this site to examine if including transport forcing by these gradients might improve comparisons. Alongshore wave height gradient $\partial H_{rms,b}/\partial y$ is estimated at Sand City by dividing the difference between CDIP-predicted H_{rms} values at Sand City and Stilwell by 4000 m (Fig. 2). An example of the relative distribution of transport rates due to the additional forcing, as well as its effect on the overall transport rate distribution at Sand City, is provided in Fig. 6. Calculated alongshore transport due to wave height gradients at the site is up to 20% of that obtained for radiation stresses alone and is always to the south. However, the mean of the dH/dy CERC contribution ($1 \text{ m}^3/\text{day}$) is only 5% of the mean of the original CERC rates ($-20 \text{ m}^3/\text{day}$) (Fig. 6). With the expanded transport formulation, the daily migration–transport correlation coefficient for periods excluding resets remains just 0.01. For this reason the expanded formulation will not be included in the remainder of this study; all reported sediment transport estimates will be based on the original CERC formula.

To resolve the noise problem described above, four different filtering techniques are used that examine rate correlations from different perspectives. First, a simple running average technique is applied to compute migration and transport rates over a longer time step that exceeds the noise floor. Second, a low-pass filter with varying cut-off frequencies is applied to the complete time series of mean daily migration and transport at each site to remove high frequency noise effects and focus on longer-term trends. Third, correlations are performed only including days with the highest 10% of transport rates for each site, anticipating that there is a threshold of transport required to initiate rip channel migration. Fourth, daily rates are cumulatively summed, a method which is shown to be equivalent to applying a graduated low-pass filter that also damps high frequency noise and emphasizes seasonal oscillations. In all cases, reset events are excluded from the analysis. This four-part analysis is followed by a brief discussion of the anomalous Sand City site, an idealized migration–transport relationship, and tidal signatures in rip migration.

4.1. Time-averaged filtering

Uncertainty in the measured migration rates is reduced by averaging the daily rates over longer intervals (in a manner similar to Holman et al., 2006). It is determined that 8-day-averaged rates are required for migration values to be well distinguished from digitization noise error. For 8-day averaged synthetic Gaussian migration time series, the RMS migration rate is determined to be approximately 1.4 m/day, with a 95% exceedance value of 2.2 m/day. For inter-reset periods, the 8-day averaged RMS rip migration rates range from 2.2 m/day at Sand City to 4.7 m/day at Marina, all of which are at or above the 95% confidence limit for the synthetic noise. For all days and all sites combined, 60% of 8-day mean migration rate magnitudes exceed the corresponding 8-day RMS noise rate. The correlations of CERC-estimated 8-day-averaged transport rates with the corresponding rip migration rates for inter-reset periods are listed for each site in Table 2, column 4. At the anomalous Sand City site, despite the longer averaging periods, the correlation of migration and CERC model transport rates is still only 0.06. Nearly all calculated mean daily sediment transport rates are directed northward at this location (skewness of rates = -3.3 ; see Fig. 6), while in contrast, 41% of daily mean migration rates are toward the south and migration rates have a slightly southward skewness ($+0.07$). At the more exposed Stilwell site, a higher correlation, $r = 0.60$, was found between daily 8-day-averaged sediment transport and rip migration rates. Alongshore transport rates for the single recorded year at Marina have a similar correlation, 0.58.

4.2. Low-pass filtering

A generalization of time averaging is examined by applying a 4th order Butterworth, zero phase-shift, time-domain low-pass filter to the rip migration and CERC model sediment transport rate time series, and then recomputing the correlations. Filtering out frequencies above $1/(8 \text{ days})$ only increases the inter-reset time series correlation for daily rates at Sand City to $r = 0.06$, confirming the anomalous nature of the site. In contrast, it significantly improves them to $r = 0.66$ at Stilwell, and $r = 0.60$ at Marina (Table 2, column 5). As an example, pre- and post-filter time series are compared for the Stilwell site in Fig. 7. Correlation values for low-pass-filtered migration and transport rates at each site are plotted against cut-off filter frequency in Fig. 8, with cutoff frequencies ranging from $1/(360 \text{ days})$ to $1/(5 \text{ days})$. As expected, r generally increases as more high frequency energy is excluded (though correlations at Sand City only reach 0.33). The highest correlations are found at $1/(360 \text{ days})$ for the three-year dataset at Sand City, at $1/(90 \text{ days})$ for Stilwell and close to $1/(25 \text{ days})$ for the shorter, one-year Marina time series. The maxima do not

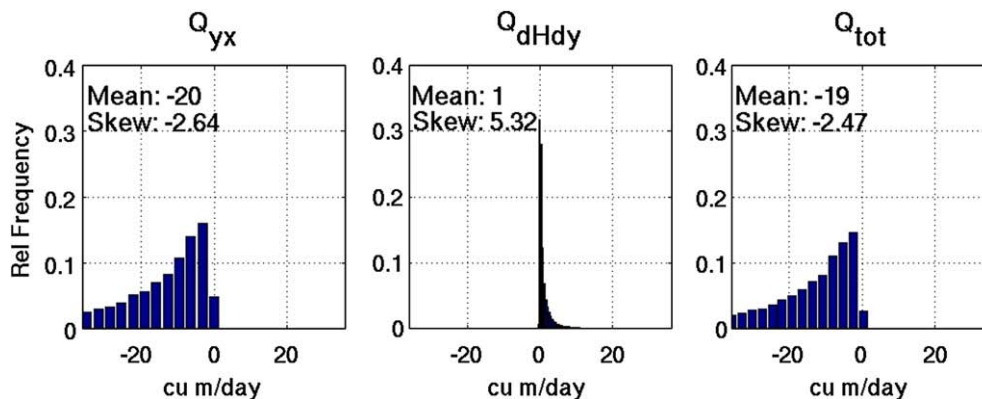


Fig. 6. Relative frequency distributions of estimated sediment transport contributions over three years at Sand City due to $S_{yx,s}$ (Eq. (1); left panel), $\partial H/\partial y$ (second term in Eq. (2); center panel), and total overall transport including both contributions (full Eq. (2); right panel). Transport due to $S_{yx,s}$ is almost entirely negative, leading to a purely northward alongshore transport. In contrast, the contribution due to the alongshore wave height gradient is smaller, but largely positive. When contributions are summed, the resulting distribution has a less negative mean and skewness, but continues to exhibit a strong northward bias.

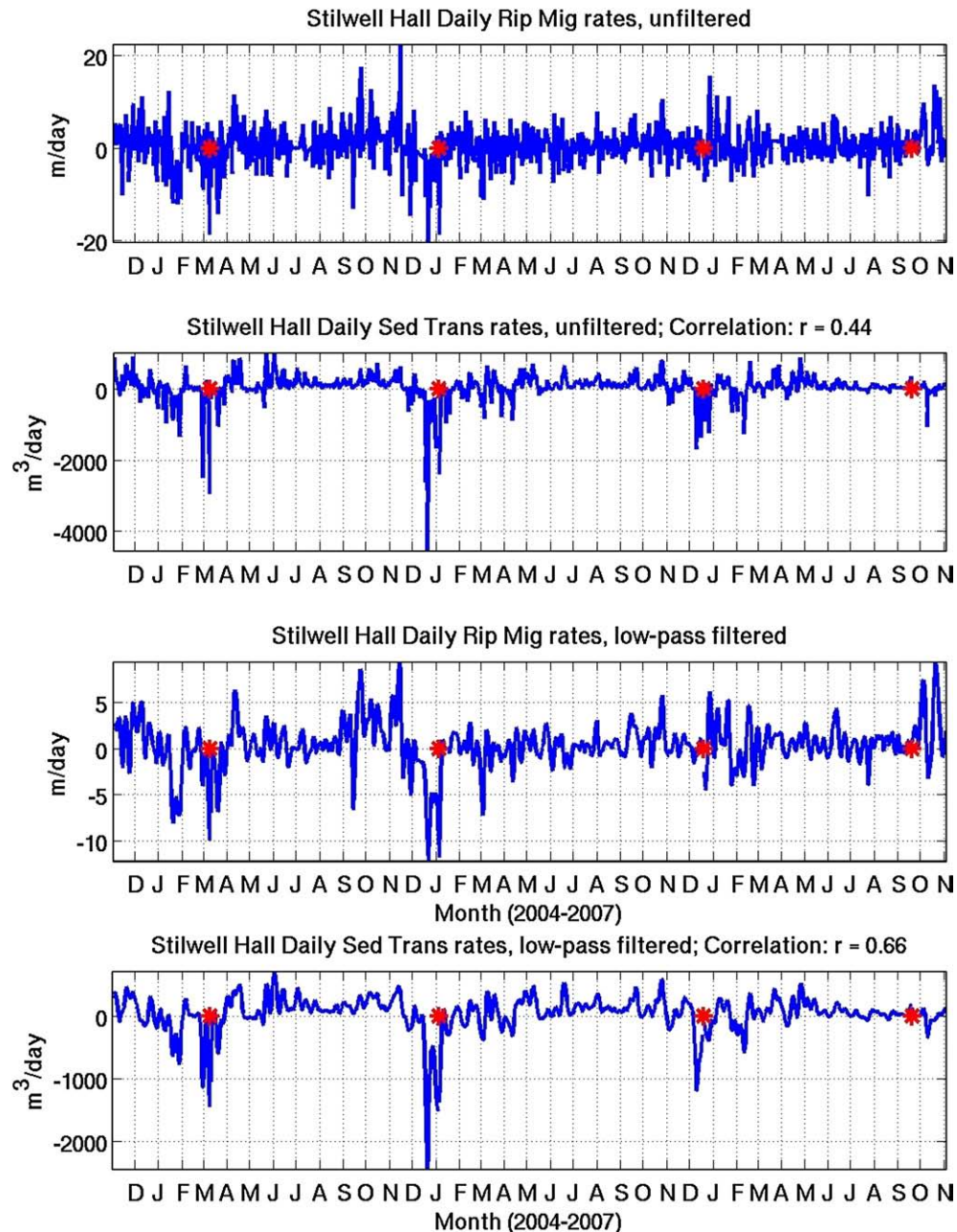


Fig. 7. Time series of measured alongshore rip channel migration and CERC model sediment transport for Stilwell Hall site before and after low-pass filtering. Top two panels show unfiltered rates, which have correlation $r = 0.44$ for non-reset days. For bottom two panels, a 4th order Butterworth low-pass digital filter is applied to each time series with $f_{\max} = 1/(8 \text{ days})$, improving the correlation to $r = 0.66$. Excluded reset days are marked with asterisks on each panel.

always occur at the yearly frequency because of the datasets' relatively short length and the skewed nature of the data, in which most of the migration occurs over three winter months.

4.3. High energy filtering

An examination of daily rip migration and sediment transport rate time series suggests that migration may lag behind transport, particularly during the milder spring and summer wave climate at the Stilwell and Marina sites. In general, a gradual southward sand transport begins in the early spring at both sites but is initially accompanied by little or no southward rip migration until later in the summer. At the Stilwell site from July to September in 2005 and 2006, daily rip migration rates are near zero (Fig. 7, upper panels), while calculated daily sand transport rates average about $200 \text{ m}^3/\text{day}$ toward the south. At the end of these periods, however, daily rates

jump to 500 and then $800 \text{ m}^3/\text{day}$ southward, coincident with the sudden shifts to higher rip migration rates in the same direction. At Sand City, calculated mean sand transport is $75 \text{ m}^3/\text{day}$ for the same slow periods, after which it abruptly doubles to over $150 \text{ m}^3/\text{day}$. At the Marina site in 2007, estimated sand transport averages around $400 \text{ m}^3/\text{day}$ for July to early September, then spikes to $1600 \text{ m}^3/\text{day}$ in early September and October, at roughly the same time as daily migration rates begin to surpass $10 \text{ m}/\text{day}$.

These results suggest that there may be a critical alongshore sand transport rate for initiation of measurable alongshore rip migration that is usually not produced by the smaller summer waves in Monterey Bay. However, this rate is most probably site-specific and dependent on additional factors such as rip channel spacing, grain size, and beach slope. For exposed sites like Stilwell and Marina, the critical transport rate appears to be approximately $500\text{--}1000 \text{ m}^3/\text{day}$, but at sheltered Sand City it may be significantly less owing to the

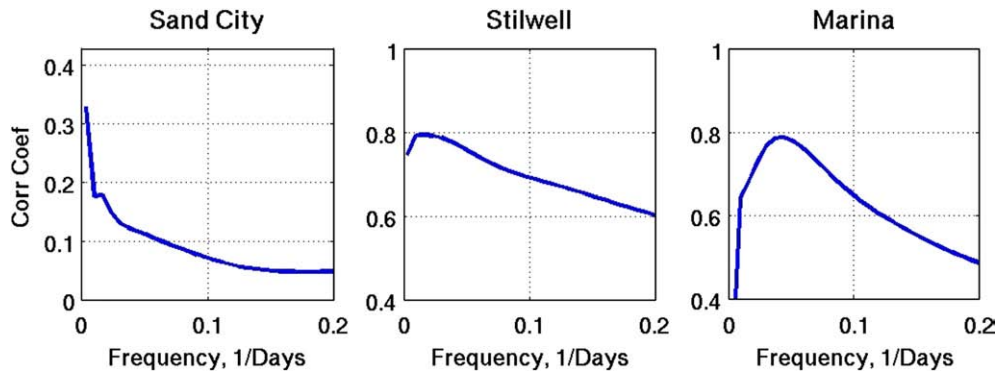


Fig. 8. Variation of correlation coefficient between daily rates of rip migration and sediment transport as a function of the low-pass cut-off frequencies ranging 1/(360 days) to 1/(5 days). Highest correlations are achieved for lower frequencies, although peak correlation does not always coincide with the lowest frequency, likely because of seasonal irregularities. The steep drop in correlation at Marina occurs at 1/(360 days), because this corresponds to the entire length of the dataset.

finer sand size. Rip channel spacing clearly plays a role in determining its estimated value (via the transport reductions mentioned in Section 3.2.2).

If such a critical alongshore transport rate exists, correlations that included only higher energy days would be significantly better than those for the entire migration and transport dataset for a given location. To test this, the original migration and transport rate datasets are restricted to days with the highest 10% of alongshore transport rate magnitudes at each site (i.e., greater than 1300 m³/day at Sand City and 3900 m³/day at Stilwell and Marina). Relative to the original time series, correlations for the limited datasets increase to $r=0.23$ at Sand City, $r=0.66$ at Stilwell and $r=0.54$ at Marina (Table 2, column 6).

4.4. Cumulative summing

Cumulatively summed daily migration rates are next compared with cumulatively summed net transport rates for inter-reset periods at each site. The summed migration rates represent the average displacement of all the rips in a rip field from their most recent post-reset positions at a given time (i.e., mean migration distance), while the summed transport rates provide an estimate of the net amount of sediment that has moved past an arbitrary cross-shore transect at the measurement site since the last reset event (i.e., net alongshore transport).

The summing process is equivalent to a low-pass filter, as may be illustrated by representing rate data as a Fourier series, $q_s = A_0 + \sum_{n=1} A_n \cos(n\omega_1 t - \varphi_n)$, in which φ_n is the phase of the sinusoidal component at frequency $n\omega_1$ with amplitude A_n , and the constant term A_0 represents the mean migration or transport rate. Integrated (i.e., summed) over time,

$$Q_s = \int q_s dt = A_0 t + \sum_{n=1} \frac{A_n}{n\omega_1} \sin(n\omega_1 t - \varphi_n). \quad (4)$$

The lower frequencies ($n\omega_1 < 1$) are amplified by the factor $1/n\omega_1$ while the higher frequencies ($n\omega_1 > 1$, corresponding to periods less than 6.28 days) are increasingly damped. Cumulative sums of migration and transport rates thus damp high frequency noise and emphasize longer-period, well-correlated seasonal trends. When Eq. (4) is applied to rate data from the Stilwell site, yearly oscillations are amplified over 200 times by the filtering process relative to single-day cycles, while monthly oscillations are amplified 30 times. The integrated total Q_s now also includes a linearly increasing component $A_0 t$ that, if nonzero, will accumulate with time and ultimately outpace all oscillatory contributions. As will be seen below, this linear trend can have a strong influence on correlations of cumulatively summed data.

Summed mean migration distances (for inter-reset periods) are plotted together with summed net sediment transport in Fig. 9, with a separate panel for each site. The calculated net transport generally follows the mean rip migration. The seasonal signatures of large scale climate forcing are clearly visible in the mean migration and net transport patterns of Fig. 9, particularly for the more westward facing Stilwell and Marina sites. At Stilwell (with a shore normal of 290°), a gradual southward transport and migration in the spring and summer months accelerates in the fall as larger northern swell begin to arrive. This trend is sharply reversed in November to January of each year by intense, relatively short-term migrations toward the north, forced by the large, storm-generated western swell that impinge on the coastline with a southerly approach angle (Fig. 10). At Marina (shore normal 278°), a very similar pattern was recorded for 2007, marked by an extremely sharp northward reversal in early December that coincided with the arrival of an intense winter storm out of the west. In contrast, Sand City's northwestward-facing shoreline (shore normal 310°) is subject to an almost year-round southerly approach angle for incident waves and a consistent northward mean flow along the shoreline. Only in the fall and early winter months is the northward trend briefly reversed by the arrival of large northern Pacific swell. (See Appendix A for discussion of wave directional errors and the lack of seasonal transport patterns at Sand City.)

At Sand City, cumulative migration and net transport are both heavily biased northward, and seasonal trends are missing from the calculated sediment transport record. At the Stilwell and Marina sites, transport directions are more balanced, with clearer seasonal variations. The maximum rip field displacement between resets is 400 m (northward) at Sand City, but only 200–300 m (southward) at Stilwell and Marina. In contrast, the net transport for the period at Sand City (3.3×10^4 m³) is significantly less than values for Stilwell (5×10^4 m³) and Marina (10^5 m³). The pronounced seasonal variations in cumulative migration and net transport that occurred in 2004–2005 at Stilwell are significantly milder for 2006–2007. This seasonal variation is prominent in the 2007 cumulative migration record at Marina but less apparent in the calculated net transport. The lag of mean rip migration behind net sediment transport that was described in Section 4.2 is visible on Fig. 9 in the summer and fall of each year, most clearly at Stilwell and Marina. It also introduces an offset in the linear best-fit line plotted for those sites in Fig. 11.

Correlations of mean rip migration and calculated net sediment transport for inter-reset periods are higher than those obtained by any of the three preceding filtering methods (Table 2, column 7). Correlation coefficient r reaches 0.94 at Sand City, 0.76 at Stilwell, and 0.87 at Marina. The high correlation at Sand City is initially surprising, given the poor comparison of other filtered migration and sediment transport rates relative to the other two sites. However, further examination shows the result to be heavily influenced by the

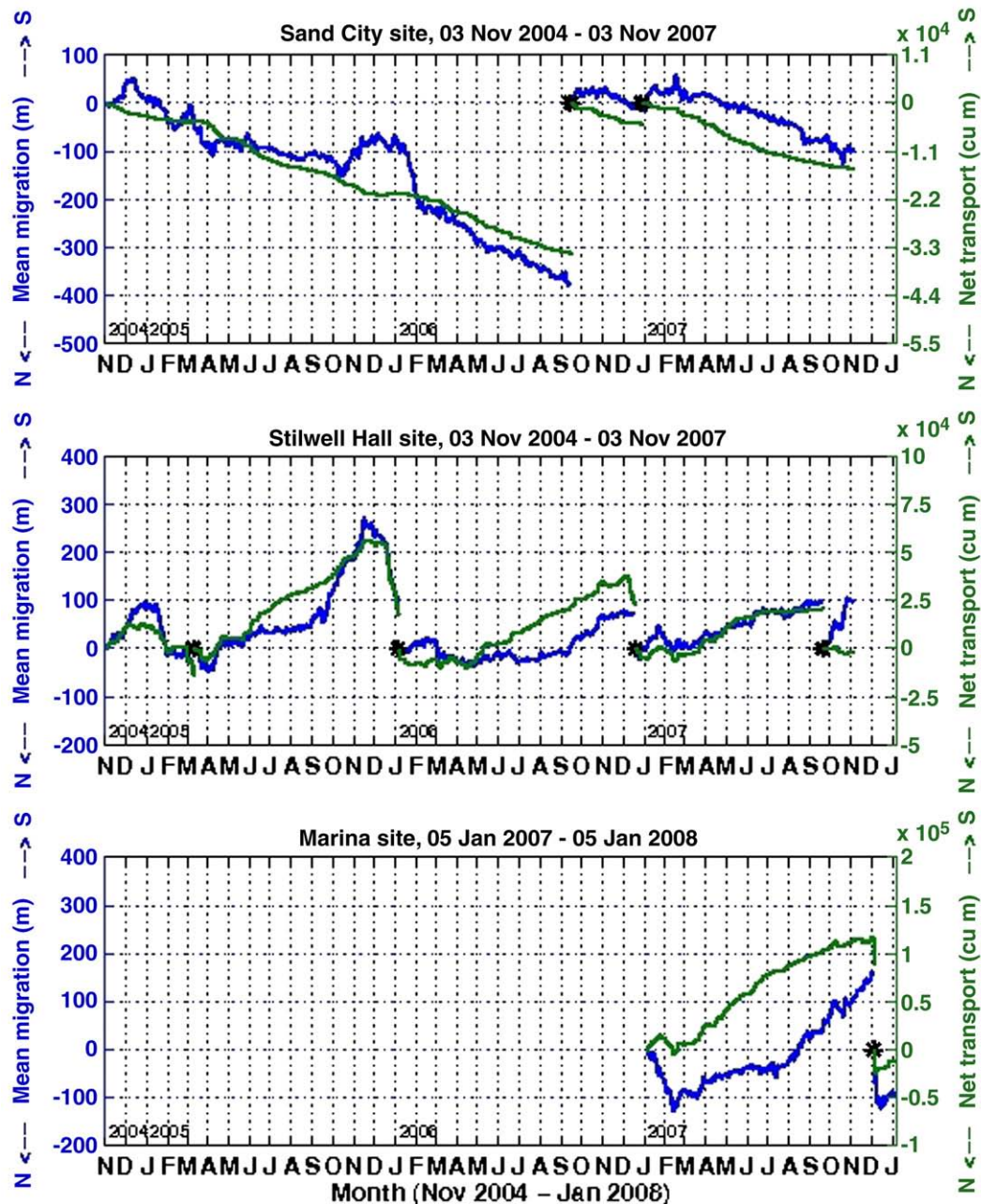


Fig. 9. Mean rip migration (blue, left scale) and sediment transport (green, right scale) for the three video study sites, calculated by cumulatively summing mean daily rates. The generally uniform migration and transport direction at Sand City contrasts with oscillatory behavior seen at Marina and Stilwell, though seasonal oscillations are apparent at all three sites. Significant northward migration and transport are consistently seen at all sites in December to March, while a southward trend is generally apparent between September and December. Visually identified rip field resets are marked with asterisks.

strong northward trends of migration and transport at this southernmost site. When the linear trend is removed from both mean migration and net transport time series, r drops to 0.18 at Sand City, while detrended values at Stilwell ($r=0.62$) and Marina ($r=0.34$) are less severely affected.

The high correlation of mean rip channel migration with net alongshore sediment transport calculated with the CERC formula corresponds to previous results. Holman et al. (2006) found high correlation with a proxy of alongshore current proportional to $H^{1/2}\sin 2\alpha$, which is similar to the $b_2(f)$ input to the radiation stress used in the CERC formulation, and Ruessink et al. (2000) found migration proportional to alongshore wave power, which is implicit in the CERC formulation.

It should be noted that correlation values from the low-pass filter imposed by cumulative summing are larger than the corresponding Butterworth-low-pass-filtered maxima shown in Fig. 8, because the summing process includes some contributions from every frequency component. These results support the existence of a fundamental connection between migration and transport at seasonal timescales.

4.5. Anomalous Sand City

Although an exhaustive investigation is beyond the scope of this paper, it seems appropriate to suggest reasons for the anomalously poor correlation results at the Sand City site. In the authors' view, the mismatch between transport and migration is most likely due to site-

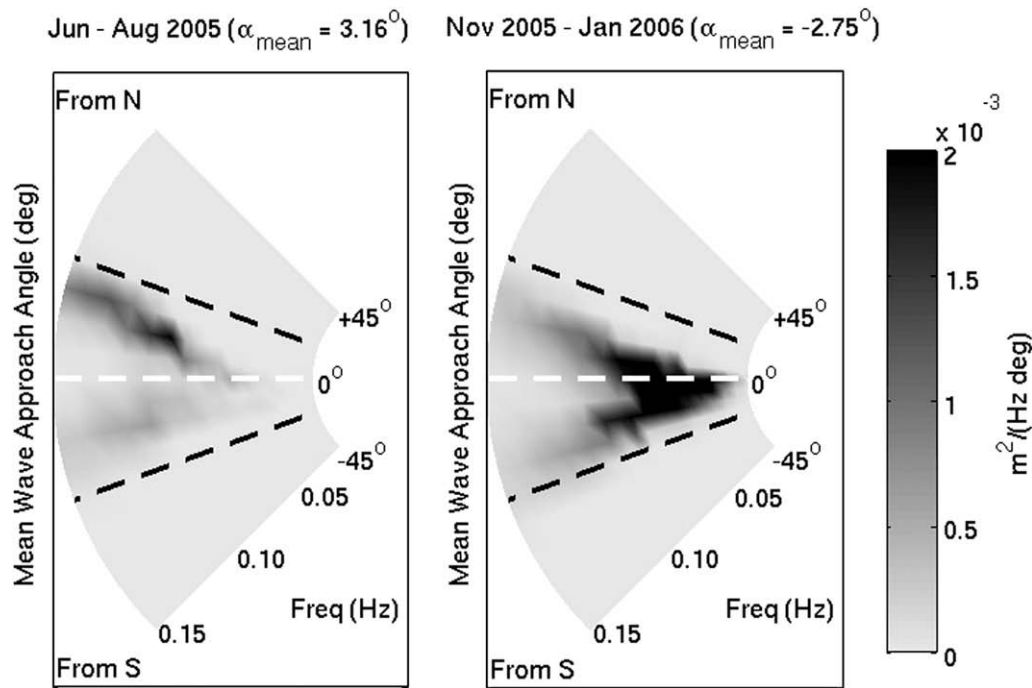


Fig. 10. Wave roses showing mean wave directions and frequencies at 15 m depth, offshore of Stilwell site, as estimated by CDIP spectral refraction program. Directions are relative to shore normal. Left panel represents three months in summer of 2005 ($\bar{H}_{rms} = 0.73$ m), and right panel represents three months in winter of 2005–06 ($\bar{H}_{rms} = 0.73$ m). Mean approach angle for the entire period, α_{mean} , is 3° north of shore normal in summer and 2.8° south of shore normal in winter. Black dashed lines on each panel correspond to $\pm 20^\circ$, confirming that nearly all wave approach angles for both time periods are contained within a range that is close to shore normal (white dashed line).

specific measurement errors, the effects of neglected local shoreline irregularities, and the site's unusual wave characteristics. Measurement errors, including outdated bathymetries and incorrect estimates of shoreline orientation, are discussed further in the Appendix A. An important break in the shoreline occurs at Tioga Avenue, 400 m north of the Sand City site, where large amounts of concrete and other construction materials have been dumped onto the beach and surf zone. It is probable that the resulting mini-peninsula blocks at least some southward transport toward the Sand City site, which reduces the seasonal southward rip migration shown in the top panel of Fig. 7 relative to the other two sites and may also act to focus or reflect shoaling waves. There is a storm drain outfall 50 m south of the Sand City camera tower, which scours a channel into the beach face each winter and contributes additional sediment to the surf zone. Finally, the Sand City location features both a significant alongshore wave height gradient and generally lower wave energies than are found farther north. As shown in this study, the inclusion of $\partial H / \partial y$ in the expanded CERC formula can change alongshore transport rates by up to 20%; however, a true estimate of its effects may require a more accurate local gradient rather

than the large-scale average used here. The Sand City site's milder wave climate results in correspondingly slower bathymetric change. Video-estimated rip migration rates are closer to the noise floor than at Stilwell and Marina and thus also more likely to be obscured.

4.6. The migration–transport relationship

A highly simplified picture of migrating rip channels is presented in Fig. 12 to illustrate the quasi-linear relationship between alongshore transport and rip migration. For such an idealized rip field, a mean migration of, say, $\Delta y = 10$ m to the south can most simply be represented as a translation of each rip channel by 10 m in that direction. The associated net transport must fill in the northern side of each channel while removing sand from its southern side. This would most likely result from a southward-flowing alongshore current. Conservation of mass dictates that flow traveling southward from a shoal into a deeper rip will slow down, dropping some of its sediment load along the northern edge of the rip. Upon reaching the rip's southern edge, the flow must then accelerate onto the shoal,

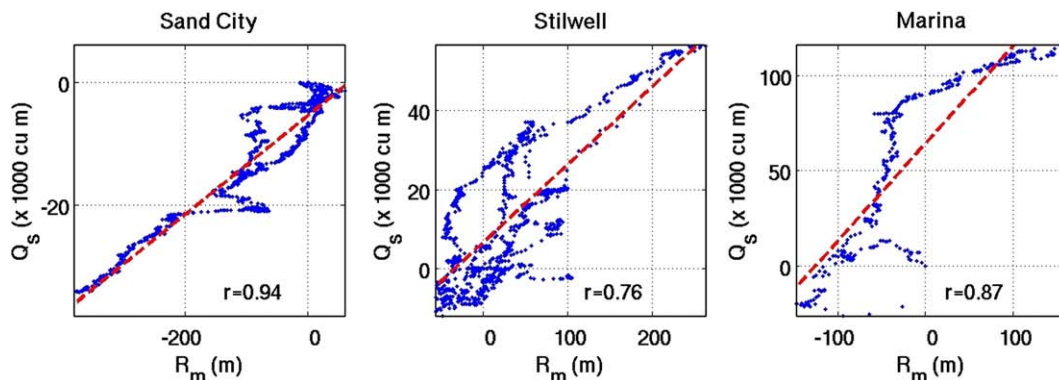


Fig. 11. Correlations of mean rip migration, R_m , and net sediment transport, Q_s , (as predicted by the CERC formula) for the three study sites. The linear least-square best fit is indicated by the dashed line. Correlation coefficients are provided in the lower right corner.

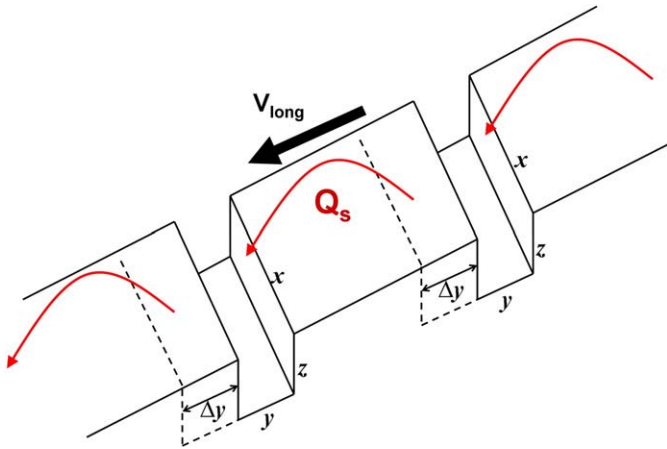


Fig. 12. Simplified picture of relationship between mean rip migration and net sediment transport. Rip channels are treated as rectangular holes in a flat seabed, each of length x , width y , and depth z , with alongshore current flowing in a direction perpendicular to the channel axes. If alongshore flow removes sediment from the downcoast side of each channel and deposits it on the upcoast side of the next one, the channels will migrate in the same direction as the transport. Net transported volume will be proportional to the amount removed from the downcoast side of each rip and thus linearly proportional to the alongshore distance, Δy , traveled by each migrating channel: $Q_s \sim xz\Delta y \sim \Delta y$.

suspending and removing sediment. Over the longer term, these variations will reshape the rip channel and shift it southward.

In this scenario, neglecting other sources, the volume of transported sediment over a given period will be directly proportional to the volume of each rip channel, and the channel migration rate will be linearly related to the alongshore transport rate. Assuming an average surf zone width of 100 m and mean rip channel depth of 2 m, comparable to values seen in southern Monterey Bay, a rip migration rate of 1 m/day would require a sediment transport rate of at least 200 m³/day. An overall migration of 200 m will thus need a net sediment transport volume of at least 4×10^4 m³. Despite a highly simplified analysis, this estimate is of the same order as those obtained in southern Monterey Bay using more complex alongshore transport formulations and recorded wave data (Fig. 7). The idealized estimate above assumes that all transported sediment is used to enable rip migration, while in reality a portion of such sediment might also come from regions between rips, and much of it will bypass a number of channels before finally settling to the bed.

4.7. Tidal effects on migration

Rip migration processes on weekly to monthly timescales are investigated by examining energy density spectra. Migration rate time series for selected inter-reset periods are divided into linearly detrended ensembles of 56 days (Sand City and Stilwell) and 28 days (Marina), overlapped by 50%. The length of the time series was chosen to minimize spectral leakage at the hypothesized fortnightly spring–neap tidal cycles. Spectra of rip migration rates at the three sites are plotted versus frequency for oscillatory periods exceeding 2.5 days in Fig. 13. The spectral noise floor is indicated (assuming white noise variance for the synthetic mean RMS migration rate described at the beginning of Section 4), and is not significant. For the three-year dataset at Stilwell, a peak occurs for a period of 28 days that is significant to at least 80% confidence, suggesting that the lunar tidal cycle may have an effect on alongshore sediment flows and accompanying rip migration rates. The three-year Sand City and one-year Marina datasets both feature a peak near 0.073 days^{-1} , corresponding to a period of approximately 14 days. A less significant spectral peak is also visible close to $1/(7 \text{ days})$ for the two southern locations, possibly indicating that the 14- and 28-day cycles are in-phase harmonics resulting from an asymmetric system response.

These results suggest that there may be enhanced migration at times when the tidal range is greatest, and both the highest and lowest portions of the beach are subjected to more intense wave breaking and increased sediment suspension. Tidal signatures similar to these are commonly detected in measurements of alongshore currents (e.g., Thornton and Kim, 1993). Alongshore flows tend to be weak or nonexistent during lower tides but become stronger at higher tides (Brown, 2009), and stronger currents also appear to be associated with greater rip migration (e.g., Holman et al., 2006). Field measurements on a macrotidal beach suggest that sediment suspension can be enhanced due to increased bed roughness during falling tides (Masselink and Pattiaratchi, 2000) and tidally generated fluctuations in the beach groundwater table (Masselink and Turner, 1999).

5. Summary and conclusions

Daily rip channel locations are determined from time-lapse video images at three sites along southern Monterey Bay for periods of one to three years, and daily migration rates (averaged over all rips in the rip field) are computed. The video digitization error is estimated to be 11.5 m by having four individuals identify rips on a 110-day record. The performance of the CDIP spectral wave propagation model is validated by comparison with nearshore ADCP measurements, and model-predicted radiation stresses, S_{yx} , achieve a correlation of $r = 0.94$ with S_{yx} values computed from ADCP data at Sand City. For each site, the CDIP model is then used to refract measured offshore waves into the surf zone, where the CERC formula is applied to generate estimates of alongshore sediment transport rates. An expanded CERC transport formulation that also includes effects of alongshore wave height gradients is applied to the Sand City site, where such gradients are significant.

Rip migration measurements and CERC model alongshore transport estimates are correlated to test the hypothesis that the alongshore migration rate of rip channels may be expressed as a linear function of the local alongshore sediment transport rate over longer timescales. A parallel simulation conducted with random Gaussian time series indicates that daily rip migration rates will not generally be distinguishable above the noise associated with digitization. Correlations of daily migration and transport rates are indeed relatively low, so several alternative filtering methods are used to compare them in ways that will overcome the noise barrier. Correlations using an expanded CERC model that includes forcing by alongshore wave height gradients to calculate transport at Sand City are little changed from the standard CERC-predicted values, so that formulation is excluded from further consideration. Gaussian-noise simulations identify a minimum time step of approximately 8 days, below which averaged rip migration rate data will likely be indistinguishable from digitization noise. Rip migration and sediment transport rates averaged over 8 days attain correlation coefficients 50–100% higher than those found with daily rates. Low-pass filtering with a cutoff frequency of $1/(8 \text{ days})$ gives coefficient values slightly worse than those from 8-day-averaged rates at each site. Correlating only the 10% of days with the highest transport rates significantly improves upon daily correlation results at Sand City as well as at Stilwell and Marina. Cumulatively summed rates result in nearly doubled correlation values relative to daily rates. Correlations at the Sand City site remain anomalously low for all filtering methods except cumulative summing.

Results obtained with each filtering method provide insight into the nature of the migration–transport relationship. The moderate increases in correlation values obtained with 8-day-averaged migration and transport rates emphasize the challenges of accurately representing complex nearshore processes, even after data are filtered. The low-pass filtering analysis highlights important longer-period oscillations (such as tidal and seasonal cycles) that might influence alongshore rip migration patterns. Improved correlations of

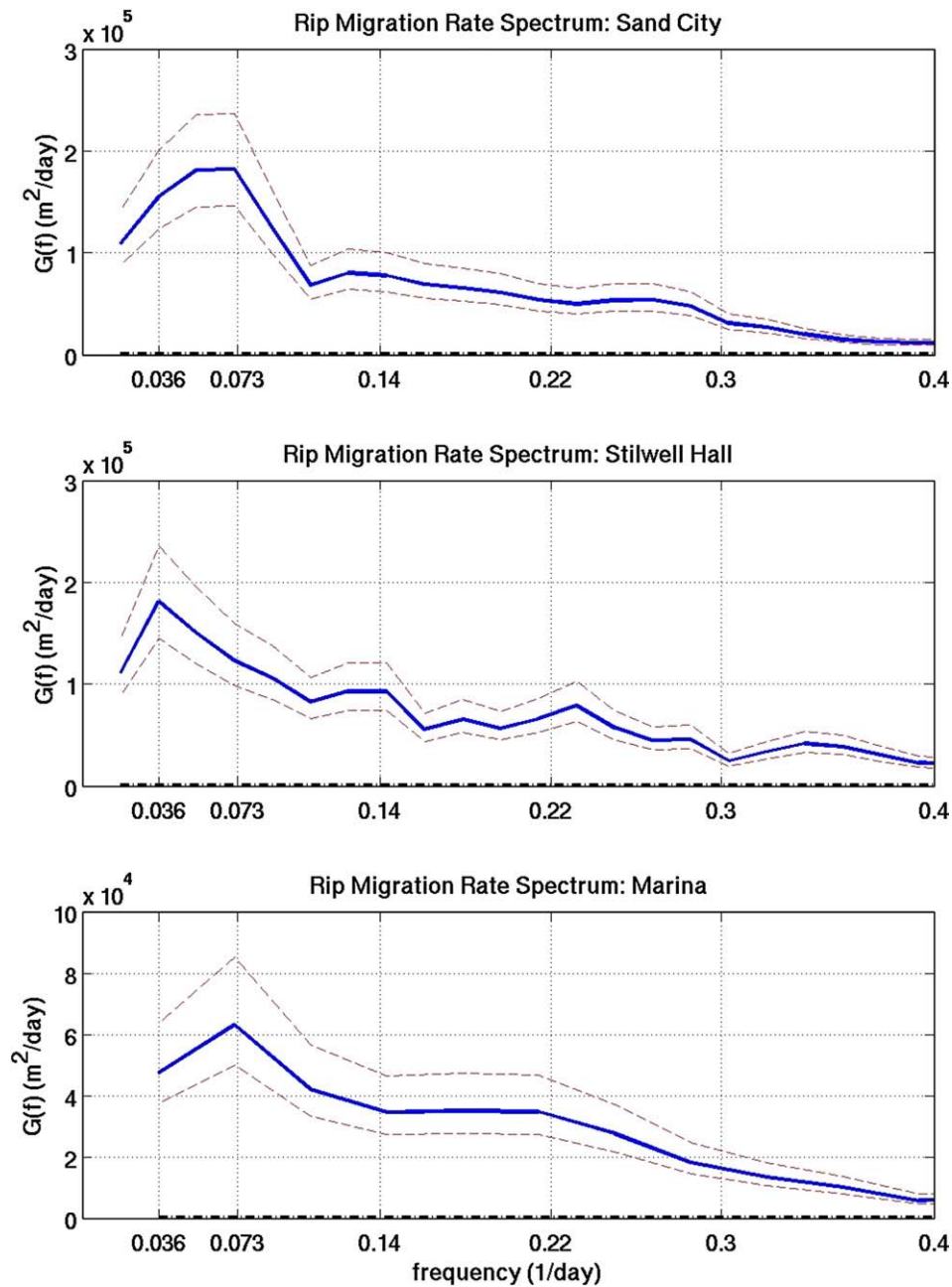


Fig. 13. Frequency spectra of daily rip migration rates for inter-reset periods at the three study sites. Eighty percent confidence intervals are indicated by dashed lines. The three-year data set at Stilwell shows a significant spectral peak at approximately 0.036 days^{-1} (28-day period) and suggests a second peak at approximately 0.14 days^{-1} (7-day period). A significant peak also occurs near 0.073 days^{-1} (14-day period) for the three-year Sand City and one-year Marina datasets. This may signal the influence of the lunar tidal cycle on alongshore sediment transport patterns, or the existence of an optimal depth for accelerated rip migration. The noise floor corresponding to a variance of $(8.5 \text{ m/day})^2$ is shown on each set of axes as a heavy dash-dot line, to emphasize the relative strength of these signals.

daily rates obtained under higher energy conditions suggest that there may be a limited range of conditions over which a linear relationship applies. Cumulatively summed migration and transport rates can be used to track the mean migration of each rip field and the net amount of sediment transported north or south along the beach at each site. Plots of these quantities suggest that rip migration might lag behind sediment transport, particularly in milder summer months when the minimum energy and transport levels necessary for migration may not be attained by the smaller waves. On the basis of the high correlations obtained between cumulatively summed migration and transport rates, it is concluded that the alongshore migration rate of rip channels may be expressed as a linear function of the local alongshore sediment transport rate over longer timescales.

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Appendix A. Error analysis

Daily migration–transport rate correlations can be weakened by a variety of measurement errors intrinsic to the process of recording these datasets. As discussed in Section 4, measurement uncertainty for rip locations at each site is expected to be roughly Gaussian-distributed. When migration rates of multiple rips are averaged, the mean error is reduced as the number of averaged rip timelines (N) increases:

$$\varepsilon_{\text{avg}} = \frac{1}{N} \sum_{n=1}^N \varepsilon_n, \quad (5)$$

where ε_{avg} represents the error in the averaged rip migration rate for a given day and ε_n is the Gaussian-distributed migration rate error for each individual rip. For simulated, random migration rate errors that are Gaussian-distributed with zero mean and a standard deviation of 8.5 m, Eq. (5) results in an averaged error distribution with standard deviation ranging from 2.5 m (for 12 rips) to 4.2 m (for 4 rips). Positive and negative errors can be summed in the equation because they are treated as a continuous sequence of values.

On the southern Monterey Bay coastline, where wave approach is close to shore normal year-round, accurate values for incident angles are essential to accurate alongshore sediment transport estimates. Maximum achievable accuracy for breaking wave angles, however, is probably $\pm 3^\circ$ owing to errors in wave direction, shoreline orientation, and/or model bathymetry. While wave directional uncertainties at offshore buoys can be $\pm 5^\circ$, they are smaller owing to refraction and Gaussian-distributed at breaking depth, and thus unlikely to cause a consistent incident angle bias.

Incorrect shore normal orientation is the most likely source of wave angle bias. In this study, shore normal was measured by multiple methods, including smaller scale ($O(200\text{ m})$), shore-based GPS and theodolite surveys, estimates derived from nearshore bathymetry contours, and larger-scale linear fits to several kilometers of average coastline data. For the Sand City site, results range from 310 to 312° true north. Although the lowest value, 310° , was adopted for this study, comparisons with mean rip migration data suggest that the site's coastline may be even more westward-facing (see Fig. 9). If the shore normal is arbitrarily shifted to 307° , adjusted alongshore transport results then exhibit seasonal oscillations that appear more like those in the rip migration data. At Marina, a shore-normal angle of 280° instead of 282° visually improves the fit of mean rip migration and net transport. However, in each case overall correlations of migration and transport rates decline rather than increase.

Errors in modeled bathymetry are the likely source of small ($<5^\circ$) directional biases that are often identified in CDIP-modeled wave angles. In southern Monterey Bay, several of the NOAA bathymetric surveys used by CDIP were acquired in the early 1930s (NOAA, 2010b) and depths in some areas may have changed significantly. To check for a consistent directional bias in model output at Sand City, mean directions were computed and compared for each frequency bin using CDIP-modeled and ADCP-measured wave spectra in 2006–07. Because the directional spread at the site is nearly as small as the uncertainties in ADCP directional measurements, a definitive conclusion was not reached. ADCP mean directions were generally similar to CDIP values, and average model bias did not exceed 1° for any frequency bin.

In the extended CERC formulation calculations, additional errors may have resulted from incorrect values of alongshore wave height gradients, estimated for Sand City using the large-scale, simplified two-point difference method described in Section 4. The accuracy of that technique was tested by computing gradients over a six-month period for smaller-scale alongshore ranges of 1–3 km (5–15 data points) surrounding the Sand City site and compared to $\partial H_{\text{rms},0}/\partial y$ values estimated with the two-point method. Gradients generated using the shorter ranges were found to have 6–10 times greater variability than those estimated using the simplified two-point method, but mean gradients over the period were nearly the same

(within 5% for the 2–3 km ranges), suggesting that the estimate used in this analysis is a reasonable approximation over the longer term.

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LITTORAL CELLS, SAND BUDGETS, AND BEACHES: UNDERSTANDING CALIFORNIA'S SHORELINE

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Understanding California's Shoreline

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EXECUTIVE SUMMARY

The coastline of California can be divided into a set of distinct, essentially self-contained littoral cells or beach compartments. These compartments are geographically limited and consist of a series of sand sources (such as rivers, streams and eroding coastal bluffs) that provide sand to the shoreline; sand sinks (such as coastal dunes and submarine canyons) where sand is lost from the shoreline; and longshore transport or littoral drift that moves sand along the shoreline. Sediment within each cell includes the sand on the exposed or dry beach as well as the finer-grained sediment that lies just offshore.

Beach sand moves on and offshore seasonally in response to changing wave energy, and also moves alongshore, driven by waves that usually approach the beach at some angle. Most beach sand along the coast of California is transported from north to south as a result of the dominant waves approaching the shoreline from the northwest, although alongshore transport to the north occurs in some locations and at certain times of the year in response to waves from the south. Average annual rates of littoral drift typically range from about 100,000 to 1,000,000 yds³/yr along the California coast.

Sand budgets have been developed for many of California's littoral cells by calculating or estimating the amount of sand added annually from each source or lost to each sink, and by documenting the volume of sand moving alongshore as littoral drift by using harbor dredging records as proxies. It is the balance between the volumes of sand entering and leaving a littoral cell over the long-term that govern the long-term width of the beaches within the cell. Where sand supplies have been reduced through the construction of dams or debris basins in coastal watersheds, through armoring the seacliffs, by mining sand or restricting littoral transport through large coastal engineering structures, the beaches may temporarily or permanently narrow.

The impacts of human activities on the amount of sand supplied to California's beaches have been well documented. While there is a public perception that Southern California beaches have narrowed in recent years, fueled at least in part by the stormy 20-year El Niño dominated period that extended from 1978 to 1998 and severely eroded many beaches, long-term changes in beach width are still being studied.

Beach nourishment or beach restoration is the placement of sand on the shoreline with the intent of widening a beach that is naturally narrow or where the natural supply of sand has been significantly reduced through human activities. Nourished shorelines provide a number of benefits including increased area for recreation, increased revenue from tourism, habitat improvement for shore dependent species, greater protection of the coastline from coastal storms, reduced need for armor, and increased public access.

To date, opportunistic beach fill has provided the majority of sand historically used for beach nourishment in California. Over 130 million yds³ of sand were added to the beaches of southern California between 1930 and 1993 as a by-product of several large coastal construction projects and from the dredging of existing harbors and new marinas. As a result, the beaches of Santa Monica Bay and the Silver Strand, for example, are much wider than they were under natural conditions. Although the amount of sand provided by these projects has dropped sharply, the use of sand retention structures, such as groins or offshore breakwaters, has been effective in stabilizing the sand and maintaining wider beaches at many locations.

Beach nourishment has emerged as an option in recent years for portions of the southern California coastline (northern San Diego County and portions of Santa Barbara and Ventura counties, for example) where beaches are narrow and back beach or cliff top development is being threatened. While nourishment may appear to be an attractive alternative to coastal armoring or retreat, there are a number of issues or considerations that need to be carefully considered and addressed. These include the source and method of obtaining appropriate sand, costs and impacts of removing and transporting large volumes of sand to the site, financial responsibility for the initial project and subsequent re-nourishment, the potential impacts of sand placement, and the lifespan of the nourished sand. Due to the high littoral drift rates that characterize most of the California coast, sand added to a beach that is narrow to begin with cannot be expected to remain at that location for any extended period of time. Sand retention systems have been used effectively at a number of sites in California, however, as a way to significantly extend the lifespan of a beach nourishment project.

CHAPTER 1

INTRODUCTION

People have been interested in beaches and coastal processes for many years. Researchers have observed that beach width can change significantly over a range of time periods, from hours and days to years and decades. Long-term erosion or narrowing of any California beach is of concern to coastal managers as well as the general public.

In an effort to better understand the processes that change beaches, scientists use the concept of sand budgets to identify and quantify, to the degree possible, additions and losses of sand that influence beach width. By the 1960's, researchers recognized that the coastline of California could be separated into distinct, essentially self-contained regions or cells that were geographically limited. For example, beach sand in the Santa Barbara area originated from the watersheds and the coastline in the Santa Barbara area, and beach sand in San Diego or Santa Cruz originated in those geographic areas.

Coastal geologists and engineers termed these essentially self-contained coastal units littoral cells. These cells are geographically bounded by specific physical features that act as barriers to sediment movement, and contain additional features that either provide or remove sand from the cell. Understanding this setting allows researchers to focus on the major elements influencing specific beach or shoreline areas. This report discusses the physical process (littoral drift) that moves sand from one location to another within littoral cells. Littoral cell boundaries, features within the cell that supply sand to the beaches (sources), or remove sand from beaches (sinks) are also explained.

The methods used to develop sand budgets are first illustrated and then summarized for California's major littoral cells. Information is provided on how development associated with California's urbanizing society has altered the sand budgets of many of California's littoral cells, generally by decreasing the input of sand into the cell. This report concludes with a discussion of how the state is attempting to replace the sand lost through human activities (dam removal and beach nourishment) and the issues raised by such restoration activities.

The California Coastal Sediment Management Workgroup (CSMW), a taskforce of state and federal agencies seeking to resolve coastal sediment management issues, and the University of California at Santa Cruz, have developed this report as part of their public outreach and education effort associated with the CSMW's Sediment Master Plan, or SMP. A more detailed report on specific sand budgets for California's major littoral cells has been completed and is a complement to and resource for this more general discussion (Patsch and Griggs, 2006). Funding for both studies was provided by the California Resources Agency as part of a Coastal Impact Assistance Program grant for the SMP. The document was prepared with significant input from CSMW members, but does not necessarily represent the official position of member agencies.

CHAPTER 2

AN OVERVIEW OF LITTORAL CELLS AND LITTORAL DRIFT

WHAT IS LITTORAL DRIFT?

Researchers have learned that sand is in constant motion along California's coastline, and only resides "temporarily" on an individual beach. An alongshore or littoral current is developed parallel to the coast as the result of waves breaking at an angle to the shoreline. This current and the turbulence of the breaking waves, which serves to suspend the sand, are the essential factors involved in moving sand along the shoreline. As waves approach the beach at an angle, the up-rush of water, or swash, moves sand at an angle onto the shoreface. The backwash of water rushes down the shoreface perpendicular to the shoreline or a slight downcoast angle, thus creating a zigzag movement of sand (Figure 2.1). This zigzag motion effectively results in a current parallel to the shoreline. Littoral drift refers to the movement of entrained sand grains in the direction of the longshore current.

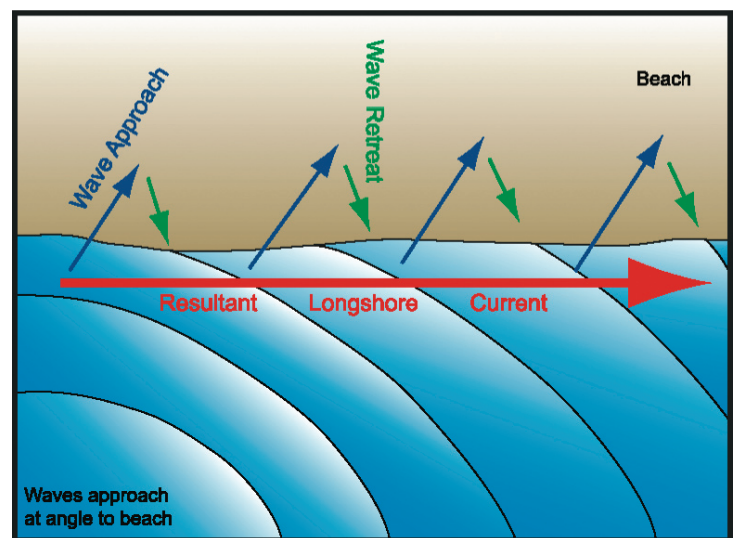


Figure 2.1: Development of longshore current as a result of waves approaching the beach at an angle. Littoral drift refers to the net movement of sand grains in the directions of the longshore current.

Littoral drift can be thought of as a river of sand moving parallel to the shore, moving sand from one coastal location to the next and so on until the sand is eventually lost to the littoral system. Littoral drift or transport in California can occur alongshore in two directions, upcoast or downcoast, dependent on the dominant angle of wave approach (Figure 2.2). Along the California coast, southward transport is generally referred to as downcoast and northward transport is considered upcoast. If waves approach perpendicular to the shoreline, there will be no net longshore movement of sand grains, no littoral current, and thus no littoral drift. Longshore transport for a reach of coast will typically include both upcoast and downcoast transport, often varying seasonally.

Gross littoral drift is the total volume of sand transported both up and downcoast, while net littoral drift is the difference between the two volumes. In other words, along a particular segment of coastline, there may be 200,000 yds³ of sand transported in a southerly or downcoast direction each year, and 50,000 yds³ transported in a northerly or upcoast direction. The gross littoral drift would be 200,000 + 50,000 or 250,000 yds³, whereas the net drift would be 200,000 – 50,000 or 150,000 yds³ downcoast.

For most of California, from Cape Mendocino south to San Diego, waves from the northwest have the greatest influence on littoral drift, and thus, a southward net littoral drift of sand dominates

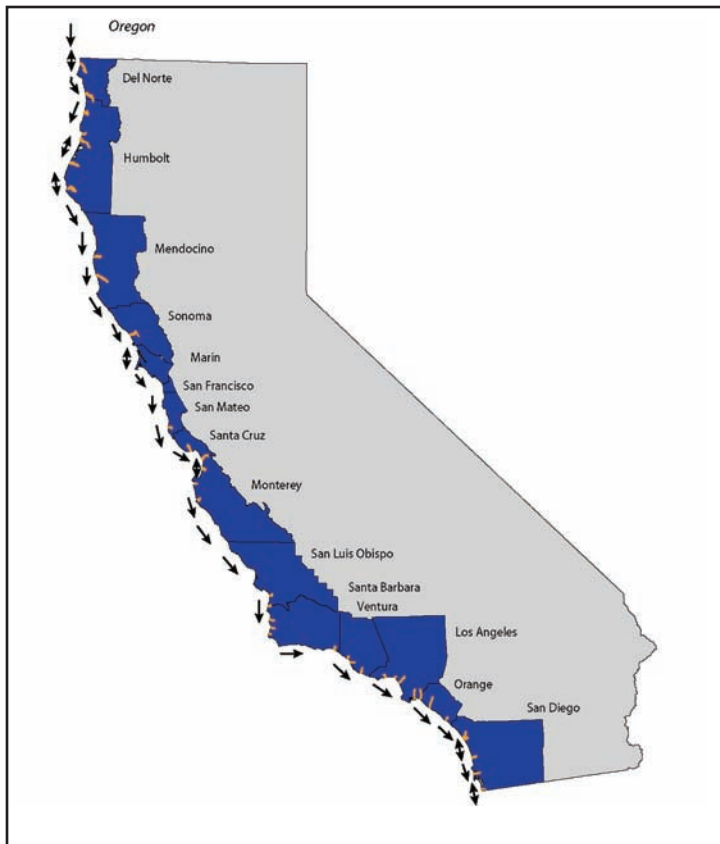


Figure 2.2: Net littoral drift directions in California

(Figure 2.2). The more energetic winter waves generally approach from the northwest direction, driving littoral drift southward or southeastward along the beaches. There are also areas such as southern Monterey Bay, and Oceanside, where longshore transport to the north may take place. During El Niño winters, waves generally come from the west or southwest and the predominance of southward transport is reduced. Transport may be to the northwest, or upcoast, in most of southern California during the summer months when southern swell dominates.

Coastal engineering structures designed to widen or stabilize beaches, such as groins, the construction of harbor entrance jetties and breakwaters, and also the stability or lifespan of beach nourishment projects, are all closely tied to littoral drift direction and rate. Interrupting or disrupting the littoral drift or “river of sand”, in addition to the benefits of retaining sand and widening beaches, can have serious consequences to the downdrift shorelines, including increased beach or cliff erosion and, in the case of a harbor entrance, costly dredging. Erosion of downdrift properties may necessitate the emplacement of additional coastal armoring, which extends the disruptions to the shoreline farther downdrift.

WHAT CONSTITUTES BEACH SAND?

Whereas it is common practice to refer to most beach sediment as “sand”, grain sizes on beaches in California range from very-fine grained sand to cobbles as a result of differences in the wave energy, and the material available to any particular beach. Geologists and engineers classify sediment by size (e.g. silt, sand, pebbles) because different size materials behave very differently and sediment of different sizes is stable on different beaches. The Wentworth scale is

one of the classification schemes most commonly used and it groups sediment by grain diameter (millimeters) based on powers of two (Krumbein, 1936). According to this scale, sand is defined as all particles between 0.0625 mm and 2 mm in diameter, although sand is further broken down into fine-grained, medium-grained, etc. (Table 2.1). The phi scale was introduced as an alternate measure of sediment size based on the powers of two from the Wentworth scale and is commonly used in the coastal geology community. It is important to note that larger phi sizes correspond to smaller grain sizes (Table 2.1).

Wentworth Scale Size Description	Phi Units Φ	Grain Diameter (mm)
Boulder	-8	256
Cobble	-6	64
Pebble	-2	4
Granule	-1	2
Very Coarse Sand	0	1
Coarse Sand	1	0.5
Medium Sand	2	0.25
Fine Sand	3	0.125
Very Fine Sand	4	0.0625
Silt	8	0.004
Clay	12	0.00024

Table 2.1: Wentworth scale of sediment size classification—Note that larger Phi sizes indicate smaller grain size

LITTORAL CUT-OFF DIAMETER

Very fine-grained sand, ranging from 0.0625 to 0.125 mm in diameter (4ϕ to 3ϕ), typically doesn’t remain on the exposed (dry) portions of most California beaches due to the high-energy wave environment. An investigation of littoral transport processes and beach sand in northern Monterey Bay (Hicks, 1985), discovered that there is a littoral cut-off diameter, or a grain-size diameter, characteristic of any particular segment of coast. The cut-off diameter serves as a functional grain size boundary in that very little material finer-grained than this diameter actually remains on the exposed beach. The cut-off diameter along any particular beach or stretch of coast is primarily a function of wave energy at that location.

Studies along the coast of northern Santa Cruz County, which is a relatively high-energy, exposed coast, determined a littoral cut-off diameter of ~ 0.18 mm (2.5ϕ) for this stretch of coast, with very little finer sand remaining on the exposed beaches. In southern California, where much of the coast is protected from strong wave action by the sheltering effect of the Channel Islands, the littoral cut-off diameter is smaller, typically around 0.125mm (3ϕ). When estimating or calculating inputs to a sand budget or planning a beach nourishment project, it is important to consider the littoral cut-off diameter. Sand placed on the beach or entering a littoral cell that is finer than the littoral cut-off diameter will not remain on the dry beach.

THE BEACH PROFILE

The exposed (dry) beach is the visual portion of a profile of sediment that extends from the back of the beach to some depth (commonly referred to as “closure depth”) representing the point beyond which it is believed that there is little net seasonal movement of sand on- and offshore. The grain size distribution varies along this profile

perpendicular to the shoreline, and the overall distribution of size can be represented by an “envelope” of grain sizes. The coarsest materials within this envelope reside on the beach itself; successively finer-grained materials are present further offshore along the profile. Materials within the nearshore are an important part of the beach and related system. Sediment smaller than the cut-off diameter may move into the nearshore and help support the beach profile. It may also move alongshore as littoral drift.

We do not currently have the historical information needed to quantify changes in nearshore sand volumes. This report focuses on the changes and processes affecting beach sands, which provides an adequate surrogate for the total volume of sediment moving alongshore as littoral drift.

LITTORAL CELLS

The California coast can be divided into a number of individual segments within which littoral sediment transport is bounded or contained. These essentially self-contained segments have often been referred to as beach compartments (Figure 2.3; Inman and Frautschy, 1966) or littoral cells.

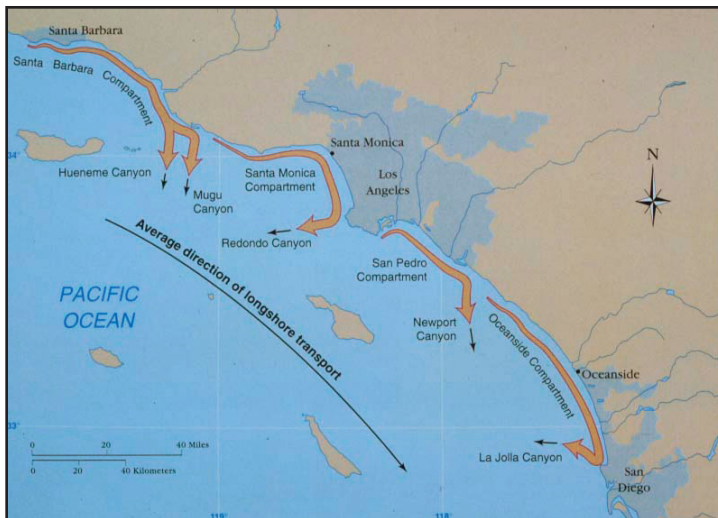


Figure 2.3: Littoral cells in southern California

Each cell has its own source(s) of sand, littoral drift, and ultimately, a sink or sinks where sand is lost permanently from the littoral cell (Figure 2.4). Sediment within a littoral cell consists of sand on the exposed or dry beach as well as the finer grained materials residing in and moving through the adjacent nearshore environment. Typical sources and sinks are described in detail in Chapter 3. The littoral cell concept has been perhaps the most important discovery in the field of coastal and beach processes in the last 50 years. It has enormous value in understanding coastal processes, sand input, output, storage and transport, and provides an extremely valuable and useful framework for assessing any human intrusions into the coastal zone.

The upcoast boundary of a littoral cell is typically a rocky headland, littoral barrier or sink such that littoral drift into the cell from the adjacent upcoast compartment is restricted or minimal. Sand enters the littoral cell primarily from streams and rivers draining to the shoreline and from bluff erosion, and is transported alongshore by littoral drift. Ultimately, sand is lost from the compartment offshore into the head of a submarine canyon or beyond the reach of longshore transport, onshore into coastal dunes, or in some cases, to sand mining.

CROSS-SHORE TRANSPORT

During large storm events, sand may be either transported offshore or onshore from the seafloor seaward of the surf zone. Thus the nearshore area may be either a source or sink for beach sand. However,

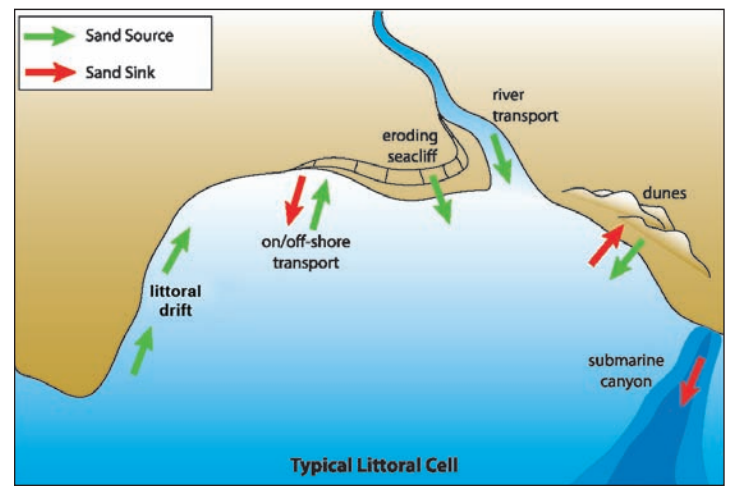


Figure 2.4: Sources and sinks in a typical littoral cell in California

for most littoral cells we simply don't have adequate information to quantify this cross-shore transport and, therefore, the importance of the sand in the nearshore area to littoral sand budgets is poorly understood.

LIMITATIONS TO THE LITTORAL CELL CONCEPT

Ideally, each littoral cell exists as a distinct entity with little or no transport of sediment between cells. It is believed that many headlands form nearly total barriers to littoral drift, but under particular conditions, such as during large storms, significant sand may be suspended and carried around points or across the heads of submarine canyons onto the beaches of adjacent cells. Fine-grained materials being transported in suspension behave differently than sand moving along the surface of the beach or nearshore zone, and the littoral cell boundary concept does not apply to these materials.

Nevertheless, while boundaries have been delineated for California's major littoral cells (Figure 2.5; also see Chapter 4), there are still uncertainties and information gaps on these often well-studied cells: Where are the actual boundaries of each littoral cell? Does significant sand transport take place around or across these “boundaries”? What is the dominant littoral drift direction throughout each cell? These are a few of the questions that remain partially unanswered.

The application of a budget to understand changes in and processes affecting beach sand is a useful tool in coastal land use management and coastal engineering. It is an essential step in understanding sand routing along the coast. One of the first sediment budgets for a littoral cell was created in the region from Pismo Beach to Santa Barbara, estimating each sand input and output along this portion of the central coast of California (Bowen and Inman, 1966). This budget has proven to be a valuable template for subsequent studies.

Our historic lack of understanding of littoral cells and their importance, or the failure to incorporate this type of information early on in the decision-making process in large watershed or coastal engineering projects has resulted in costly problems to society. For example, ongoing harbor entrance channel dredging is required where these projects were constructed in the middle or downcoast ends of littoral cells with high drift rates (Griggs, 1986). The reduction of sand delivery to beaches due to impoundment of sediment behind dams in coastal watersheds has contributed to cliff and beach erosion and the loss of recreational benefits. An improved qualitative and quantitative understanding of littoral cells and sand budgets can help us to resolve existing coastal sediment problems and also inform future planning so as to avoid the mistakes of the past.

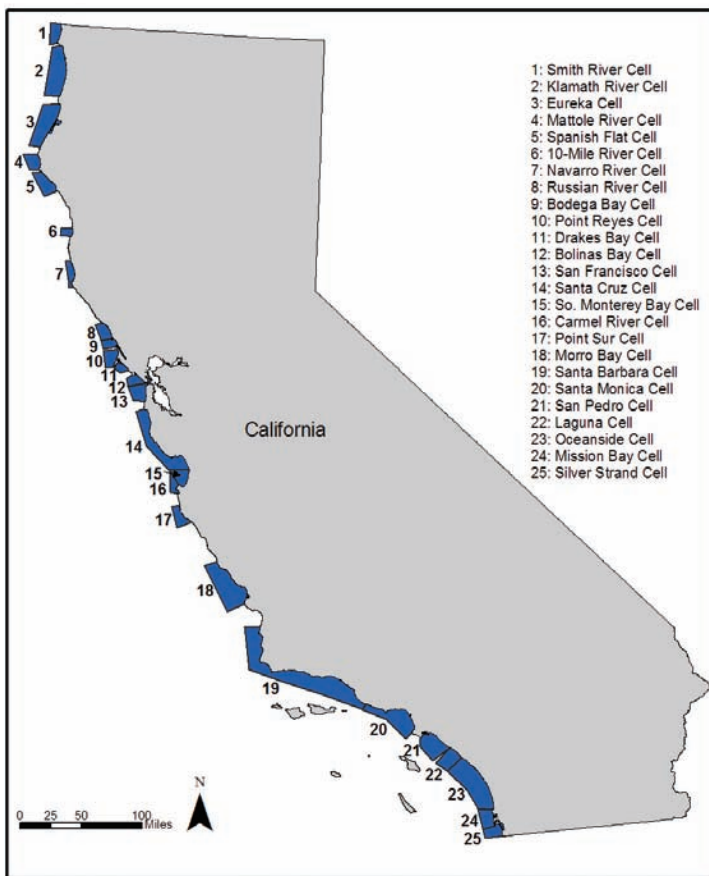


Figure 2.5. California's littoral cells (Habel and Armstrong, 1978)

SEASONAL AND DECADAL MOVEMENT OF SAND WITHIN A LITTORAL CELL

The shoreline within a littoral cell is dynamic, changing with the rhythms of the tides, seasons, and long-term climatic shifts, including fluctuations of sea-level. Beaches respond with great sensitivity to the forces acting on them, primarily wind and waves. Waves provide the energy to move sand both on- and offshore as well as along-shore. The beach is a deposit of well-sorted material that appears to be stable, but in reality, the beach and sand in the nearshore are in constant motion on-, off-, and alongshore. This motion occurs underwater and on both short term (individual waves) and long-term (seasonal and decadal) time scales.

As sea level changes with tidal cycles, so does the width of the exposed beach. In addition to daily variations, long-term fluctuations in sea level occur over hundreds and thousand of years as a result of global climate change. Sea level has been rising for about 18,000 years, and it is assumed by virtually all coastal and climate scientists that it will continue to rise into the foreseeable future. Over the past century, sea level has risen relative to the coastline in southern California by about 8 inches (20 cm), and at San Francisco by about 9 inches (23 cm).

Beach widths in California also change on a seasonal scale, due to changes in weather, storm intensity, and wave climate (Figures 2.6 and 2.7). Seasonal beach erosion is typically a recoverable process; beach width narrows each winter and generally widens the following summer. In the winter, the coast experiences an increase in storms and wave energy. The increased wave energy tends to erode the beach, and moves sand into the nearshore where it is stored in sand bars. These sand bars tend to reduce the wave energy hitting the shoreline because the waves will break farther offshore (over the bars), losing some of

their energy before reaching the shoreline. As the winter storms pass and the wave intensity is reduced, the smaller, less energetic spring and summer waves begin to dominate. These smaller waves rebuild the beach with the sand moved offshore during the winter storms. Figure 2.7 shows a beach in central California (A) during the summer when smaller waves have moved sand onshore to build a wide beach, and (B) in winter when large storm waves have narrowed the beach by moving sand onto offshore bars.

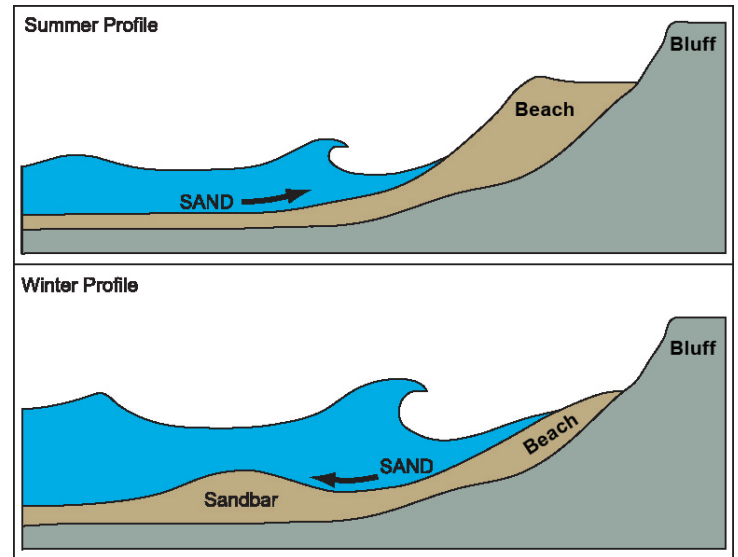


Figure 2.6: Summer profile (also known as the swell profile) results from waves with low heights, and long periods and wavelengths. The beach is characterized by a steep foreshore and a broad berm (a terrace formed by wave action along the backshore of a beach). The winter beach profile (also known as the storm profile) is a response to higher waves, shorter wave periods, and shorter wavelengths. Waves become erosive and cut away at the berm, transporting sand onto offshore bars where it is stored until the following summer.

Over years and decades, beaches can erode (narrow), advance (widen), or remain in equilibrium, as a result of available sand within a littoral cell. When sand supply is reduced through the construction of dams or altered by large coastal engineering structures such as breakwaters or jetties, affected beaches can experience permanent erosion or take years or decades to re-establish equilibrium. This loss of sand and beach width may be recoverable, however, if the sand supply is restored.

Large-scale ocean warming episodes related to El Niño occur in the Pacific Ocean when mean sea level in California can be elevated by up to 15 cm or more for several months to a year. El Niño winters are also characterized by more frequent and vigorous storms over the Pacific, and severe beach erosion can result when large waves approaching from the west or southwest arrive simultaneously with very high tides. Research on changing climate conditions has identified periods, sometimes lasting several decades, when El Niño events are much more severe than those occurring during La Niña periods (characterized by cooler temperatures, decreased storm intensity and rainfall), such as the period from the mid-1940's to 1978. Although the timing of these decadal-scale changes are not predictable, cycles of more frequent El Niño events have been recognized when increased storm intensity and duration result in increased beach loss and cliff erosion. The most recent cycle of intense El Niño events began in 1978. Winter storms of 1982-1983 and 1997-1998, in particular, caused severe beach erosion along California's shoreline and significant damage to oceanfront structures and coastal infrastructure.



Figure 2.7: Seasonal beach changes

A. Wide, summer beach at Its Beach in Santa Cruz (October 1997) B. Narrow winter beach at Its Beach in Santa Cruz (February 1998)

CHAPTER 3

ELEMENTS INVOLVED IN DEVELOPING SAND BUDGETS FOR LITTORAL CELLS

Beach sand is in a constant state of flux, moving on-, off- and alongshore under the influence of waves and currents. Sand is transported to beaches from a variety of sources, including rivers, seacliffs or dunes, updrift beaches and possibly offshore sources (Figure 2.4). Sand generally remains at a given location on a beach for only a short time before it is entrained and moved on as littoral drift. When the removal of sand (output) exceeds that being transported in (input), beach erosion or narrowing results. Conversely, beach widening results when sand input exceeds output, or when some barrier to littoral transport (a groin or jetty for example) is constructed that leads to sand storage (output is reduced). Beaches are said to be in equilibrium when sand inputs are approximately equal to sand outputs.

A sand budget is an attempt to quantify changes in the on-shore sand volume along a stretch of coast by applying the principle of conservation of mass. In order to develop a sand budget, estimates must be made of the primary sand sources (input) and sand losses (output) for a stretch of shoreline. Balancing or creating a sand budget for a reach of coast is similar to balancing a checkbook. Sand sources such as river inputs, seacliff or dune erosion, longshore transport from upcoast areas, beach nourishment and onshore transport from the nearshore can be thought of as deposits (inputs) into the account (Figure 2.4). Sand sinks (e.g., submarine canyons, dune growth, longshore transport out of an area, offshore transport and sand mining) represent outputs from the system or debits to the account (Figure 2.4). The difference between the total volume of sand provided by all sand sources and the volume lost to all sinks within a particular littoral cell will equal the change in sand volume or storage within that compartment and provide insight on the stability of the beach or particular stretch of coast (Table 3.1).

Sources of Sand	Sinks for Sand	Balance
Longshore Transport In	Longshore Transport Out	Accretion
River Inputs	Offshore Transport	Erosion
Seacliff or Bluff Erosion	Dune Growth	Equilibrium
Gully Erosion	Sand Mining	
Onshore Transport	Submarine Canyons	
Dune Erosion		
Beach Nourishment		

Table 3.1: Sources and sinks of sand and the resulting balance in the development of a sand budget.

A sand budget can be developed to represent short-term conditions, such as seasonal or yearly changes. However, when planning a large engineering, restoration or nourishment project or other alteration to the coast, it is best to construct a long-term sand budget that includes historic and present conditions. Many assumptions and errors involved in the data analysis and interpretation of a sand budget can be reduced when a budget spans a greater length of time and averages out year-to-year variations in the components.

It is the balance between sand sources and sinks within each littoral cell that govern the long-term width of beaches within a beach compartment. If there is a significant reduction in the amount of

sand reaching a particular stretch of coast, the beach should gradually erode or narrow. Conversely, if there is an increase of sand in a particular area, the beach should advance seaward, or widen.

COMPONENTS OF A SAND BUDGET

The main challenge in developing a sand budget is quantitatively assessing all sources and sinks to a reasonable degree of accuracy. A thorough literature search should be performed to find the most up-to-date information on each component. Along the California coast, most of the naturally supplied beach sand comes from river and stream runoff with a lesser amount derived from the erosion of coastal cliffs and bluffs. Sand is lost from littoral cells predominantly to submarine canyons, to sand dunes to a lesser extent, and perhaps to offshore transport during extreme storm events. Sand mining directly from the beach historically was a major loss for some littoral cells, but most of this has now been eliminated.

Sand contributions from seacliff erosion, rivers, and dunes as well as other components of the budget, have been or can be quantified or calculated with some effort for many of the state's littoral cells (Patsch and Griggs, 2006; Patsch, 2005). The volume of materials dredged from harbors within the littoral cell can serve as a surrogate (or check point) for the volume of littoral drift at a specific location. The following sections give more specific information on the difficulties and limitations involved in calculating or estimating contributions and losses for a sand budget.

River Inputs (Source): Rivers contribute the majority of sand to most beaches in California. Physical and chemical weathering slowly breaks down the rocks from coastal mountains into smaller fragments. The broken-down boulders, cobbles, gravel, sand, silt and clay move into mountain streams and creeks through rainfall, runoff, and slope failures, and the sediments are sorted and transported downstream into larger streams or rivers. As sediments travel down stream, they break down and become smaller. Large cobbles and boulders are often left upstream because the river does not have enough energy to transport them downstream. Sediment is transported in streams either as suspended load (the finer-grained sediment which makes it look muddy), or as bedload (the coarser material that is transported along the bed of the stream). Most of the suspended load consists of clay and silt, except during high discharge events when significant volumes of sand can be transported in suspension and delivered to the shoreline. Although the total amount of sediment carried as bedload is much less than that carried in suspension, most of the bedload is sand and will contribute directly to the littoral sand budget.

Eventually, the smaller cobbles, sand, silt and clay will reach the shoreline. The finer silt and clay particles are too small to settle and remain on the beach, and consequently are carried offshore by coastal and offshore currents, and eventually deposited on the seafloor nearby or perhaps many miles away. Offshore mudbelts are fairly common, where much of the fine-grained sediment eventually ends up. Most sand-sized material will remain on the beach, and gradually be moved alongshore by littoral drift, thereby feeding down-coast beaches. The finer-grained sand may, however, move into the nearshore zone and also be transported alongshore.

Sand contributions for the majority of the coastal rivers and streams in California have been determined using daily measured values of water discharge, or probabilities of discharge events, to develop "sediment-rating curves". These curves show the relationship between the volume of water discharge and sand loads for individual streams.

Sediment rating curves can be used to estimate the annual sediment

yield from individual rivers and streams. Using these curves, average sand loads (sediment sufficiently coarse to remain on the beach) have been calculated for most of the rivers and streams in California (Willis and Griggs, 2003; Slagel, 2005). Under historical or natural conditions about 13-14.5 million yds³ of sand was being delivered annually to the coast of California from 37 major rivers and streams. This volume has been reduced about 23% statewide through impoundment behind dams, such that, on average, about 10,000,000 yds³ of sand is presently delivered to the coast each year.

The methodology used in these two studies is believed to be the most reliable approach currently available for determining sand contributions to the shoreline from rivers; however it is not without error. Some gauging stations are often well upstream from the mouth of the river; thus, sediment loads may differ significantly between the gauging station and the shoreline due to deposition or erosion that may occur along the stream channel or flood plain between the gauging station and the river mouth.

Sediment delivery by rivers to California's littoral cells is extremely episodic. Most sediment discharged by any particular stream typically occurs during several days of high flow each year. Additionally, sediment discharge during a single year of extreme flood conditions may overshadow or exceed decades of low or normal flow. For example, the Eel River transported 57 million tons of suspended sediment on December 23, 1964, representing 18% of the total sediment discharged by the river during the previous ten years. This one-day discharge is greater than the total average annual suspended sediment discharge for all rivers draining into the entire California coastline. On some streams, however, little or no sediment discharge data may exist for the flood or large discharge events that transport the greatest volumes of sediment. As a result, rating curves may not adequately predict sand transport from water discharge records during the high discharge events. Data or calculations for sediment impounded behind dams can help fill such gaps or deficiencies in sediment discharge records (Slagel, 2005).

Fluvial sediment discharge has also been shown to vary widely from El Niño to La Niña periods (Inman and Jenkins, 1999), such that the length of historic streamflow record from any particular gage may or may not be representative of long-term conditions. In Southern California, mean annual stream flow during wet El Niño periods exceeded that during the dry periods by a factor of about three, while the mean annual suspended sediment flux during the wet periods exceeded the sediment transported during dry periods by a factor of about five (Inman and Jenkins, 1999).

At their best, data on fluvial sand discharge are believed accurate to within about 30% to 50% (Willis and Griggs, 2003). Yet, the amount of sand transported and delivered to the shoreline by streams is an extremely important component of all sand budgets for California.

Reductions to Fluvial Inputs: Damming of rivers or streams reduces sediment delivery to the coast by both trapping sand in the reservoirs and reducing peak flows that transport the greatest amount of sediment. Most of California's large dams, under good management, have reservoir capacities sufficient to absorb all incoming water during a normal winter, releasing low flows to downstream areas during the spring and summer months. The magnitude and frequency of peak flows are therefore reduced, decreasing the river's ability to transport material downstream (Figure 3.1). Dams act as complete barriers to bedload and trap most of the suspended sediment load, except during large flood events when flows overtop the dam or pass through the spillway. The average trapping efficiency (the amount

of suspended sediment trapped by the dam) for most coastal dams in California is about 84% (Brune, 1953; Willis and Griggs, 2003).

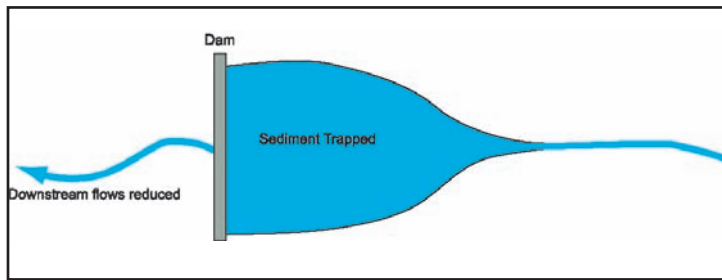


Figure 3.1: Dams trap sediment, preventing it from moving downstream to the shoreline, in addition to reducing the river's flow volume and thus its ability to transport sediment.

Recent work by Willis and Griggs (2003) and Slagel (2005) indicate that the present day delivery of sand to the shoreline has been reduced to about 10 – 11 million yds³/year, or approximately a 23-25% reduction from natural conditions, due to the more than 500 dams on California's coastal streams. Approximately 3 million yds³ of sand is trapped each year and a total of about 163 million cubic yds³ of sand has now been deposited behind dams on the state's 21 major rivers (Slagel, 2005). The great majority of this reduction is concentrated in southern California (Tables 4.1 and 4.2; These two tables list only the amounts of sand provided to California's ten major littoral cells under natural and present-day conditions, and do not include all of the state's major coastal rivers and dams analyzed by Slagel [2005] and Willis and Griggs [2003])

Sand mining in Northern California coastal watersheds and along stream channels has removed an estimated 9 million yds³ (11 million tons) of sand and gravel annually on average, and similar operations in Southern California have removed about 41.5 million yds³ (55.8 million tons) annually on average (Magoon and Lent, 2005). It is unclear how much of this sand and gravel would naturally be delivered to the coast by rivers, but sand mining may play a major role in the reduction of sand delivery by rivers to the shoreline.

If sand supply from rivers is continually reduced through impoundment behind dams, as well as through sand and gravel mining from stream beds, then beaches should eventually be deprived of a significant portion of their predominant sand source. Over decadal time scales, beaches should, therefore, narrow or erode, assuming no change in littoral transport rates (Figure 3.2). Littoral drift rates are a function of the amount of wave energy, the angle of wave approach, and the sand available for transport. More wave energy and a greater angle of wave approach will generate larger littoral drift rates.

Seacliff erosion (Source): Seventy-two percent of California's 1,100-mile coast consists of seacliffs or coastal bluffs, which, when eroded, may contribute sand to California's beaches. Coastal cliffs that consist of materials such as sandstone or granite that break down into sand-sized grains will contribute directly to the beaches. Fine-grained rocks that consist of silt and clay (shales or mudstones), on the other hand, will not contribute significantly to beaches.

The geology of the seacliffs along the coast of California varies widely alongshore and, therefore, the amount of sand contained in the cliffs or bluffs also varies from place to place. Typically, where the coastal cliffs consist of uplifted marine terraces, there is

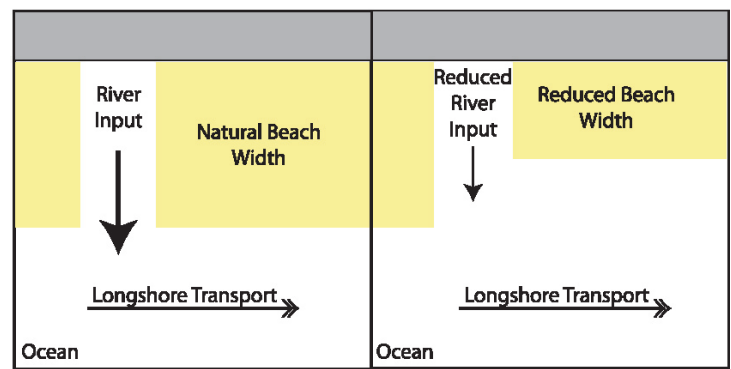


Figure 3.2 illustrates beach narrowing expected from a reduced sand supply. A simplified littoral cell is presented with a single river as the only sand source, thus ignoring sand contributions from cliffs and other budget components. If the amount of sand delivered by the river is reduced, and the littoral drift remains the same, then the downdrift beach volume or width should decrease over time.

an underlying, more resistant bedrock unit and an overlying sandy deposit, consisting predominantly of relict beach sand. Each unit will have its own particular sand content. In order to make qualitative assessments or quantitative measurements of the contribution of coastal cliff retreat to beaches, it is necessary to divide the coast into manageable segments somewhat uniform in morphology and rock type. Estimates of sand contributions from individual segments can then be combined to arrive at a total contribution of beach sand over a larger area, such as an individual littoral cell.

The annual production of sand coarse enough to remain on the beach resulting from seacliff erosion (Q_s) along a segment of coastline is the product of: 1- the cross-sectional area of seacliff (Area = along-shore cliff length x cliff height); 2- the average annual rate of cliff retreat, and; 3- the percentage of material larger than the littoral cut-off diameter (Figure 3.3):

$$Q_s \text{ (ft}^3\text{/yr)} = L_c * E * (H_b * S_b + T_t * S_t)$$

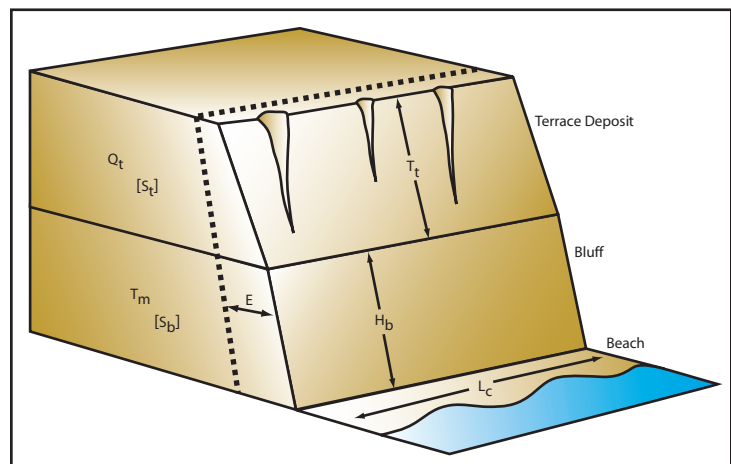


Figure 3.3: Seacliff showing the components involved in calculating sand contribution: L_c is the alongshore length of the cliff (ft); E is erosion rate (ft/yr); H_b is bed-rock height (ft); S_b is percentage of sand size material larger than the cutoff diameter in bedrock; T_t is thickness of the terrace deposit (ft); and S_t is percentage of sand larger than the cutoff diameter in the terrace deposit. T_m (Tertiary Marine) represents geology of the bedrock, and Q_t (Quaternary Terrace) represents geology of the capping terrace deposit.

The methodology for determining sand contributions from seacliff erosion is simpler than the process used to determine river contributions of sand. However, these calculations still have a high degree of uncertainty. The most difficult element of this methodology to constrain is the long-term seacliff erosion rates due to the high spa-

tial variability and episodic nature of cliff or bluff failure. Seacliff erosion rates are typically determined by precisely comparing the position of the cliff edge over time on historical stereo aerial photographs (Griggs, Patsch and Savoy, 2005).

On a state-wide basis, contributions to beach sand from seacliff erosion tend to be much less than those from streams. However, such contributions may be very important locally where very sandy cliffs are rapidly eroding and there are no large streams (Runyan and Griggs, 2003). For example, while bluff erosion contributes less than one percent of the sand to the Santa Barbara littoral cell, bluff erosion is believed to contribute about 31% and 60% of the sand to the Laguna and Mission Bay littoral cells, respectively. Also, recent research in the Oceanside littoral cell, utilizing composition of sand in the bluffs and beaches, as well as very precise LIDAR (a very precise, laser-based, topography measuring system) measurements of coastal bluff retreat (over a relatively short 6-year period) concluded that bluffs may contribute 50% or more of the sand to beaches in this littoral cell.

Beach Nourishment (Source): Beach nourishment is used to describe sand artificially added to a beach and/or the adjacent nearshore that would not have otherwise been provided to the littoral cell. It is a way to artificially widen otherwise narrow or eroding beaches, and has occurred more frequently in southern California than in other region of the state. Historically, sand placed on the beach or just offshore has come from a variety of sources, including: dredging of coastal harbors, lagoons, bays, estuaries or river channels; coastal construction projects where dune or other excavated sand is placed on the beach; and, dredging of offshore areas. Most beach nourishment projects have served dual purposes, i.e., the primary purpose was to create a marina, clear a river channel for flood control, restore a coastal wetland or excavate a construction site, and the secondary purpose of the project was to nourish or widen the beach.

When developing a littoral budget, sand excavated from offshore, coastal or inland sources is considered to be an additional source of sand to the littoral cell, and thus labeled as nourishment. Harbor entrance bypassing operations or channel maintenance dredging do not represent new sources of sand, because they are simply moving the sand to a new location within the same cell, and so are not considered nourishment.

Cross-shore exchange (Source/Sink): Quantifying the potential movement of sand between beaches and the nearshore and offshore areas is the most challenging and poorly evaluated sand budget element. Cross-shore transport can result in either a net gain or loss for the beach. A comparison of sediment composition (e.g., distinct minerals contained in the sand) between beach, nearshore and shelf sand is often used as evidence for a net onshore or offshore transport; however, the similarity in composition only indicates that an exchange has taken place. It rarely indicates direction of transport or volumes of sand moved, which are necessary for development of a sand budget.

Whether or not sand is moved on- or offshore is controlled by factors such as wave energy and tidal range, bottom slope and the grain size of the sand. In order to thoroughly evaluate this component it would be necessary to have data on the precise thickness or depth of beach-sized sand over large offshore areas and to know how this has changed over time. With the large shelf areas typically involved, a small increase in the thickness of the sediment veneer over an extensive area can produce a large volume of sand in storage. We

simply don't have these data, and it would require long-term studies to determine how the distribution of sand changes over time. In developing sand budgets, it is often assumed that net cross-shore exchange of sand is zero, such that the volumes of sand transported on- and offshore are balanced, unless sediment data are available on a particular area of interest. In other cases, however, unaccounted for losses are usually ascribed to offshore transport.

Offshore dredge disposal: There are several littoral cells where large volumes of beach size sand that have been dredged from harbors or channel entrances have been or continue to be transported offshore for disposal, thus removing this material permanently from the littoral system. Offshore disposal can, therefore, be a significant littoral sand sink.

Close to a million cubic yards of sand on average is dredged from the Humboldt Bay entrance channel every year and transported to EPA's Humboldt Open Ocean Disposal Site (HOODS; Tom Kendall, USACE). Sediment lost to the littoral cell from dredging and offshore disposal was also a major issue in San Diego. About two million cubic yards of sediment was scheduled for dredging as part of the deepening of San Diego Bay for larger U.S. Navy vessels. This sediment was originally intended for the SANDAG nourishment project, but was disposed of offshore due to ordinance found in the dredge spoils from the bay. These are very large volumes of potential beach sand that are being removed more-or-less permanently from the littoral system for different reasons. This is an issue that merits further investigation in order to document how extensive these losses are, where they are taking place, and what options exist for possible utilization of these materials in the adjacent littoral cells.

Dune Growth/Recession (Sink/Source): Sand dunes occur adjacent to and inland from beaches at many locations along the coast of California. Dunes are created where ample fine-grained sand is available with a persistent onshore wind and a low-lying area landward of the beach where the sand can accumulate. Typically, if the shoreline is backed by seacliffs, dunes can't accumulate or migrate, and thus will not grow to any significant size. In many areas of California, such as the area north of Humboldt Bay, Golden Gate Park in San Francisco, southern Monterey Bay, The Pismo Beach area, and areas along Santa Monica Bay, wind-blown sand has created large dune complexes.

Dunes commonly represent sand permanently lost from littoral cell budgets, constituting a significant sink to a cell. For example, it has been estimated that an average of 200,000 yd³/yr of wind-blown sand is permanently lost from the beaches along the 35-mile coastline from Pismo Beach to Point Arguello (Bowen and Inman, 1966; Figure 3.4). On the other hand, in areas such as the Southern Monterey Bay littoral cell, dune erosion and recession play an important role as a sand source to the littoral budget. While uncommon, sand may be blown onto the beach from a coastal dune area (representing a source).

Dune migration, growth and erosion (or deflation) can be measured from aerial photographs or in the field and converted into sand volumes. Dune growth and deflation illustrate the need to introduce a time element into sand budgets. One major storm can erode the portion of dunes closest to the ocean (i.e., the foredune), which were previously considered a sink, returning the sand to the beach. However, many studies have concluded that this type of foredune erosion may occur for only a few days during a major storm event and is followed by a prolonged period (from years to decades) of foredune growth.



Figure 3.4: Pismo Dunes in San Luis Obispo County. Copyright © 2002 Kenneth & Gabrielle Adelman California Coastal Records Project, www.Californiacoastline.org.

Losses into Submarine Canyons (Sink): Submarine canyons that extend close to shore (e.g., Mugu, Redondo, Newport and Monterey submarine canyons) (Figure 3.5) serve as effective barriers to littoral drift and terminate most littoral cells in California. These canyons are the largest permanent sink for sand in California. Sand accumulates at the heads of these submarine canyons and, through



Figure 3.5: Monterey Submarine Canyon

underwater sand flows or turbidity currents, is funneled away from the shoreline and deposited in deep offshore basins.

It is believed that an average of over a million cubic yards of sand is annually transported down into Mugu Submarine Canyon, thus terminating the littoral drift within the Santa Barbara littoral cell. Monterey Submarine Canyon (Figure 3.5), located in the center of Monterey Bay, is one of the world's largest submarine canyons and is over 6,000 feet deep. An average of at least 300,000 yds³ of sand is annually lost down this canyon. As part of sand budget calculations, after all sand

sources and other sinks are first accounted for, any remaining sand in the budget is assumed to be directed into a submarine canyon, where one exists and reaches close enough to the shoreline to trap littoral drift, and is permanently lost to the littoral cell.

Sand Mining (Sink): Sand and gravel removed from riverbeds, beaches, dunes and nearshore areas for construction and/or commercial purposes, represents a significant permanent sink for some of California's littoral cells. Sand mining along the beaches of California and Oregon began in the late 1800s when there seemed to be an overabundance of sand and no obvious impacts from mining. Overall in northern California, (i.e., from the Oregon border to the Russian River), about 8 million yds³ (11 million tons) of sand and gravel are removed each year from the coastal streambeds (Magoon and Lent, 2005). In southern California, the annual total is nearly 41.5 million yds³ (56 million tons), primarily in the greater Los Angeles and San Diego areas.

Beach or streambed sand mining has historically been a large sink for beach sand in some specific locations; however the volumes removed are difficult to quantify for the purposes of a sand budget. Due to the proprietary (and therefore publicly unavailable) nature of sand mining operations, gathering information on specific mining practices for a given river or beach within a littoral cell may not be possible. Information on mining should be included in long-term sand budgets when available. While there are still extensive sand and gravel mining operations along many streambeds in California, direct removal of sand from the beach along the coast of California was mostly terminated by the early 1990's. However, mining of the back beach still occurs at some sites (e.g., near Marina in southern Monterey Bay) (Figure 3.6).



Figure 3.6: Sand is still mined directly from the back beach in the Marina area of southern Monterey Bay (2005). Copyright © 2005 Kenneth and Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org.

LITTORAL DRIFT CHECK POINTS

Direct measurement of the volume of sand moving as littoral drift would confirm estimated sand inputs from streams and bluffs; however, such direct measurement is unfortunately not feasible. However, California's four large ports and 21 small craft harbors (Figure 3.7) can serve as constraints, or check points, on this volume when developing sand budgets. Half of the littoral cells in California (10 of the 20 cells) contain at least one harbor that effectively traps the littoral drift. These coastal sand traps, however, are very different from dams and reservoirs, which keep sand from ever entering the littoral system.

Much of the sand moving along the coast as littoral drift is caught

in either harbor entrances or designed trapping areas, dredged, and, with few exceptions, placed downdrift. The configuration and

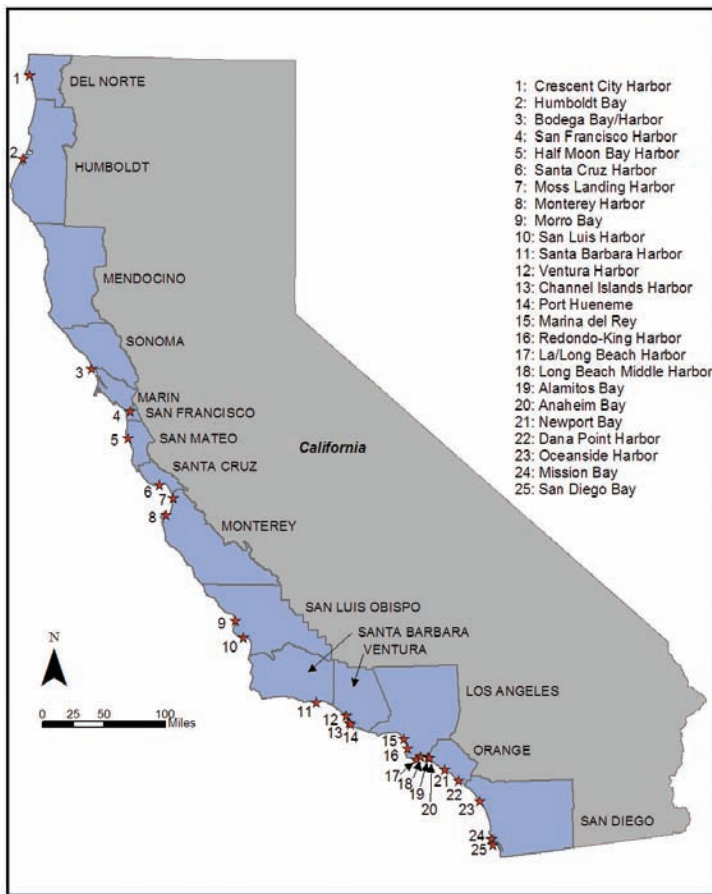


Figure 3.7: California's harbors and location by county.

geometry of some harbors (e.g., Ventura and Channel Islands; Figure 3.8) were designed to trap littoral drift before it enters the harbor's navigation channel. Sand resides in these sediment traps until it is dredged, typically once or twice a year. Other harbors (e.g., Humboldt Bay, Oceanside, and Santa Cruz harbors) were not designed with a specific sediment trapping area. Thus, once the sand residing upcoast of the first jetty reaches the jetty tip, littoral drift travels around the jetty and accumulates in the harbor entrance channel, often forming a sandbar. While some littoral drift may naturally bypass the entrance channel, especially at those harbors designed without a specific trapping area, harbor dredging records are the most dependable numbers currently available for estimating long-term annual gross and, occasionally, net littoral drift rates.

For purposes of sand budget calculations, there must be enough sand

being added to the littoral cell to balance the average dredged volume. Some littoral cells have more than one harbor, and thus multiple check points for quantifying the cell's littoral drift. These cells provide optimum conditions for developing reliable sand budgets.

Inherent errors do exist when using harbor entrance dredging volumes to estimate littoral drift as checkpoints in the development of



Figure 3.8: Ventura Harbor: maintenance dredging in 1972. Copyright © Kenneth and Gabrielle Adelman, California Coastal Records Project www.Californiacoastline.org

littoral cell sand budgets, however. Errors involved in estimating dredging volumes include, but are not limited to, the type of equipment used to dredge, and the time frame of sand removal and placement. There can also be uncertainties involved in the pre-dredge conditions and the method used to determine the reported volume of sand dredged from a location.

Other uncertainties include: 1—harbors, (e.g., Oceanside) where detailed studies indicate that littoral drift reverses seasonally, such that sand can be dredged twice, and; 2- significant natural bypassing of sand beyond the dredging area can also occur (e.g., again at Oceanside, where sand appears to have been transported offshore and formed a permanent bar) (Dolan, Castens, et al., 1987; Seymour and Castel, 1985).

It is believed, however, that the margin of error involved in estimating dredged sand volumes is still significantly lower than the error associated with quantifying the annual volumes of most sand sources and sinks within littoral cells (such as the sand contribution from streams and cliff erosion and sand lost to submarine canyons). For most harbors, entrances or trapping areas form nearly complete littoral drift traps. Where long-term data exist, which tend to average out year to year fluctuations, harbor dredging records provide rational check points for littoral cell sand budgets.

CHAPTER 4

SAND BUDGETS FOR CALIFORNIA'S MAJOR LITTORAL CELLS AND CHANGES IN SAND SUPPLY

The beaches of southern California are intensively used recreational areas that generate billions of dollars of direct revenue annually. Wide, sandy beaches, used by people playing volleyball, sunbathing, swimming, jogging and surfing, are the quintessential image of southern California. Wide, sandy beaches, however, were not always the natural condition. Many of these beaches have been artificially created and maintained through human intervention, including placement of massive amounts of sand and the construction of groins, jetties and breakwaters (Flick, 1993). The rate at which sand was added to these beaches, however, has diminished over the past 30 years, fueling the public's perception of erosion and the narrowing of the beaches. Sand sources for most of the littoral cells in southern California are minimal to begin with, and have been reduced further through stream channel sand mining and the damming of rivers, and, to a lesser extent, armoring of seacliffs and reduction in beach nourishment projects.

Sand is naturally supplied to the beaches of California's littoral cells from a combination of river discharge, seacliff erosion, and dune deflation or erosion. In addition, sand has been added to the beaches historically through various beach nourishment projects. These elements are included as inputs for the sand budgets presented in this summary for the major littoral cells in California. The cells described include (Figure 2.5) Eureka, Santa Cruz, Southern Monterey Bay, Santa Barbara, Santa Monica, San Pedro, Laguna, Oceanside, Mission Bay, and Silver Strand littoral cells.

Table 4.1 summarizes selected major littoral cells and the relative importance of individual sand sources to the total sand supplied to the cells. These data were developed for and derived from the more detailed companion study which quantified sand budgets for these littoral cells (Patsch and Griggs, 2006). Under present-day (i.e., dams in place) conditions (excluding beach nourishment), and based on all data published to date, fluvial inputs constitute about 87% of the sand entering California's major littoral cells and 90% of the sand provided to southern California beaches (from Santa Barbara to the Mexico border). Seacliff erosion contributes 5% of the sand to the major littoral cells statewide, and about 10% of the sand reaching the beaches in southern California. Dune recession statewide accounts for 8% of the sand in the statewide analysis but is 0% in southern California.

When beach nourishment is taken into account as a contributing source of sand, the relative importance of rivers, bluffs, and dune erosion statewide drops to 72%, 4% and 7% respectively in California's major littoral cells, with beach nourishment accounting for the remaining 17% of the sand input. In southern California, beach nourishment represents 31% of the sand supplied to the beaches, thus reducing the importance of river and bluff inputs to 62% and 7% respectively.

Table 4.2 is a summary of the anthropogenic reductions to the sand supplied to the major littoral cells in California and to southern California from armoring of seacliffs and damming of rivers. In addition, these reductions are contrasted against the sand supplied through beach nourishment, and a net balance associated with these anthropogenic changes is shown. The greatest reduction in sediment supplied to southern California results from the damming of rivers. Such damming has reduced the apparent volume of sand

Littoral Cell	All Sand Volumes in yd3/yr	Rivers	Bluff Erosion	Dunes	Beach Nourishment	Total Sand Supply
Eureka	Total "Actual" sand contribution	2,301,000	0	175,000	0	2,476,000
	% of Budget	93%	0%	7%	0%	100%
Santa Cruz	Total "Actual" sand contribution	190,000	33,000	0	0	223,000
	% of Budget	85%	15%	0%	0%	100%
Southern Monterey Bay	Total "Actual" sand contribution	489,000	0	353,000	0	842,000
	% of Budget	58%	0%	42%	0%	100%
Santa Barbara	Total "Actual" sand contribution	2,167,000	11,000	0	0	2,178,000
	% of Budget	99%	1%	0%	0%	100%
Santa Monica	Total "Actual" sand contribution	70,000	148,000	0	526,000	744,000
	% of Budget	9%	20%	0%	71%	100%
San Pedro	Total "Actual" sand contribution	278,000	2,000	0	400,000	680,000
	% of Budget	41%	0%	0%	59%	100%
Laguna	Total "Actual" sand contribution	18,000	8,000	0	1,000	27,000
	% of Budget	66%	31%	0%	4%	100%
Oceanside	Total "Actual" sand contribution	133,000	55,000	0	111,000	299,000
	% of Budget	23%	9%	0%	19%	51%*
Mission Bay	Total "Actual" sand contribution	7,000	77,000	0	44,000	128,000
	% of Budget	5%	60%	0%	35%	100%
Silver Strand	Total "Actual" sand contribution	42,000	0	0	256,000	298,000
	% of Budget	14%	0%	0%	86%	100%
Total	Total "Actual" sand contribution	5,695,000	335,000	528,000	1,338,000	7,896,000
	% of Budget	72%	4%	7%	17%	100%
Southern CA Total: (Santa Barbara cell to Mexico)	Total "Actual" sand contribution	2,715,000	301,000	0	1,338,000	4,354,000
	% of Budget	62%	7%	0%	31%	100%
Total: Without Beach Nourishment	All	87%	5%	8%	N/A	6,558,000
	Southern CA	90%	10%	0%	N/A	3,016,000

Table 4.1: Summary of the average annual (post-damming and seacliff armoring) sand contributions from rivers, seacliff erosion, dune recession, and beach nourishment to the major littoral cells in California. * Gully erosion and terrace degradation accounts for the remaining 49% of the sand in the Oceanside littoral cell. This category is not accounted for in this table. Nourishment data is for the period 1930–1993. (For data sources see Patsch and Griggs, 2006)

reaching the beaches within the state's major littoral cells and to southern California cells by about 43% and 47%, respectively. The reduction in southern California equates to nearly 2.4 million yds³ of sand annually (Willis and Griggs, 2003). Seacliff armoring has

reduced the sand supplied to the major littoral cells and southern California's beaches by 11% and 10%, respectively. The southern California reduction is about 35,000 yds³ annually, still less than 7% of the total sand input to all of these littoral cells.

Littoral Cell		Rivers (dams)	Bluff Erosion (armor)	Total Reduction	Beach Nourishment	Balance (nourishment-reductions)
Eureka	Reduction yd ³ /yr	N/A	N/A	N/A	0	N/A
	Percent Reduction	N/A	N/A	N/A		
Santa Cruz	Reduction yd ³ /yr	6,000	8,000	14,000	0	-14,000
	Percent reduction	3%	20%	6%		
Southern Monterey Bay	Reduction yd ³ /yr	237,000	N/A	237,000	0	-237,000
	Percent reduction	33%	N/A	33%		
Santa Barbara	Reduction yd ³ /yr	1,476,000	3,000	1,479,000	0	-1,479,000
	Percent reduction	41%	19%	40%		
Santa Monica	Reduction yd ³ /yr	29,000	2,000	31,000	526,000	495,000
	Percent reduction	30%	1%	13%		
San Pedro	Reduction yd ³ /yr	532,000	0	532,000	400,000	-132,000
	Percent reduction	66%	0%	66%		
Laguna	Reduction yd ³ /yr	0	1,000	1,000	1,000	0
	Percent reduction	0%	13%	4%		
Oceanside	Reduction yd ³ /yr	154,000	12,000	166,000	111,000	-55,000
	Percent reduction	54%	18%	47%		
Mission Bay	Reduction yd ³ /yr	65,000	17,000	82,000	44,000	-38,000
	Percent reduction	91%	18%	50%		
Silver Strand	Reduction yd ³ /yr	41,000	0	41,000	256,000	215,000
	Percent reduction	49%	0%	49%		
Total	Reduction yd ³ /yr	2,540,000	43,000	2,583,000	1,338,000	-1,245,000
	Percent reduction	43%	11%	39%		
Southern CA Total	Reduction yd ³ /yr	2,297,000	35,000	2,332,000	1,338,000	-994,000
	Percent reduction	47%	10%	44%		

Table 4.2: Summary of the anthropogenic reductions to the sand supplied to the major littoral cells in California and to southern California, due to seacliff armoring and the damming of rivers. In addition, sand supplied to the cells through beach nourishment is shown for the period 1930–1993. Note: sand bypassing at harbor entrances is not included in the nourishment volume.

CHAPTER 5

DISCUSSION OF BEACH NOURISHMENT IN CALIFORNIA

Beach nourishment or beach restoration is the placement of sand on the shoreline with the intent of widening beaches that are naturally narrow or where the natural supply of sand has been significantly reduced through human activities. Although there are several different approaches to beach nourishment, procedures are generally distinguished by methods of fill placement, design strategies, and fill densities (Finkl, et. Al. 2006; NRC, 1995; Dean, 2002). Types of nourishment according to the method of fill emplacement include the following (Figure 5.1; Finkl, et. al. 2006)):

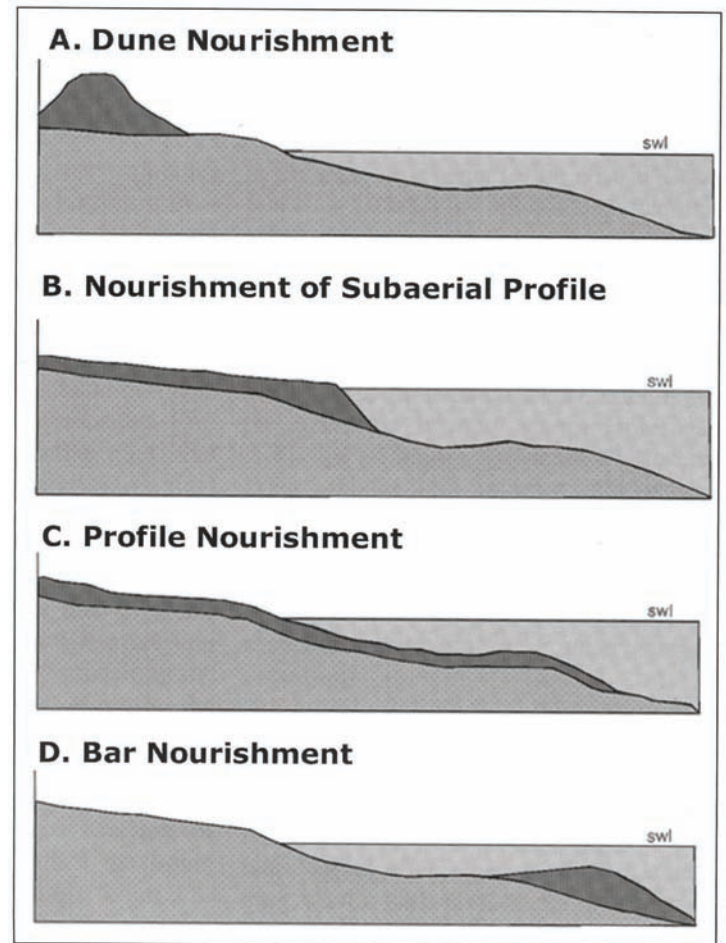


Figure 5.1. Methods of beach nourishment defined on the basis of where the fill materials are placed (from Finkl, Benedet and Campbell, 2006).

- (a) Dune nourishment: sand is placed in a dune system behind the beach.
- (b) Nourishment of subaerial beach: sand is placed onshore to build a wider and higher berm above mean water level, with some sand entering the water at a preliminary steep angle.
- (c) Profile nourishment: sand is distributed across the entire beach and nearshore profile.
- (d) Bar or nearshore nourishment: sediments are placed offshore to form an artificial feeder bar.

Nourished shorelines provide two primary benefits: increased area for recreation and greater protection of the coastline against coastal storms. Other potential benefits include, but are not limited to, increased tourism revenues, increased public access, reduced need for hard protective structures, higher property values, enhanced

public safety and restored or expanded wildlife habitats.

Beach nourishment in California has been concentrated primarily in the southern part of the state. Flick (1993) summarized the history of beach nourishment in southern California and determined that over 130 million yds³ of sand was added to those beaches between 1930 and 1993. About half of this amount was divided evenly between the Santa Monica and the Silver Strand littoral cells where the beaches widened significantly in response to this nourishment. Wiegel (1994) prepared a very thorough evaluation of ocean beach nourishment along the entire USA Pacific Coast; however, the report is mostly about Southern California because of the numerous beach nourishment projects that have taken place there.

What is clear is that there are major differences between the tectonic, geomorphic, oceanographic, climatic, and wave conditions along the Pacific Coast as compared to the Atlantic and Gulf Coasts. In addition to these inherent geological and oceanographic differences, there is a pronounced difference in the practice of beach nourishment (Finkl, et. al., 2006). Large nourishment projects using sand from offshore are common along the Atlantic and Gulf Coasts, but beneficial or opportunistic sediment (from coastal construction, channel maintenance and bypass operations) predominate on the West Coast (Herron, 1987; Flick, 1993; Wiegel, 1994).

The California Beach Restoration Study (2002) is a comprehensive assessment of California's beaches and their economic benefits, beach nourishment and restoration, as well as an evaluation of the major sources of sand to the state's beaches and how these have been impacted by human activity (<http://www.dbw.ca.gov/beachreport.htm>). The report concludes that continued loss of many public beaches could be substantially reduced by beach nourishment.

Opportunistic beach nourishment, which has provided the majority of sand historically used for beach nourishment in southern California, occurs when beach-compatible sand from a harbor development or expansion project, excavation for a large coastal construction project (e.g., El Segundo Power Plant or Hyperion Sewage Treatment Plant construction) or other construction or maintenance project is placed on nearby beaches. In other words, such sand is a byproduct of some construction or maintenance project that was not undertaken with beach replenishment or nourishment as a specific goal, but rather as an added benefit.

In addition to opportunistic beach nourishment there are other projects (the largest example being the 2001 SANDAG project in San Diego County) where sand has been delivered to the coastline with the sole purpose of widening the existing beaches. Sand may come from either terrestrial (stream channels or dunes, for example) or offshore sources (the inner shelf).

Beach nourishment, unless it takes place where there is a headland or other natural barrier to littoral transport, or unless it is accompanied by some structure or mechanism of holding the sand in place (e.g., groins), may not provide a long-term solution to narrow beaches or beach erosion in California, simply because the high to very high littoral drift rates that characterize most of California's shoreline will tend to move any additional sand added to the shoreline alongshore.

In the absence of any major reductions in littoral sand supply (due to either large-scale climatic fluctuations or human activities), beaches over the long-term will tend to approach some equilibrium size or width; e.g. a summer width that will vary about some mean from year to year. This width is a function of a) the available littoral sand, b) the location of barriers or obstructions to littoral transport (Everts

and Eldon, 2000; Everts, 2002) c) the coastline orientation, and d) and littoral drift direction and rate, which is related to the amount of wave energy incident on the beach and the angle of wave approach.

In northern Monterey Bay, for example, because of the direction of dominant wave approach and the coastline orientation, those shorelines oriented northwest-southeast, or east-west (and where littoral transport barriers exist), such as the Santa Cruz Main Beach, Seabright Beach, or the inner portion of Monterey Bay, have wide well-developed beaches (A. Figure 5.2). In contrast, where the coastline is oriented essentially north-south (from Lighthouse Point to Cowell's Beach (B. Figure 5.2) and the Opal Cliffs shoreline between Pleasure Point and New Brighton Beach, for example), and where no significant littoral drift barriers exist, beaches are narrow to non-existent because littoral drift moves the sand along this stretch of coast rapidly without any retention.



Figure 5.2. The coastline of northern Monterey Bay at Santa Cruz illustrating how the orientation of the coastline determines whether or not a beach forms. Where the shoreline is oriented essentially east-west and littoral barrier exist (A), wide stable beaches have formed. Where the coastline is oriented essentially north-south and there is no barrier, beaches rarely form (B). North is up in the photograph.

FACTORS AFFECTING THE LONGEVITY OF A BEACH NOURISHMENT PROJECT

It has often been assumed that the important parameters in the durability or longevity of a beach nourishment or replenishment project include the alongshore length of the nourishment project, the density or volume of fill placed, grain size compatibility with the native beach, the use of sand retention structures such as groins in conjunction with sand placement, and storm activity following nourishment. Those nourishment projects that had the greatest alongshore dimensions have been shown to last longer than shorter beach fills.

Fill Density: Density of the fill refers to the volume of sand per unit length of shoreline. The longevity of a nourishment project has often been assumed in the past to be directly related to fill density, with greater fill densities yielding longer life spans. In California, the initial fill densities range from 20,000 cubic yards per mile to 2,128,000 cubic yards per mile.

Grain Size: Grain size compatibility between the native beach and the fill material is also perceived to be an important factor in the lon-

gevity or durability of a nourished beach. Beach fill must be compatible with the grain sizes of the native sand (as coarse as or coarser than the native sand) such that the waves will not immediately carry the sand offshore. If the fill sand is to remain on the dry or exposed beach under prevailing wave conditions at the particular site, it must be larger than the littoral cut-off diameter.

Sand Retention Structures: Coastal structures aimed at retaining sand, such as groins or detached offshore breakwaters, have been successful in extending the life span of nourishment projects. For example, groins throughout the Santa Monica littoral cell and groins placed on beaches in Capitola, Ventura, Redondo Beach and Newport Beach have all been successful at stabilizing beach fill projects. However, if there is not enough sand in the system to begin with, groins will not be effective, as was the case at Imperial Beach where a series of groins has not been adequate to combat erosion. Groins will continue to trap littoral drift in the years following a beach nourishment project, thus maintaining the updrift beach. Groins must be considered on a regional scale, however. While beaches updrift of groins will be stabilized or widened, beaches downdrift of a groin may experience erosion once their sand supply is cut-off. A series of groins along the shoreline of interest in conjunction with beach nourishment may be an effective way to address downdrift beach erosion.

Offshore breakwaters have been widely used in Europe and in a few locations in the United States to stabilize or widen beaches by reducing wave energy and littoral drift in the lee of the breakwater. These offshore structures can be either slightly submerged, at sea level, or slightly above sea level. The offshore breakwater at Venice is a good example of the effects of such a structure in California, where the beach landward of the breakwater significantly widened (Figure 5.3). The Santa Barbara breakwater was completed in 1929 as a detached offshore structure. Although the purpose of the breakwater was to provide a protected anchorage for boats, accretion of littoral sand in the lee of the structure by the fall of 1929 had become so serious that the breakwater was extended to the beach at Pt. Castillo, a distance of about 600 feet. This was followed by rapid deposition of sand on the west or up-coast side of the structure (Griggs, Patsch and Savoy, 2005).

Detached offshore breakwaters can effectively reduce wave energy at the shoreline, thereby widening or stabilizing otherwise narrow or eroding beaches. They are not without their impacts, however: high construction costs, navigation hazards for vessels, dangers for recreational coastal water users, as well as a reduction in sand transport to down coast beaches are all important considerations.

Storm Intensity: The life span of beach nourishment projects has been correlated with storm intensity to which a fill is exposed. Large or extreme storms, such as those that have occurred during El Niño years, have caused increased beach erosion, whether nourished or not. Sand removed from the beaches during these large storm events is often deposited on offshore bars where it is stored until the smaller waves associated with the summer months carry the sand back to the beach. During conditions of elevated sea levels and very large waves, sand may be transported offshore into deep enough water where summer waves cannot move the sand back onshore. Longshore transport may also increase with the larger storm waves, thus reducing the residence time of the sand on a nourished beach.

During the strong 1997-98 El Niño, however, monthly beach surveys collected along 22 miles of Santa Cruz County coastline showed that although the beaches experienced extreme erosion during the



Figure 5.3. Offshore breakwater at Venice where beach has widened in protected area behind breakwater (2004). Photo © Kenneth and Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org

winter months, by the end of the summer of 1998 all but one beach had returned to their original pre- El Niño widths (Brown, 1998).

ISSUES INVOLVED WITH BEACH NOURISHMENT

While beach nourishment appears to be an attractive alternative to either armoring the coastline with seawalls, riprap or revetments, or to relocating threatened structures inland, as with any large construction project, there are a number of issues or considerations that need to be carefully evaluated and addressed. In California, littoral cells span large stretches of the coastline, from 10 miles to over 100 miles in length, and, in most locations, experience high net littoral drift rates (from 150,000 yd³/yr to over 1 million yd³/yr). As a result, the life span or longevity of sand placed on a particular beach may be short (less than a single winter, in some cases) due to the prevailing winter waves transporting the sand alongshore as littoral drift. Properly constructed and filled retention structures (groins, for example) can help increase the longevity of beach fill.

In addition, potential considerations associated with beach nourishment in California include costs, financial responsibility for the initial project and subsequent re-nourishment, the source and method for obtaining sand, transportation of large quantities of sand to the nourishment site, and the potential smothering or temporary loss of marine life or habitats when placing the sand.

The availability of large quantities of beach compatible sand is a significant issue that has not been completely explored. Sand exists offshore in large volumes but it may not always be beach compatible. In addition, there are environmental and habitat issues that need to be evaluated and possibly mitigated. Some offshore areas are protected, such as the 400 miles of coastline included within the Monterey Bay National Marine Sanctuary, and for which dredging sand from the seafloor is a complex issue with a long list of environmental concerns and probable opposition.

While consideration is being given to removing sediment from behind dams essentially completely filled (e.g., Matilija Dam on the Ventura River and Rindge Dam on Malibu Creek) and placing such sediment on the beach, there is not yet any agreed upon approach for accomplishing this objective. Dam removal followed by natural fluvial transport, trucking, and slurry pipelines have all been studied and each has their costs and impacts. Even though this sediment would have been delivered to the shoreline by these streams under pre-dam natural conditions, accomplishing the same “natural process” today is far more complex. The release of all of the impounded sediment

would overwhelm any downstream habitats that are now being protected. In addition, the current USEPA guidelines do not normally allow any sediment to be placed on beaches when the amount of fines (silt and clay) is over 20% (the so-called 80:20 guideline, or acceptable sediment for beach nourishment must consist of at least 80% sand and no more than 20% silt and clay). Unfortunately, the sediment transported by streams and trapped behind dams doesn't follow this 80:20 guideline and contains far more than 20% silt and clay. As a result, most sediment impounded in reservoirs might not be acceptable to the EPA for beach nourishment under such criteria, even though these same streams naturally discharge such sediment every winter to the shoreline, where waves and coastal currents sort out all of this material. The USEPA has and is working with project proponents to identify appropriate conditions that allow the use of sediments with a fine-grained content greater than 20% to be used for beach restoration purposes. These conditions are described in CSMW's Sand Compatibility and Opportunistic Use Program (SCOUP) report. (<http://www.dbw.ca.gov/csmw/csmwhome.htm>).

If inland sources of beach compatible sand can be located, approved, and transported to the coastline, there are additional challenges of getting the material onto the beach and spreading it out in a timely manner. A 200,000-yds³ beach nourishment project, for example, would require 20,000 10-yds³ dump trucks.

In California, obtaining sand from an inland source to place on the beach is far more costly than sand from offshore sources, primarily due to significantly higher removal and transport costs. Inland sources provided by trucking would also have environmental impacts associated with the quarrying, transport, and placement of the sand. Estimates in the Monterey Bay area for truck delivered beach-quality sand in 2004 were around \$21/yd³. The offshore area in this location is a National Marine Sanctuary such that dredging sand from the seafloor is not acceptable under existing policies. The estimated cost associated with delivering ~240,000 yd³ of sand (to build a beach ~3,000 feet long and 100 feet wide) from an inland source from a recent proposal for a nourishment project in southern Monterey Bay would be ~\$5.5 million dollars (~\$23/yd³) (O'Connor and Flick, 2002).

It is also important to look objectively at the logistics of a nourishment project of this scale. Placing 240,000 yd³ of sand on the beach would require 24,000 10-yd³ dump truck loads of sand. If a dump truck could deliver a load of sand to the beach and dump it every 10 minutes, 48 truckloads could be dumped in an 8-hour day. Keeping this process going 7 days a week could deliver 1440 truckloads or 14,400 yd³ each month. At this rate, it would take over 16 months to complete this nourishment project. There are also issues of delivering sand in the winter months when high wave conditions might make truck traffic on the beach difficult; placing sand in the winter months would also reduce the lifespan of the nourished sand. However, beaches are used the most during the summer months. While none of these are overwhelming obstacles, beach nourishment from inland sources by truck is not a simple or straightforward process. Smaller-scale maintenance projects would take proportionally less time to deliver smaller amounts of sand, and while more logistically feasible, don't have the impacts of larger projects.

Beach nourishment projects using terrestrial or inland sources of sand can be very expensive undertakings and any such project will probably have to be re-nourished on a regular basis unless the sand is retained. The limitations and costs associated with beach nourishment and re-nourishment must be balanced by the ultimate benefits of the project, including the recreational, environmental, and

economic value of widening a beach, in addition to the back-beach protection offered to development by a wider beach.

NOURISHMENT HISTORY OF INDIVIDUAL LITTORAL CELLS

In California, beach nourishment (not including harbor bypassing) has historically provided on average ~1.3 million yd³ annually to the beaches in southern California (Point Conception to the international border), representing 31% of the overall sand budgets in the area (Table 4.1). Large quantities of sand excavated during major coastal construction projects, such as the excavation associated with the Hyperion Sewage Treatment Facility (17.1 million yd³ from 1938-1990) and Marina del Rey (~10 million yd³ from 1960-1963) in the Santa Monica littoral cell, as well as the dredging of San Diego Bay (34 million yd³ between 1941-1985) have provided millions of cubic yards of sand to the beaches of southern California (see comprehensive summary articles by Flick, 1993 and Wiegel, 1994 for detailed discussion of southern California beach nourishment projects.). Between 1942 and 1992 about 100 million yd³ of material were placed on the beaches with approximately half of the sand derived from harbor or marina projects (Flick, 1993).

Santa Monica Littoral Cell: In the Santa Monica littoral cell, over 29 million yd³ of sand has been placed on the beaches since 1938 for projects where the primary objective was not specifically beach nourishment. As a result, the shoreline in many areas of Santa Monica Bay advanced seaward from 150 to 500 feet from its earlier natural position. Although the majority of beach fill was placed prior to 1970, beaches in this area are still wider than their natural pre-nourished state, due, in large part, to the construction of retention structures to hold the sand in place. Currently, there are 5 breakwaters, 3 jetties and 19 groins along the nearly 19 miles of shoreline from Topanga Canyon to Malaga Cove, effectively retaining the sand before it is lost into Redondo Submarine Canyon. Sand retention structures have been very effective at maintaining the wide artificial beaches in the Santa Monica littoral cell because of the nearly unidirectional longshore transport to the southeast.

San Pedro Littoral Cell: In the San Pedro littoral cell, federal, state and local governments fund ongoing beach nourishment at Sunset Beach (just downcoast of Seal Beach) to maintain a wide enough beach to meet the recreational needs of the area and to mitigate for the erosion caused by the construction of the Anaheim jetties. The area is nourished with ~390,000 yd³ of sand annually. Herron (1980) stated that 22,000,000 yd³ of sand from harbor and river projects have been placed on the 15 miles of public beaches of the San Pedro littoral cell.

Oceanside Littoral Cell: Nearly 11.9 million yds³ of sand were placed on the beaches of the Oceanside Cell between 1943 and 1993 (Flick, 1993). This represents an annual average rate of about 250,000 yd³. Most of this sand has come from the dredging of Agua Hedionda Lagoon and Oceanside Harbor which each contributed about 4 million yd³ in 1954 and 1961, respectively. About 1,300,000 million yd³ were trucked from the San Luis Rey River bed to the Oceanside beaches in 1982. Two smaller projects, construction of the San Onofre Nuclear Power Plant and nourishment of Doheny Beach, each generated about 1,300,000 million yd³.

Mission Bay Littoral Cell: The beaches in the Mission Bay littoral cell have also benefited from large construction projects along the coastline. Nearly 4 million cubic yards of sand dredged from Mission Bay to create the aquatic park and small craft harbor were placed on the beaches to create wider recreational areas. The upcoast jetty at

Mission Bay now holds the southern portion of Mission Beach in place. A concrete seawall about 13 feet above mean sea level backs the Mission Beach area but was overtopped during both the 1982-83 El Niño and the unusual storm of January 1988 (Flick, 2005).

Silver Strand Littoral Cell: The Silver Strand littoral cell is somewhat unique in the region in having an overall net littoral transport from south to north. The nearly 35 million yds³ of sand placed on its beaches since 1940 represents the most highly altered stretch of beach in southern California (Flick, 1993). Much of this volume, about 26 million yds³, was excavated from the massive expansion of naval facilities in San Diego Bay just after WWII. Prior to this effort, the Silver Strand had been a relatively narrow sand spit separating San Diego Bay from the ocean, which was occasionally overwashed by storm waves.

THE SAN DIEGO ASSOCIATION OF GOVERNMENTS (SANDAG) BEACH NOURISHMENT PROJECT

The most recent large-scale, non-opportunistic beach nourishment project in California with the sole purpose of widening the beaches was completed in San Diego County in 2001. Approximately 2-million yds³ of sand were dredged from six offshore sites and placed on 12 beaches in northern San Diego County at a total cost of \$12.25 million dollars or \$5.83/yd³ (Figure 5.4). This project was coordinated by local governments working together through SANDAG and was funded by \$16 million in state and federal funds and about \$1.5 million from the region's coastal cities. It was seen as an initial step in overcoming what has been perceived as a severe sand deficit on the region's beaches.

A total of six miles of beaches were nourished from Oceanside on the north to Imperial Beach on the south (Figures 5.4 & 5.5). Eighty-five percent of the sand went to the beaches of the Oceanside Littoral Cell. A comprehensive regional beach-profiling program had been in place since the 1983 El Niño event, which provided a baseline for monitoring the results or status of many of the individual nourished sites. Sixty-two beach profile lines were surveyed, typically in the fall and in the spring. Seventeen of these profile lines either already existed or were established at the individual beach nourishment sites (Coastal Frontiers, 2005).

While it is difficult to completely evaluate and summarize the vast amount of beach survey data that have been collected in this report, it is important to try and extract some overall measures of performance or behavior following the nourishment if we are to derive any useful conclusions from this large project.

At 14 of the 17 nourishment sites surveyed, the beach width (determined by the mean sea level shoreline position) narrowed significantly between the fall of 2001 (immediately following sand placement) and the fall of 2002. While the surveyed beaches showed initial increases in width of 25 to over 100 feet from the nourishment, most of these beaches narrowed 20 to 60 feet during the first year following sand emplacement. Twelve of the 17 sites showed further decreases in width over year two, and 13 of these sites continued to decrease in width in the 3rd year. Three of the beaches in the Oceanside Cell showed modest width increases (6 to 15 feet) in the first year following nourishment, but in the two following years all declined in width.

A very detailed study of the Torrey Pines State Beach fill project was carried out as part of the post-nourishment monitoring (Seymour, et al. 2005). This fill was 1600 feet long and included about 330,000 yds³ of sand, one of the larger fills. Rather than being constructed as a sloping fill, the upper surface was level and terminated in a near-

vertical scarp about 6 feet high. Profiles 65 feet apart were collected bi-weekly along 1.8 miles (9500 feet) of beach and extended

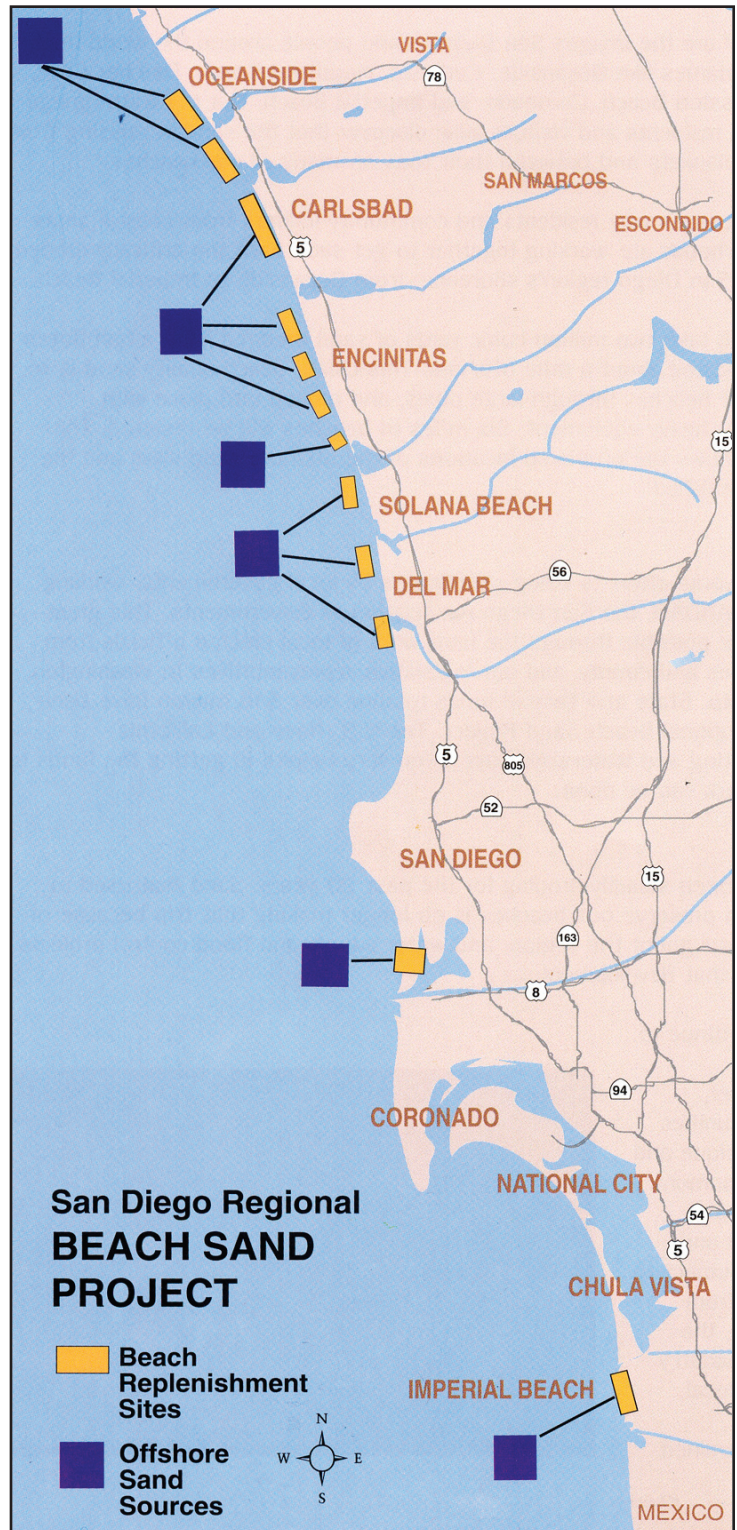


Figure 5.4. Offshore sand sources and nourishment sites for the 2001 SANDAG 2,000,000 yds³ beach nourishment project.

offshore to a depth of 26 feet. The temporal and spatial resolution provided by this surveying program, in combination with offshore wave measurements, provided an exceptional database for documenting the relationship between wave conditions and the behavior of a beach fill (Seymour, et. al., 2005).

The fill was completed near the end of April, 2001 (Figure 5.6). Wave



Figure 5.5: Beach nourishment at South Carlsbad State Beach. In July 2001, 150,000 yds³ of sand were placed on this beach in a fill that was 2000 feet long, 180 feet wide and up to + 12 feet msl.

conditions during the summer and fall were mild, with significant wave heights (the average of the highest 1/3 of the waves) generally less than 3 feet except for a few incidents of waves as high as 5 feet. The front scarp of the fill remained intact and there were only modest losses at the ends of the fill.

At noon on Thanksgiving Day, November 22, 2001, significant wave heights reached nearly 10 feet and remained in the range of 9 to 10.5 feet for seven hours. The fill was overtopped and began to erode quickly. By daylight on November 23, the fill had been almost completely eroded to the riprap at the back of the beach (Seymour, et al., 2005). The fill was stable for approximately 7 months of low wave energy conditions, but was removed within a day when the first large waves of the winter arrived.

Some overall conclusions can be drawn from the four years of published beach surveys in the nourished areas (Coastal Frontiers, 2005). The performance of the individual beach fills varied considerably. At some sites, such as Del Mar, Moonlight, and South Carlsbad, the gains in the shorezone (defined as the subaerial or exposed portion of the beach as well as the nearshore sand out to the seasonal depth of closure) that occurred during placement of fill were short-lived. At other sites, such as Mission Beach and Oceanside, the gains in the shorezone persisted through the time of the Fall 2004 survey. In many cases, dispersal of the fill was accompanied by shorezone volume gains on the downdrift beaches. Both the grain size of the sand and the volume of the fill were important factors in how long nourished sand



Figure 5.6. Aerial view of the Torrey Pines beach fill project (from Seymour, et.al., 2005).

remained on the beach. For the smaller fills, erosion or losses from the ends of the fills were significant. One very small nourishment site in the Oceanside cell (Fletcher Cove) received a small volume of very-fine grained sand and it was removed very quickly.

Nearly all of the sand added to the beaches in the SANDAG project tended to move both offshore and also alongshore with the arrival of winter waves although much of this has persisted just offshore in the shorezone. This sand does provide some benefits including dispersing some of storm wave energy and flattening the beach profile. However, most of the general public expects to see a wider exposed beach as the benefit of a beach nourishment project. It is important to understand for the SANDAG project or any nourishment plan or proposal, that most beaches have some normal or equilibrium width, as discussed earlier. Without either regular or repeated nourishment or the construction of a retention structure, such as a groin, to stabilize or hold a beach fill, there is no reason why in an area of significant longshore transport and moderate to large winter wave conditions that the sand should stay on the exposed beach for any extended period of time. The considerations that need to be weighed prior to any beach nourishment project are whether the benefits of littoral cell or shorezone sand increases, and the potentially short-term or temporary beach width increases resulting from beach nourishment are worth the initial investment and continuing costs.

CHAPTER 6

CONCLUSIONS

Before large-scale human influence or interference, the majority of beaches in southern California were relatively narrow. Large coastal construction projects, the creation and expansion of harbors and marinas, and other coastal works found a convenient and cost-effective disposal site for excavated material on the beaches in southern California, thus creating the wide sandy beaches that people have come to expect in this region, particularly along the beaches of the Santa Monica littoral cell and the Silver Strand cell. The majority of sand was placed before the mid-1960's, however. Since then, the rates of nourishment have dropped sharply. In many cases, sand retention structures such as groins, built in conjunction with the placement of beach-fill, have been successful in stabilizing the sand and maintaining wider beaches. Carefully designed retention structures have been shown to extend the life of beach nourishment projects and should be considered when planning beach restoration projects in the future. A single episode of beach nourishment, however, will not provide a permanent solution to areas with naturally narrow beaches or to problems associated with beach erosion. Any potential California beach nourishment program should be viewed as a long-term and ongoing process.

When assessing the success or failure of a nourishment project, one must look beyond the individual beach where the nourishment took place and examine the regional effects throughout the entire littoral cell. Often the nourished site serves as a feeder beach, providing sand to be transported by littoral drift to "feed" or nourish the down-drift beaches. Where littoral drift rates have been documented they are typically in the range of about a mile-per-year (Bruun, 1954; Wiegel, 1964; Griggs and Johnson, 1976), although this will depend upon the wave energy, the orientation of the shoreline, and the angle of the dominant wave approach. Depending on the potential littoral drift in an area, as well as the coastline configuration and barriers to littoral transport, nourishment projects may or may not have a fairly short residence time on a particular beach. However, if well planned on a regional scale, the placed sand should feed the down-drift beaches until ultimately ending up in a submarine canyon, offshore, or retained behind a coastal engineering structure.

Because of California's high littoral drift rates, the emplacement of a well-designed, properly constructed and filled retention structure is also a very important consideration in the success or longevity of any beach fill or nourishment project. Groins and offshore breakwaters have been used successfully in a number of locations in California to widen or stabilize beaches (Ventura, Santa Monica and Newport Beach, for example). Retention structures can make the difference in the long-term success of a beach nourishment project. It is recommended that all existing retention structures and their effectiveness and impacts be evaluated so as to learn from past experiences and improve on their use in the future by mitigating any potential negative impacts.

When engineering a beach nourishment project in California, it is important to consider such elements as grain size compatibility, fill density, or the volume of sand per unit length, possible sand retention structures and the effects on down drift beaches, the rate and direction of littoral drift, and wave climate (including storm duration and intensity).

Harbor maintenance and large construction projects along the coast

may be excellent sources of opportunistic beach nourishment. There are many difficulties associated with nourishing the beach with sand taken from an inland or terrestrial source including the 80:20 rule, cost, financial responsibility of the project, the source and method for obtaining sand, transporting large quantities of sand to the nourishment site, and the potential for covering over marine life or habitats when placing the sand. Offshore sand sources also have their limitations and impacts including costs, location of compatible sand offshore, permit issues such as environmental impacts associated with disturbing the seafloor habitat, transporting and placing large quantities of sand (Figure 5.5) increased turbidity, etc.

The limitations and costs associated with beach nourishment must be balanced by the ultimate benefits of the project including public safety and access, expanded wildlife habitat and foraging areas, the economic and aesthetic value of widening a beach, in addition to the back-beach or coastal protection offered by a wider beach.

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Dune erosion threatens the Ocean Harbor House apartment complex on Del Monte Beach, Monterey CA (October 2005). Copyright © 2005 Kenneth and Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org.



Very wide beach at Venice Beach, CA (October 2002). Copyright © 2005 Kenneth and Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org.

DEVELOPMENT OF SAND BUDGETS FOR CALIFORNIA'S MAJOR LITTORAL CELLS

EUREKA, SANTA CRUZ, SOUTHERN MONTEREY BAY, SANTA BARBARA, SANTA MONICA (INCLUDING ZUMA), SAN PEDRO, LAGUNA, OCEANSIDE, MISSION BAY, AND SILVER STRAND LITTORAL CELLS

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CALIFORNIA COASTAL SEDIMENT MANAGEMENT WORKGROUP

Development of Sand Budgets for California's Major Littoral Cells
Eureka, Santa Cruz, Southern Monterey Bay, Santa Barbara, Santa
Monica (including Zuma), San Pedro, Laguna, Oceanside, Mission
Bay, and Silver Strand Littoral Cells

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Opal Cliffs, Santa Cruz CA. Copyright © 2002 Kenneth & Gabrielle Adelman

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ABSTRACT

Sand moves along the coast of California, under the influence of waves, feeding California's intensively used beaches. The consequences of interrupting littoral drift through the construction of jetties, breakwaters and groins, are well known along California's coast. Construction of the Santa Barbara Harbor (initiated in 1927) and the consequent interruption of littoral drift was perhaps the first well-studied example. Average annual dredging volumes at some harbors now reach over 1,000,000 yds³ annually with costs in excess of \$1,000,000. A regional understanding of littoral cell boundaries and sand budgets is an important tool in coastal land use management and coastal engineering, and it is an essential step in understanding sand routing along the coast. Long-term average annual dredging volumes can provide useful proxies for littoral drift rates at specific locations within littoral cells. Many harbors function as efficient littoral drift traps, such that average annual dredging volumes are among the most representative and reliable values we have for the littoral drift rates within individual littoral cells.

In this study, sand budgets were developed for all of California's major littoral cells (including the Eureka, Santa Cruz, Southern Monterey Bay, Santa Barbara, Santa Monica (including Zuma), San Pedro, Laguna, Oceanside, Mission Bay, and Silver Strand littoral cells) using all available historic data on natural sand inputs, sand losses and beach nourishment, in addition to long-term dredging volumes. Estimates were made of the anthropogenic reductions to the sand supply in these littoral cells due to the damming of rivers, armoring of seacliffs, and mining of beach sand. Overall, damming of rivers has resulted in the reduction of about 23% of the natural sand supplied to the coast, a volume over ~2,500,000 yd³/yr. The armoring of seacliffs has reduced the sand supply to these littoral cells from cliff and bluff erosion by 11% or ~43,000 yd³/yr. Sand mining from the beaches of southern Monterey Bay took place until ~1985 at a rate of about 180,000 yd³/yr but was terminated in the 1980's with only a single sand plant still operating, which now removes about 130,000 yd³/yr.

Beach nourishment has added ~1,338,000 yd³/yr on average to the overall sand budget for California's major littoral cells, all of this along the Southern California shoreline. Beach nourishment alone, however, has not completely supplemented or replaced the volume of sand prevented from reaching the beaches through damming and armoring seacliffs; excluding additional losses from sand mining, there remains a statewide, net deficit on the order of ~1,245,000 yd³/yr, primarily along the southern California coastline.

OVERVIEW

The beaches of southern California are intensively used recreational areas generating billions of dollars of direct revenue annually (King, 1999). These wide, sandy beaches, used by people playing volleyball and sunbathing, are the quintessential picture of southern California. Wide, sandy beaches, however, were not always the natural condition in southern California. Many of these beaches have been artificially created and maintained through human intervention, including placement of massive amounts of sand and the construction of groins, jetties and breakwaters (Wiegel, 1994; Flick, 1993). Without human influence, the beaches along this coastline would be, for the most part, narrow and difficult to access. The narrow, marginal beaches would be insufficient for the recreational demands imposed on the shoreline today. The rate of nourishment, however, has been diminishing over the past 30 years, fueling the public's perception of rapid beach erosion and the narrowing of the beaches. In many places, the beaches are merely returning to their natural, non-nourished state. Sand sources for most of the littoral cells in southern California are minimal to begin with, and have been reduced further through the damming of rivers, armoring of seacliffs, and reductions in beach nourishment projects.

Sand is naturally supplied to the beaches of California's littoral cells or beach compartments from a combination of rivers, seacliff erosion, dune deflation or erosion, as well as gullying and erosion of upland materials. In addition, sand has been added to the beaches historically through beach nourishment. In this study, sand budgets were developed for the major littoral cells in California (including the Eureka, Santa Cruz, Southern Monterey Bay, Santa Barbara, Santa Monica [including the Zuma Beach cell, now recognized as distinct from the Santa Monica cell], San Pedro, Laguna, Oceanside, Mission Bay, and Silver Strand littoral cells) to determine the relative importance of each sand source and the extent to which the sand supplied to these cells has been reduced through the armoring of seacliffs, damming of rivers and mining of beach sand.

Magoon and Lent (2005) have also recently summarized what is known about sand and gravel mining in California streams, which represents a potential long-term loss of sand to the shoreline. They have determined that a total of about 50 million yds³ of sand and gravel are removed annually through streambed mining. It is unclear, however, how much of this material would naturally be delivered to the coast. These losses have not been included in the individual littoral cell budgets.

Inman and Chamberlin (1960) and Inman and Frautschy (1966) initially developed the concept of littoral cells or

beach compartments, and delineated individual cells along the southern California coast. Habel and Armstrong (1978) subsequently made an attempt to divide up almost the entire California coast into littoral cells, although for the central and northern portions of the state, there was no cell by cell research carried out to verify the cell boundaries or whether the cells they labeled existed as self contained compartments. We now know, for example, that some of the cells they defined do not exist and that these areas are parts of adjacent cells (the "Half Moon Bay cell", for example, is not a separate cell but the northern portion of the Santa Cruz cell). There are other cells (the Zuma cell or sub-cell), for example, that we believe are distinct compartments, but which in 1978, were shown as part of the larger cells (in the case of the Zuma cell, it was included as part of the Santa Monica cell). For these reasons, and because some of the cells are either poorly defined or understood (most of the cells north of San Francisco, for example) we focused our efforts on the major littoral cells where we felt there was a combination of available information or coastal sediment management interest. Unless there were agreed upon changes in littoral cell boundaries, as described above, however, we used the boundaries originally listed in Habel and Armstrong.

Individual sand budgets for the major littoral cells are presented in Chapters 2-10. Table i gives an overview of the relative importance of sand sources for each littoral cell in addition to the overall importance of each component to the littoral cells in California. Under present, dammed conditions, (excluding beach nourishment) fluvial inputs constitute about 87% of the sand entering California's major littoral cells, and contribute 90% of the sand to southern California (from the start of the Santa Barbara littoral cell to the international border). On a state-wide basis, contributions to beach sand from seacliff erosion tend to be much less than those from streams. However, such contributions may be very important locally where very sandy cliffs are rapidly eroding and there are no large streams (Runyan and Griggs, 2003). For example, while bluff erosion contributes less than one percent of the sand to the Santa Barbara littoral cell, bluff erosion is believed to contribute about 31% and 60% of the sand to the Laguna and Mission Bay littoral cells, respectively. Also, recent research in the Oceanside littoral cell, utilizing composition of sand in the bluffs and beaches, as well as very precise LIDAR measurements of coastal bluff retreat (over a relatively short 6-year period) concluded that bluffs may contribute 50% or more of the sand to beaches in this littoral cell.

Dune deflation or erosion, statewide, accounts for 8% of the littoral sand (excluding beach nourishment). When beach nourishment is taken as a contributing source of sand, the relative importance of rivers, bluffs, and dunes statewide drops to 72%, 4% and 7% respectively in California's major littoral cells with beach nourish-

ment accounting for the remaining 17% of the sand. In southern California, beach nourishment represents 31% of the sand supplied to the beaches, thus reducing the importance of river and bluff inputs to 62% and 7% respectively.

Table ii is a summary of the anthropogenic reductions to the sand supplied to the major littoral cells in California, and to southern California specifically (from Santa Barbara to the international border) due to the armoring of seacliffs and the damming of rivers in addition to the sand supplied through beach nourishment. Sand bypassing at harbor entrances is not included in the nourishment volume because this is sand that is already in the system and is essentially just being moved within the cell. The greatest reduction in the sand supplied to southern California is from the damming of the rivers, which contribute the majority of sand to the littoral cells. Damming has reduced the sand reaching the beaches in southern California by 47% of the natural fluvial sand yield, which totals nearly 2.3 million cubic yards of sand annually. Seacliff armoring has reduced the sand supplied to southern California's beaches by 10% of the natural sand supply which is over 35,000 cubic yards annually, accounting for less than 7% of the total sand input.

UNCERTAINTIES INVOLVED IN DEVELOPING LITTORAL CELL BUDGETS

While California's littoral cells or beach compartments were first recognized over 40 years ago (Inman and Frautschy, 1966), the development of detailed budgets for individual cells has not progressed very far for many reasons. There are not only major challenges in quantifying the individual source, sink and littoral drift components of individual cells, there are still fundamental uncertainties and lack of agreement regarding both the specific boundaries of some littoral cells, as well as the directions of littoral transport at specific locations.

In this report we have attempted to compile and evaluate all of the existing published sediment data for California's major littoral cells. From north to south these include: Eureka, Santa Cruz, Southern Monterey Bay, Santa Barbara, Santa Monica (including Zuma), San Pedro, Laguna, Oceanside, Mission Bay, and Silver Strand littoral cells. This in itself was a major undertaking (see References).

Streams provide the great majority of sand to California's beaches (~71% on a statewide basis) and this component is, therefore, one of the most important to quantify. Fluvial sediment transport research, however, shows that sediment transport is very episodic, even within a single year (Griggs, 1987a). In addition, there are very large differences in fluvial sand delivery in El Niño vs. La Niña years (Inman and Jenkins, 1999). Thus the time span covered by the stream gauging record on any individual stream, as well as the difficulties involved in accurately measuring coarse sediment transport, par-

Littoral Cell	All Sand Volumes in yd3/yr	Rivers	Bluff Erosion	Dunes	Beach Nourishment	Total Sand Supply
Eureka	Total “Actual” sand contribution	2,301,000	0	175,000	0	2,476,000
	% of Budget	93%	0%	7%	0%	100%
Santa Cruz	Total “Actual” sand contribution	190,000	33,000	0	0	223,000
	% of Budget	85%	15%	0%	0%	100%
Southern Monterey Bay	Total “Actual” sand contribution	489,000	0	353,000	0	842,000
	% of Budget	58%	0%	42%	0%	100%
Santa Barbara	Total “Actual” sand contribution	2,167,000	11,000	0	0	2,178,000
	% of Budget	99%	1%	0%	0%	100%
Santa Monica	Total “Actual” sand contribution	70,000	148,000	0	526,000	744,000
	% of Budget	9%	20%	0%	71%	100%
San Pedro	Total “Actual” sand contribution	278,000	2,000	0	400,000	680,000
	% of Budget	41%	0%	0%	59%	100%
Laguna	Total “Actual” sand contribution	18,000	8,000	0	1,000	27,000
	% of Budget	66%	31%	0%	4%	100%
Oceanside	Total “Actual” sand contribution	133,000	55,000	0	111,000	299,000
	% of Budget	23%	9%	0%	19%	51%*
Mission Bay	Total “Actual” sand contribution	7,000	77,000	0	44,000	128,000
	% of Budget	5%	60%	0%	35%	100%
Silver Strand	Total “Actual” sand contribution	42,000	0	0	256,000	298,000
	% of Budget	14%	0%	0%	86%	100%
Total	Total “Actual” sand contribution	5,695,000	335,000	528,000	1,338,000	7,896,000
	% of Budget	72%	4%	7%	17%	100%
Southern CA Total: (Santa Barbara cell to Mexico)	Total “Actual” sand contribution	2,715,000	301,000	0	1,338,000	4,354,000
	% of Budget	62%	7%	0%	31%	100%
Total: Without Beach Nourishment	All	87%	5%	8%	N/A	6,558,000
	Southern CA	90%	10%	0%	N/A	3,016,000

Table i: Summary of the average annual (post-damming and seacliff armoring) sand contributions from rivers, seacliff erosion, dune recession, and beach nourishment to the major littoral cells in California. * Gully erosion and terrace degradation accounts for the remaining 40% of the sand in the Oceanside littoral cell. This category is not accounted for in this table. Nourishment data is for the period 1930–1993. (For data sources see Patsch and Griggs, 2006)

Littoral Cell		Rivers (dams)	Bluff Erosion (armor)	Total Reduction	Beach Nourishment	Balance (nourishment-reductions)
Eureka	Reduction yd ³ /yr	N/A	N/A	N/A	0	N/A
	Percent Reduction	N/A	N/A	N/A		
Santa Cruz	Reduction yd ³ /yr	6,000	8,000	14,000	0	-14,000
	Percent reduction	3%	20%	6%		
Southern Monterey Bay	Reduction yd ³ /yr	237,000	N/A	237,000	0	-237,000
	Percent reduction	33%	N/A	33%		
Santa Barbara	Reduction yd ³ /yr	1,476,000	3,000	1,479,000	0	-1,479,000
	Percent reduction	41%	19%	40%		
Santa Monica	Reduction yd ³ /yr	29,000	2,000	31,000	526,000	495,000
	Percent reduction	30%	1%	13%		
San Pedro	Reduction yd ³ /yr	532,000	0	532,000	400,000	-132,000
	Percent reduction	66%	0%	66%		
Laguna	Reduction yd ³ /yr	0	1,000	1,000	1,000	0
	Percent reduction	0%	13%	4%		
Oceanside	Reduction yd ³ /yr	154,000	12,000	166,000	111,000	-55,000
	Percent reduction	54%	18%	47%		
Mission Bay	Reduction yd ³ /yr	65,000	17,000	82,000	44,000	-38,000
	Percent reduction	91%	18%	50%		
Silver Strand	Reduction yd ³ /yr	41,000	0	41,000	256,000	215,000
	Percent reduction	49%	0%	49%		
Total	Reduction yd ³ /yr	2,540,000	43,000	2,583,000	1,338,000	-1,245,000
	Percent reduction	43%	11%	39%		
Southern CA Total	Reduction yd ³ /yr	2,297,000	35,000	2,332,000	1,338,000	-994,000
	Percent reduction	47%	10%	44%		

Table ii: Summary of the anthropogenic reductions to the sand supplied to the major littoral cells in California, and to southern California specifically, due to the armoring of seaciffs and the damming of rivers in addition to the sand supplied to the cells through beach nourishment (sand bypassing at harbor entrances is not included in the nourishment volume).

ticularly at high discharge when most of the sediment is moved, lead to large uncertainties or error bars in quantifying the largest source of sand to the coastline. Some researchers believe that the values reported for annual fluvial sand delivery should be considered as + or – 30% or more.

Very little research has been carried out on the production of sand by coastal cliff or bluff erosion anywhere on the California coast (Runyan and Griggs, 2003). A detailed LIDAR-based study of sand contributions from bluff erosion along the coastline of the Oceanside cell was just completed (Young and Ashford, 2006). This was a 6 year research project, and while it did refine our previous calculations of the importance of bluff erosion to the Oceanside littoral cell sand budget, it still only covered 50 miles of California's 1100 miles of coastline. Even this detailed study only spans 6 years of relatively mild climatic conditions so that the values determined may be different under more severe weather and storm conditions.

One of the challenges with all of the data we have summarized is that they span different climatic conditions (El Niño vs. La Niña years, for example), and may or may not be representative of long-term conditions. Thus, we are constrained by the historical data that have been collected, which while considerable, still have their limitations. Surprisingly, there are relatively few detailed littoral cell budgets that have been completed in California following the first such effort by Bowen and Inman in 1966. Inman (1976) and Best and Griggs (1991 a, b) are among the few such efforts.

The Santa Barbara littoral cell is one of the earliest (Trask, 1952) and best studied in California, yet despite over 50 years of research, there are still major disagreements as to whether any littoral sand is transported around Pt. Conception, and if so, how much. While the Eureka littoral cell has been much less studied, it receives ~40% of all of the fluvial sand delivered to California's major littoral cells, yet it is not clear how much of this sand moves north, how much moves south, and how much moves offshore after it reaches the shoreline.

Littoral drift rates have been extremely difficult to document or determine. While potential littoral drift rates have been calculated from wave data, these values are extremely sensitive to near shore bathymetry, and also vary seasonally depending upon direction of wave approach. In this report we use harbor dredging rates as a reasonable proxy for littoral drift rates and as a check point in the determination of alongshore littoral drift rates for each major littoral cell. Some harbors, Santa Barbara and Santa Cruz, for example, form nearly complete littoral traps such that long-term average annual dredging rates are believed to be good estimates of net littoral drift at specific locations within a cell. In other locations, Oceanside Harbor, for example, signifi-

cant volumes of sand have been transported offshore and littoral drift reverses seasonally, which complicates the determination of net littoral drift rates (Seymour and Castel, 1985).

Despite all of these uncertainties, we believe that it is valuable to compile, evaluate and summarize all that we do know about the sand budgets for the state's littoral cells. With the state's increased interest in coastal sediments and the impacts of too little sediment along some shorelines (whether from natural processes or human impacts), and too much in other locations (ports and harbors for example), the Coastal Sediment Management Workgroup was established to carry out the necessary studies to develop a better understanding of California's coastal sediments, their sources, transport, storage and sinks, to aid in sediment management decision making. This report is a companion report to *Littoral Cells, Sand Budgets, and Beaches: Understanding California's Shoreline* (Patsch and Griggs, 2006) and is a comprehensive evaluation of what is known about the sand budgets for California's major littoral cells. As this study progressed we identified a number of specific areas where we believe additional information or more detailed studies could provide information useful in developing a better understanding of California's coastal sediment budgets that would be useful in our attempts to better "manage" the state's coastal sediments.

RECOMMENDATIONS FOR FUTURE COASTAL SEDIMENT RESEARCH

Cross-Shore Sediment Transport: Typically cross-shore transport, whether on- or offshore, is the mechanism or process called upon to explain major imbalances in the sand budgets of individual littoral cells. Specific examples where cross-shore transport is used to explain major losses of littoral sediment include the Eureka, southern Monterey Bay and Santa Barbara littoral cells. In the Eureka cell, ~2,300,000 yds³/yr of sand is discharged annually on average by the Eel River, and it is believed that the majority of this is lost offshore on the continental shelf or deposited into the Eel Submarine Canyon, although the transport paths and processes are not clear. There is also no agreement on how much of the sand in this vicinity moves north and/or south as littoral drift.

In the Southern Monterey Bay littoral cell there appears to be a convergence of littoral drift approximately mid-way between the head of Monterey Submarine Canyon at Moss Landing and the Monterey peninsula, with general agreement that significant volumes of littoral sand (~187,000 yds³/yr: Thornton, personal communication; 350,000 yds³/yr, Smith, et. al. 2005b) are carried across the shelf.

Although the mouth of the Santa Maria River has been used as the northern boundary of the Santa Barbara littoral cell for decades, there has never been agreement,

despite a number of sediment transport studies, whether sand from the 46 miles of shoreline between the Santa Maria River and Point Conception is transported around the point or is transported offshore. In order to balance the sediment budget, ~470,000 yds³/yr of sand appears to be transported offshore at this location.

Each of these three areas represent locations where large volumes of beach sand appear to be transported offshore and out of the littoral zone permanently. Yet detailed studies that document the transport paths, depositional sites or evidence for this mechanism have not been completed. Multibeam studies of these areas could confirm this transport mechanism in these areas and also, in the case of the Pt. Conception and southern Monterey Bay sites, provide evidence or confirmation that these may be potential sites for obtaining sand for potential beach nourishment.

Hyperpycnal and Gravity Flows: Two potential mechanisms for significant sand transport across the shelf are hyperpycnal and gravity flows. Recent work by the US Geological Survey along the southern California coastline (Jon Warrick, personal communication) suggests that sediment can be transported offshore during high discharge or major flooding events. This is an area where continued focused research could prove very fruitful in elucidating the timing, duration and extent of such cross-shore transport.

Sand Impoundment at Large Coastal Engineering Structures: Just as large volumes of potential littoral sediment have been impounded behind California's many coastal dams (Slagel, 2005), large volumes of beach sand have been impounded by California's many groins, jetties and breakwaters for decades. The amount of sand in storage in these locations has never been completely evaluated, but represents a large amount of littoral sand that should be considered as part of any regional sand management plan or potential nourishment program. Some beaches, for example, because of these obstructions are very wide. Could some of this sand be used elsewhere in a cell and stabilized by constructing additional groins? Documenting the history of shoreline accretion at the locations of these large structure and quantifying as accurately as possible the volumes of sand impounded would allow better analysis of littoral cell budgets at these locations and also could provide a potential source of beach nourishment.

One specific example of such an area is the 5-mile reach between the Santa Clara River and the Channel Islands Harbor where there is a 15-year history of accretion, but no overall evaluation of how much total sand has been impounded or how this has changed over time.

Losses of Sand into Submarine Canyon Heads: The most important sink for littoral sand in California are the many submarine canyons that head close to shore and intercept littoral drift. Everts and Eldon (2005) have summa-

rized the information on sand capture by the canyons of southern California, and Smith et. al. (2005a) have recently completed detailed repeat multibeam surveys of the head of Monterey Submarine Canyon that reveal the near-shore part of the canyon is a site of active sediment transport and is in a long-term phase of enlargement. We know little about the remaining canyon heads, however. Because we believe that these are the major sinks for most of California's littoral sand, it would be valuable to image these canyon head areas and document to the extent to which they serve as active sediment sinks and compile all of this information for California's major littoral cells.

Natural Beach Widths and Long-term Beach Width Changes: A study is now being completed that has been partially funded by the University of California Marine Council with assistance from the Department of Boating and Waterways on long-term changes in widths for the beaches of the Santa Barbara, Santa Monica and Zuma, San Pedro, and Oceanside littoral cells. The objectives are to utilize a representative long-term historical set of aerial photographs of the shoreline of these cells to document whether the beach widths have changed systematically over time, and if so, whether the changes have been due to natural cycles and processes (climatic change, for example), anthropogenic activities (dam construction, for example), or a combination. We need to extend these long-term beach width studies to California's other major littoral cells.

In the absence of any major reductions in littoral sand supply (due to either large-scale climatic fluctuations or human activities), beaches over the long-term will tend to approach some equilibrium size or width; e.g. a summer width that will vary about some mean from year to year. This width is a function of a) the available littoral sand, b) the location of barriers or obstructions to littoral transport (Everts and Eldon, 2000; Everts, 2000), c) coastline orientation, and d) littoral drift direction and rate, which is related to the amount of wave energy incident on the beach and the angle of wave approach. There are places in California where the conditions are conducive to the formation of wide beaches, and in these locations there is no significant or regular threat to the back beach landforms (whether dunes, bluffs or cliffs) and associated development. On the other hand, there are many areas where there are either no beaches, or only narrow or seasonal beaches, and where cliff and bluff erosion are ongoing natural processes with ongoing threats to coastal development.

Beach Widths and Cliff/Bluff Profiles: As recommended above, the long-term natural or equilibrium beach widths of the remainder of California's major beach areas (beyond the southern California littoral cells now being studied) need to be measured so that we understand how these vary throughout California's developed and intensively used beach areas. This will provide the

fundamental perspective on whether it is reasonable to expect that sand added to particular coastal areas can be expected to remain on the beaches.

Twenty-five years ago, Emery and Kuhn (1982) recognized that the shape or slope of coastal cliffs or bluffs was indicative of whether marine or terrestrial processes dominated in their formation. Vertical or near vertical cliffs are characteristic of those areas where marine processes dominate, where waves regularly reach and undercut the base of the cliff or bluff leading to failure from the bottom up. Cliffs in these locations are very steep as they are constantly being undercut and steepened. Coastlines with steep or near vertical cliffs also appear to be characterized by narrow or non-existent beaches, which is why waves regularly attack these cliffs (Figure i).

On the other hand, where coastal bluffs have a more gentle or convex profile, terrestrial erosional processes dominate, whether runoff and surface erosion, or slumping or landsliding. Terrestrial or subaerial processes thus create very different bluff or cliff profiles and occur where beaches are wide year-round such that the high tides and waves don't reach the base of the bluff (Figure ii). Thus a systematic assessment of the relationship between cliff or bluff slope and the absence or presence of a beach and its width should be carried out as a compliment to assessing long-term beach widths to provide the important background for evaluating whether efforts or plans for beach sand nourishment are likely to be successful.

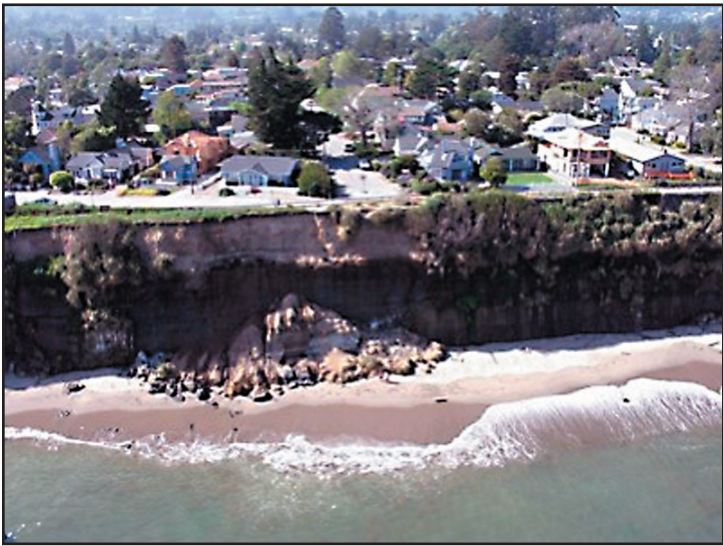


Fig i. Near vertical coastal cliffs in Capitola with narrow beach.

There is a fundamental issue that this apparent relationship raises- those shorelines with wide permanent or year-round beaches are those where beaches are stable and bluff or cliffs are not under any regular wave attack and are, therefore, not undergoing significant retreat at present (Figure ii). On the other hand, those areas where cliffs are being actively eroded by wave attack and undercutting, where homes or cliff top development is being threatened, seem to be those areas where

for some combination of reasons listed earlier, there is either a very narrow or only a seasonal beach. These are the areas where wider beaches are needed but under natural conditions, no significant or permanent protective beach has formed.



Fig ii. Gently slope bluff at Manresa Beach with wide protective beach.

There is therefore no reason, based on the existing environmental variables, why sand added to such a coastline should remain there for any significant period of time without some retention structures. We recommend studying the relationship between beach width and cliff or bluff slope as a necessary next step in assessing the potential for effective beach widening through nourishment.

CHAPTER 1

LITTORAL CELLS AND THE DEVELOPMENT OF A SAND BUDGET

Beach compartments or littoral cells form the framework for understanding the sources, transport, sinks and storage of sand in the nearshore zone along the Pacific Coast (Figure 1.1). In a typical beach compartment, littoral transport begins at a rocky headland or section of coast where the upcoast supply of sand or littoral drift is restricted or minimal. Sediments enter the littoral cell primarily from coastal streams and bluff erosion, and are transported alongshore under the influence of the prevailing wave conditions (Inman and Frautschy, 1966). Ultimately, the sand is lost from the system or cell through either a submarine canyon, a coastal dune field, or in some cases, sand mining. Ideally, each cell exists as a distinct entity with little or no transport of sand between cells. Bowen and Inman (1966) completed one of the first sand budgets of a littoral cell and were able to estimate each input and output along the central coast of California, which has proven to be a valuable reference and useful template for subsequent studies.

Lack of a quantitative understanding of littoral cells and sand budgets has become apparent along the California coast (Griggs, 1987b).



Fig 1.1: Littoral cells in Southern California. (Inman and Chamberlain, 1960; Thurman and Trujillo, 1999)

The problems and costs associated with harbor dredging where jetties or breakwaters have been constructed in the middle or downcoast ends of littoral cells with high drift rates on one hand, and the reduction of sand delivery to beaches due to impoundment of sand behind dams in the coastal watersheds (Brownlie and Taylor, 1981; Ewing et al., 1999; Norris, 1964; Willis et al., 2002) on the other, stem directly from the failure to incorporate this type of information early on in the decision-making process in large coastal engineering projects. The

application of a sand budget to the nearshore zone is a useful tool in coastal land use management and coastal engineering, and it is an essential step in understanding sand routing along the coast. On the central and northern California coastline, a large gap exists in the present state of knowledge regarding littoral cell boundaries and production, transport, storage, and loss of littoral sand within these cells.

Along California's 1,100 miles of coast, there are four large harbors (Humboldt Bay, San Francisco Bay, Los Angeles/Long Beach Harbor, and San Diego Bay) and

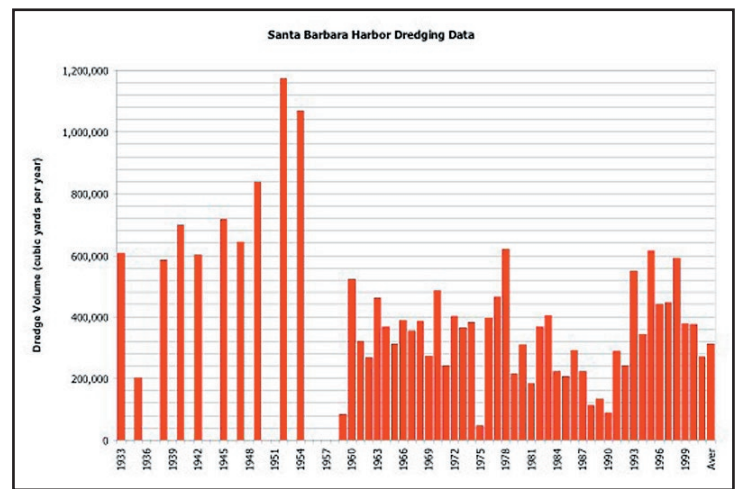


Fig 1.3: Santa Barbara harbor maintenance dredging records: 1933-2001. From 1933 to 1954 dredging of this harbor took place every 2 to 3 years. It is unknown whether data for 1955-1958 are missing or if dredging did not occur.

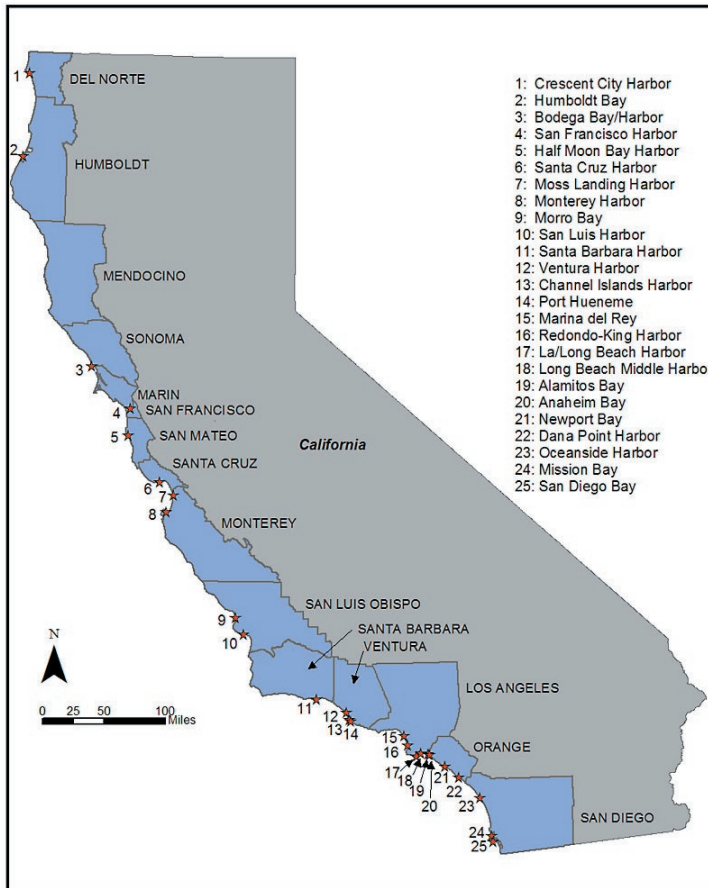


Fig 1.2: California's harbors and littoral cell boundaries. (Source: Modified from Habel and Armstrong, 1978)

21 small craft harbors with some entrance channel or breakwater protection (Figure 1.2). Additional entrance channels and small craft harbors have been proposed and are being considered as well. Each of these existing harbors occupies a position in a littoral cell (Figure 1.4) and has the potential to provide important information on the littoral drift rate or sand transport at that particular location. Although sand inputs to littoral cells from coastal streams and from cliff erosion are difficult to quantify accurately (Griggs, 1987b; Runyan and Griggs, 2002; Willis et al., 2002) due to both spatial and temporal variations in the key quantities measured, long-term average annual dredging volumes can provide a reasonable estimate on gross transport.

The record on dredging in some cases (e.g. Santa

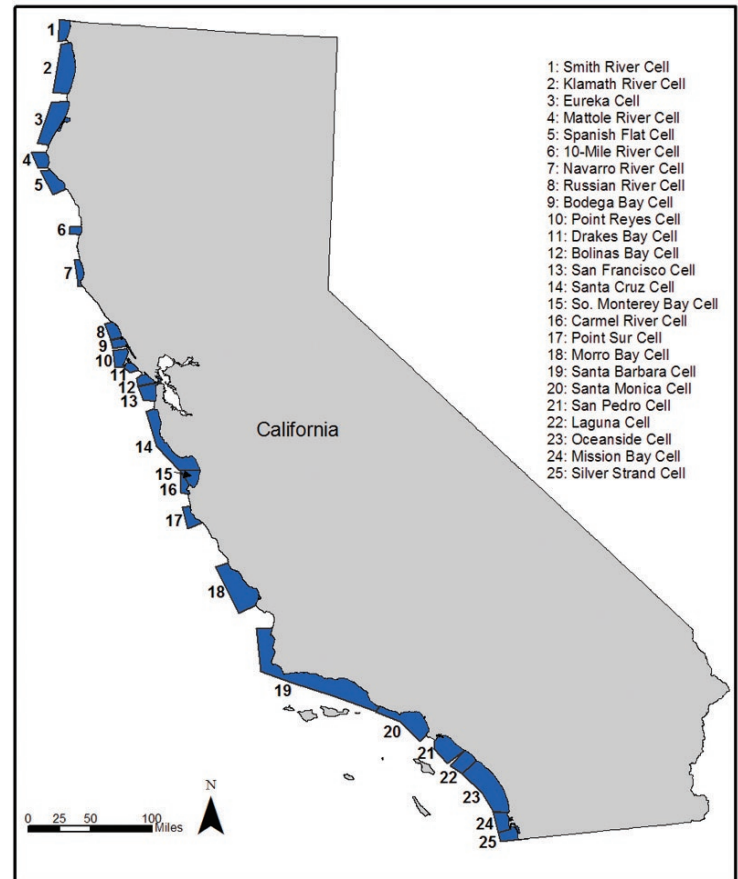


Fig 1.4. California's littoral cells (from Habel and Armstrong, 1978)

Barbara Harbor) extends back over 70 years such that the year-to-year variations can be averaged out, long-term average annual quantity calculated and long-term trends recognized (Figure 1.3). Thirty or more years of dredging data are available for other harbors. Cumulatively, the long-term data on harbor dredging has the potential to be a useful and valuable indicator of littoral drift rates at specific locations along California's 1,100

miles of coastline. These values can be used to develop sand budgets in order to gain perspective and cross check the other elements in a littoral budget, e.g. the particular input and output volumes from specific sources and sinks (i.e. rivers, cliff erosion, and submarine canyons) that are far more difficult to quantify. Littoral drift data are necessary to evaluate in the preliminary planning for any additional entrance channels or small craft harbors, and can also be used to estimate or predict future dredging costs.

PROCESSES GOVERNING SAND MOVEMENT ALONG THE CALIFORNIA COAST AND THE DEVELOPMENT OF A SAND BUDGET

Along the coast of California, a longshore or littoral current is developed parallel to the coast as the result of waves breaking at an angle to the shoreline. Researchers have learned that sand is in constant motion along California's coastline, and only resides "temporarily" on an individual beach. An alongshore or littoral current is developed parallel to the coast as the result of waves breaking at an angle to the shoreline. This current and the turbulence of the breaking waves, which serves to suspend the sand, are the essential factors involved in moving sand along the shoreline. As waves approach the beach at an angle, the up-rush of water, or swash, moves sand at an angle onto the shoreface. The backwash of water rushes down the shoreface perpendicular to the shoreline or a slight downcoast angle, thus creating a zigzag movement of sand. This zigzag motion effectively results in a current parallel to the shoreline. Littoral drift refers to the movement of entrained sand grains in the direction of the longshore current.

Littoral drift or transport can occur alongshore in two directions, either upcoast (typically to the north or northwest in California) or downcoast (to the south or southeast), depending on the dominant angle of wave approach. Longshore transport for any particular reach of coast will typically include both upcoast and downcoast transport varying seasonally. Gross littoral drift is the sum of the both components, while net littoral drift is the difference between the drift magnitudes. For example, in California, the more energetic winter waves generally approach from the northwest direction, and drive littoral drift southward along the beaches. During El Niño winters, waves generally come from the west and the southward transport is reduced. Transport is often to the northwest in most of Southern California during the summer months when southern swell dominate. For most of California, from Cape Mendocino south to San Diego, waves from the northwest have the greatest influence on littoral drift, and thus, a nearly unidirectional southward net littoral drift (Figure 1.5) of sand develops (Habel and Armstrong, 1978).

Whereas it is common practice to refer to most beach sediment as "sand", grain sizes on beaches in California range from very-fine sand to cobbles on the widely-

used Wentworth scale. The Wentworth scale classifies sediment by size in millimeters based on powers of two. According to this scale, sand is defined as all particles between 0.0625 mm and 2 mm in diameter (Table 1.1). Krumbein (1936) introduced the phi scale as an alternate measure of sediment size based on the powers of two from the Wentworth scale. Phi (ϕ) is related to the grain size by the following equation:

$$\phi = -\log_2 d$$

such that $2^{-\phi} = d$, where d is the grain diameter in mm. The phi scale is commonly used in the coastal geology community. It is important to note that larger phi sizes correspond to smaller grain sizes. Very fine-grained sand, ranging from 0.0625 to 0.125 mm in diameter (4ϕ to 3ϕ), typically doesn't remain on most California beaches due to the high-energy wave environment. Hicks (1987), in



Fig 1.5: Net littoral drift directions in California. (Source: Modified from Habel and Armstrong, 1978)

an investigation of littoral transport processes and beach sand in northern Monterey Bay, discovered that there was a "littoral cut-off diameter", or a grain size diameter, characteristic of particular segments of coast, that serves as a functional grain size boundary in that very little material finer grained than this diameter remains on the beach. The littoral cut-off diameter is primarily a function of wave energy along any particular beach or stretch of coast. Studies along the coast of northern Santa Cruz County (Best and Griggs, 1991b; Best and Griggs, 1991a; Hicks, 1985; Hicks and Inman, 1987), which is a relatively high-energy, exposed coast, indicate a littoral cut-off diameter of ~ 0.18 mm (2.5ϕ), and very little sand finer than this is retained on the exposed beach.

A sand budget employs the conservation of volume concept, and is simply an accounting of the sand entering,

leaving, or contained within a study area, in this case a littoral cell (Figure 1.6).

Wentworth Scale Size Description	Phi Units Φ	Grain Diameter (mm)
Boulder	-8	256
Cobble	-6	64
Pebble	-2	4
Granule	-1	2
Very Coarse Sand	0	1
Coarse Sand	1	0.5
Medium Sand	2	0.25
Fine Sand	3	0.125
Very Fine Sand	4	0.0625
Silt	8	0.004
Clay	12	0.00024

Table 1.1: Wentworth scale of sediment size classification.

Dean and Dalrymple (2001) compute sand accumulation in an area, ΔV_s , by

$$\Delta V_s = V_{x_1} - V_{x_2} + V_{y_1} - V_{y_2} + S$$

where

V_{x_1} = volume of sand carried into the study area along shore

V_{x_2} = volume of sand leaving the study area alongshore

V_{y_1} = volume of sand transported into the area from the landward side

V_{y_2} = volume of sand going offshore out of the area

S = volume added artificially or removed (mining) within this study area

Change in total sand volume is related to the difference in sand transported into and out of the storage area through longshore or littoral drift, the difference in sand transported to the area from landward sources, such as river discharge and seacliff erosion, and sand transported offshore, as well as sand added artificially to the area, such as beach fill or nourishment, or removed by sand mining (Figure 1.6).

Individual segments of the coast can advance, retreat, or be in a state of equilibrium depending upon the overall sand budget of the area. The response of the coastline is directly related to the volume of sand coming into a system compared to the volume of sand leaving the system. In order to formulate an accurate sand budget, information must be gathered on all the sources and sinks for each segment of coast. In California, the most logical way to compartmentalize the shoreline is to use the previously discussed concept of littoral cells.

Ideally, a littoral cell will start with a rocky promontory or headland, and moving down drift, the beach will gradually

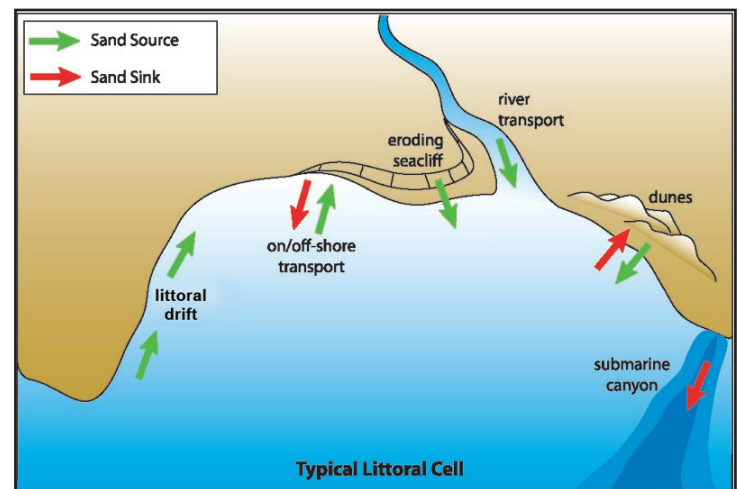


Fig 1.6: Schematic of the principal components that commonly are involved in a sand budget for littoral cells in California (modified from Komar 1996)

widen as sand is added to the cell through some combination of rivers, seacliff erosion, dune recession, gully and terrace degradation, or onshore movement of material from the continental shelf. Sand leaves the system in the form of dune growth, sand mining, offshore movement onto the continental shelf, or when it reaches the terminus of most littoral cells, a submarine canyon (Figure 1.6). Submarine canyons, if located close enough to shore, can effectively trap littoral drift and funnel sand offshore into deep enough water so as to remove the sand permanently from the littoral system. It is the balance of all of these sources and sinks within each littoral cell that governs the width or volume of the beaches in California. If there is a significant reduction in the amount of sand reaching a particular stretch of coast, beaches will narrow or erode. Conversely, if there is increase of sand in a particular area, beaches will typically widen.

COMPONENTS OF A SAND BUDGET

The main challenge in developing a sand budget for a littoral cell is quantitatively assessing all the sources and sinks to a reasonable degree of accuracy (Komar, 1996). For the purposes of this report, a thorough literature search was done to get the most up to date information on each component of the sand budgets. In addition, calculations were made for sand contributions from seacliff erosion in many of the littoral cells. Perhaps not surprisingly, new information has been developed during the course of this study, or brought to our attention by reviewers that have modified our earlier findings and conclusions.

River Inputs (Source): Rivers contribute the great majority of sand to the beaches in California. Willis et al. (2002) recently determined the sand contribution for the majority of the coastal rivers and streams in California using the daily measured values of water discharge or

probabilities of discharge events (available in the Water Supply Papers of the U.S. Geological Survey) to develop sediment-rating curves for sand-transport loads. These rating curves were then used to evaluate the total sediment yield each year from the rivers and streams. Average sand yields (sediment that is sufficiently coarse to remain on the beach) were then calculated from these data for most of the rivers and streams in California. Willis et al. (2002) determined that approximately 11,000,000 cubic yards of sand is being delivered annually to the coast of California from 37 rivers and streams. This methodology is the most reliable process to determine the sand contribution from rivers; however it is not without inherent errors. Gauging stations are often well upstream from river mouths; thus, sediment loads may change between the gauging station and the delivery to the shore.

Sand delivery by rivers to California littoral cells has also been shown to be extremely episodic (Griggs, 1987a). Most of the sand for any particular stream is discharged during several days of high flow each year. Additionally, sand discharge during a single year of extreme flood conditions may overshadow or exceed decades of low or normal flow. The Eel River transported 57,000,000 tons of suspended sediment on December 23, 1964, 18% of the total sediment load of the river during the previous ten years. This one-day discharge was greater than the average annual suspended sediment discharge of all of the rivers draining onto the entire California coastline (Brownlie and Taylor, 1981; Griggs and Hein, 1980). However, on some streams, little or no sediment discharge data may exist for the flood or large discharge events that transport the greatest volumes of sediment. As a result, rating curves may not adequately predict sand transport from water discharge records during the high discharge events when most sediment is transported.

Fluvial sediment discharge has also been shown to vary widely from El Niño to La Niña periods (Inman and Jenkins, 1999), such that the length of historic stream-flow record from any particular gage may or may not be representative of long-term conditions. In Southern California, mean annual stream flow during wet El Niño periods exceeded that during the dry periods by a factor of about three, while the mean annual suspended sediment flux during the wet periods exceeded the sediment transported during dry periods by a factor of about five (Inman and Jenkins, 1999).

At their best, data on fluvial sand discharge are believed accurate to within about 30% to 50% (Willis and Griggs, 2003). Yet, the amount of sand transported and delivered to the shoreline by streams is an extremely important component of all sand budgets for California.

Seacliff erosion (Source): Seventy-two percent of California's 1,100-mile coast consists of seacliffs. More specifically, 59% of the coast consists of actively eroding wave-

cut bluffs or terraces, which when eroded contribute sand for California's beaches. Runyan and Griggs (2002) determined the annual sand contribution from seacliff erosion for two littoral cells in California as part of a beach restoration study with the California Coastal Conservancy. The annual production of littoral sand from a segment of coastline through seacliff erosion (Q_s) is the product of the cross-sectional area of seacliff (Area = alongshore cliff length x cliff height), the average annual rate of cliff retreat, and the percentage of the material that is littoral-sized (Figure 1.7):

$$Q_s \text{ (ft}^3\text{/yr)} = L_c * E * (H_b * S_b + T_t * S_t)$$

in which L_c is the alongshore length of the cliff (ft); E is the erosion rate (ft/yr); H_b is the bedrock height (ft); S_b is the percentage by volume of beach-size material in the bedrock; T_t is the thickness of the terrace deposit (ft); and S_t is the percentage by volume of beach-size sand in the terrace deposit.

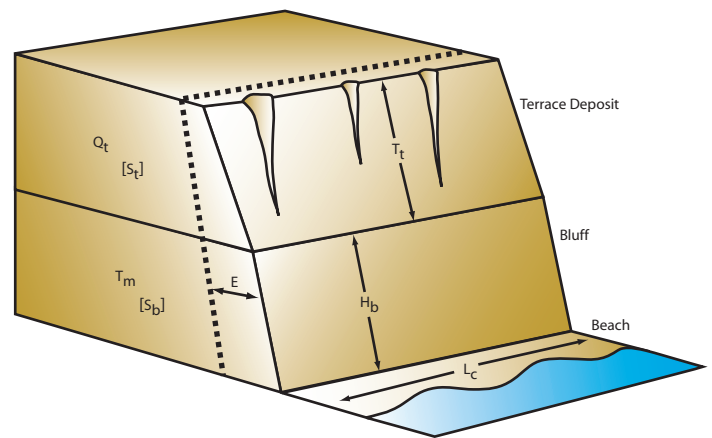


Fig 1.7 Seacliff showing the components involved in calculating sand contributions: L_c is the alongshore length of the cliff (ft); E is erosion rate (ft/yr); H_b is bedrock height (ft); S_b is percentage of sand size material larger than the cutoff diameter in the bedrock; T_t is thickness of the terrace deposit (ft); and S_t is percentage of sand larger than the cutoff diameter in the terrace deposit. T_m (Tertiary Marine) represents geology of the bedrock and Q_t (Quaternary Terrace) represents geology of the capping terrace deposit.

The geology of the seacliffs along the coast of California varies widely alongshore and, therefore, all of these parameters vary from location to location. Typically, where the coastal cliffs consist of uplifted marine terraces, there is an underlying, more resistant bedrock unit, which may vary widely in composition, and an overlying sequence of sandy marine terrace deposits, which consist predominantly of relict beach sand. Each unit must be analyzed for its individual sand content. In order to make qualitative assessments or quantitative measurements of the contribution of coastal cliff retreat to the littoral system, it is necessary to divide the coast into manageable segments that are somewhat uniform in morphology and rock type. The estimates of sand

contributions from the individual segments can then be added to arrive at a total contribution to the beach for a larger area, such as a specific littoral cell (Best and Griggs, 1991b; Best and Griggs, 1991a; Diener, 2000; Runyan and Griggs, 2002).

The methodology for determining sand contribution from seacliff erosion is much simpler than that for determining river contributions; however, these estimates still have a high degree of uncertainty. The most difficult element of this methodology to constrain is the long-term seacliff erosion rates, due to the high spatial variability and episodic nature of seacliff failure (Komar, 1996). There are many areas of the California coast where cliff erosion data have never been determined. Additionally, the amount of littoral sized sand contained in the bluffs of any particular area and will range widely. Relatively few grain size analyses have been carried out for bluff forming materials (Runyan and Griggs, 2002) along California's coastline so data on littoral sand contributions to the beach are limited. The higher the density of sampling for grain size analysis along any stretch of coast, and the more uniform the bluff forming materials, the more reliable will be the calculations of cliff or bluff contributions to the beaches of the cell.

Cross-shore exchange (Source/Sink): Potential exchange of sand between the nearshore and the continental shelf is the most difficult and poorly evaluated element in sand budgets. Cross-shore transport can represent a net gain or loss for the beach. A comparison of sand composition between nearshore and shelf sand is often used as evidence for a net onshore or offshore transport; however, the similarity in composition can only indicate that an exchange has taken place. It rarely indicates direction of transport or volumes of sand moved, which are necessary for development of a sand budget. Komar (1996) states that "... this component within the total budget remains the most poorly evaluated, and in many cases it can only be argued that this exchange between the beach and the offshore must be small compared with the other components within the budget." Recent studies in several different coastal environments have shown that net cross-shore transport can be a significant portion of the total sand budget for a particular area over decadal time scale, however. For the purposes of this research, net cross-shore exchange of sand is assumed to be zero, such that the volume of sand transported on- and offshore are balanced, unless otherwise noted. This is an area where field experiments and modeling studies could help in resolving or quantifying this component of littoral sediment budgets.

Dune Growth/Recession (Sink/Source): Wind action primarily carries sand inland from the beaches and deposits it as a foredune or within a larger dune complex (Johnson, 1959; Komar, 1996). In many areas of California, such as the Eureka and the Santa Barbara littoral cells, sand dunes constitute a significant sink to

the cell (Bowen and Inman, 1966; Winkelmann et al., 1999). Dune migration and growth can be measured from aerial photographs; these rates can be converted into sand volumes by measuring the dune width and height. Although it is most common that dunes are a sink in a littoral cell budget, sand may be blown onto the beach from an inland area representing a source of sand. Dune growth and deflation often introduces a time element into a littoral cell sand budget. One major storm can erode foredunes, which were previously considered a sink, returning the sand to the beach. However, many studies have concluded that this type of foredune erosion may occur for only a few days during a major storm event, and is subsequently followed by a prolonged period (from years to decades) of foredune growth (Komar, 1983; Komar, 1996; Thom and Hall, 1991).

Losses into Submarine Canyons (Sink): Submarine canyons that extend close to shore (such as Monterey, Mugu, Redondo and La Jolla submarine canyons; Figure 1.8) can serve as effective barriers to littoral drift and terminate most littoral cells in California (Griggs, 1985; Griggs, 1987b; Inman and Chamberlain, 1960; Komar, 1996).



Fig 1.8: Monterey Submarine Canyon

Recent high-resolution multibeam bathymetry in the head of the Monterey Submarine Canyon clearly shows the pathways for sand from the shoreline into the canyon (Figure 1.9). Sand typically accumulates in the canyon head until severe storms excite high magnitude oscilla-

tory flows within the canyon that initiate turbidity currents, which transport sediment downslope and offshore into depths of water where it is no longer a viable part of the nearshore system (Johnson, 1959; Seymour, 1986; Shepard, 1951).

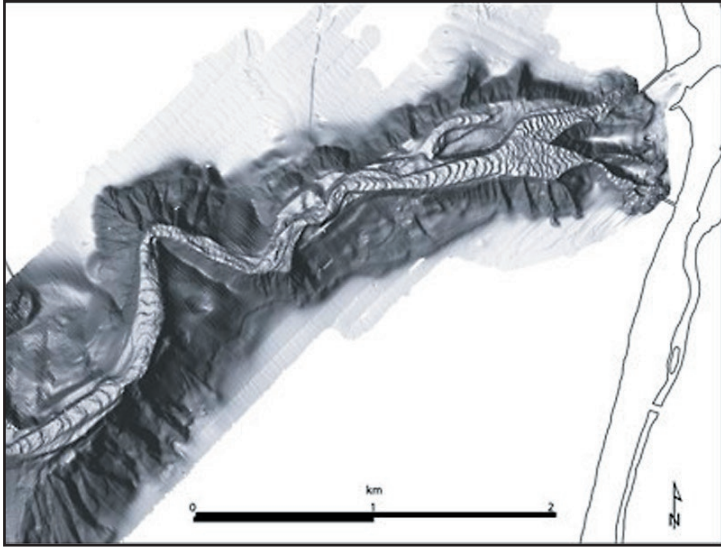


Fig 1.9. Sand waves in the head of Monterey Submarine Canyon (from Doug Smith, CSU Monterey Bay)

Inman and Chamberlain (1960) determined that approximately 200,000 cubic yards per year of sand is lost into La Jolla submarine canyon. This is enough sand to form a beach 100 feet wide, 5 feet deep, and over 2 miles long. Everts and Eldon (2005) estimate that approximately 1 million cubic yards of sand are lost into Mugu Submarine Canyon annually, while only an annual average of 1,000 cubic yards of sand are lost into Newport Submarine Canyon. These volumes span a large range and may not be representative of all canyons in California; however it is helpful to have an order of magnitude estimate for this component of a littoral cell. For the purpose of this study, the sand remaining at the end of a littoral cell, after all the sources and other sinks have been accounted for, will be directed to a submarine canyon where one exists and appears to be active.

Sand Mining (Sink): Sand and gravel are often removed from riverbeds, beaches, dunes or nearshore areas for construction and commercial purposes, representing a significant permanent sink for some of California's littoral cells. Overall in northern California, (i.e., from the Oregon border to the Russian River), about 8 million yds³ of sand and gravel are removed each year from the coastal streambeds (Magoon and Lent, 2005). In southern California, the annual total is nearly 41 million yds³, primarily in the greater Los Angeles and San Diego areas.

Sand mining has historically been a very large sink for beach sand that was difficult to quantify for the purposes of a sand budget. Due to the proprietary nature of sand mining, it is often challenging to gather information on specific mining practices for a given river or beach within

a littoral cell. Information on mining is included in the sand budgets for this report only where available. Beach sand mining was terminated along the coast of California by the late 1980's to early 1990's in all areas except for the town of Marina in southern Monterey Bay where mining of the back beach is still occurring.

Harbor Dredging (check point): California's four large harbors and 21 small craft harbors (Figure 1.2) serve as constraints, or check points, when developing sand budgets. Half of the littoral cells in California (10 of the 20 cells delineated by Habel and Armstrong, 1978; Figure 1.4) contain at least one harbor that serves as an efficient littoral trap. Sand moving along the coast in the form of littoral drift is caught in the harbor entrance or trapping area, dredged, and typically, with a few exceptions, disposed of downdrift. The jetty and breakwater configuration and geometry of some harbors (e.g. Ventura and Channel Islands harbors) were built to trap sand before it enters the harbors' navigation channel. Sand is stored in these sediment traps until it is dredged, typically once or twice a year. Other harbors (e.g. Humboldt Bay, Oceanside, and Santa Cruz harbors) were not designed with a specific sediment trapping area; thus, once the fillet of sand upcoast of the first jetty reaches its maximum capacity, littoral drift travels around the arm of the jetty and accumulates in the harbor entrance, often forming a sandbar. While a minor amount of bypassing may occur, especially for those harbors that were designed without a specific trapping area, harbor dredging records are the most robust numbers we have for determining long-term annual gross and, occasionally, net littoral drift rates. When developing a sand budget for a littoral cell, you must have enough sand coming into the system from littoral drift, streams, seacliff erosion, or beach erosion updrift of the harbor to balance the average dredged volume. Often times, a littoral cell will have more than one harbor, and thus, multiple check points for quantifying the sand budget and the transport rates for the cell—these cases are optimal for developing a reliable budget.

While long-term dredging volumes are available for many California's harbors, and while we feel that these numbers can prove very useful in the determination of littoral cell budgets, there are significant uncertainties and difficulties involved in their use. Inherent errors exist when using harbor entrance dredging volumes to estimate littoral drift as checkpoints in the development of littoral cell sand budgets. Errors involved in estimating dredging volumes include, but are not limited to, the type of equipment used to dredge, and the time frame of sand removal and placement. There can also be uncertainties involved in the pre-dredge conditions and the method used to determine the reported volume of sand dredged from a location.

At Oceanside harbor detailed studies indicate that littoral drift reverses seasonally, such that sand may enter

from either upcoast or downcoast directions and can, therefore, be dredged and counted twice. Dredging volumes at Oceanside may, therefore, represent gross vs. net littoral drift. This difference between gross and net drift can be important where significant littoral drift reversal occurs and where the configuration of the harbor entrance allows littoral drift to enter from up and downcoast directions.

There are other harbors, Santa Barbara, for example, where the combination of breakwater configuration and the location of dredge intake and discharge points, eliminate the potential for sand to enter the harbor from downcoast. As a result, there is essentially only net littoral drift at this location. Significant natural bypassing of sand across or around the dredging area can also occur (e.g., again at Oceanside, where sand appears to have been transported offshore and formed a very large permanent bar) (Dolan, Castens, et al., 1987; Seymour and Castel, 1985).

It is believed, however, that the margin of error involved in using annual dredged sand volumes as indicators of littoral drift rates, is still significantly lower than the error associated with quantifying the annual volumes of most sand sources and sinks within littoral cells (such as the sand contribution from streams and cliff erosion and sand lost to submarine canyons). For most harbors, entrances or trapping areas form nearly complete littoral drift traps. Where long-term data exist, harbor dredging records provide useful and rational checkpoints for littoral cell sand budgets. In the discussion of each individual littoral cell that follows, an effort is made to evaluate the validity or usefulness of the dredging volumes as proxies for littoral drift rates.

CHAPTER 2

EUREKA LITTORAL CELL SAND BUDGET

The Eureka littoral cell, located in northern California, is approximately 40 miles long and is bounded by Trinidad Head (Figure 2.1; Figure 2.2), a prominent rocky headland, to the north, and False Cape (Figure 2.1; Figure 2.3) to the south. At approximately its midpoint, this cell is interrupted by Humboldt Bay (Figure 2.1; Figure 2.4). Maintenance dredging of Humboldt Bay's entrance channel and bar serves as a potential indicator of the net and/or gross rate of littoral transport of sand moving alongshore in this region. Dredging of the bay's entrance channel also serves as a check-point for developing a regional sand budget for the Eureka littoral cell.

PHYSICAL SETTING

A cool and moderate climate dominates this stretch of northern California as a result of the cool, southward flowing California current. This area receives a moderate rainfall of approximately 30 to 40 inches per year between November and March, and the summers are often foggy until August. The prevailing winds in this area are from the north and northwest with average velocities from 4 to 15 miles per hour (Costa and Glatzel, 2002).

Unlike the moderate climate, the wave conditions within the Eureka littoral cell can be extreme. In fact, the wave climate in the Pacific Northwest is the most severe in the continental United States with swells from both the South and North Pacific battering the coast almost continuously. Northwestern swell dominates the wave climate; however, the most severe wave conditions typically come from southwest seas.

HUMBOLDT BAY

Humboldt Bay (Figure 2.1; Figure 2.4), located between 40 and 41 degrees north latitude, is the only major harbor between Portland, Oregon and San Francisco, California. The bay is 14 miles long with widths varying between half a mile and four miles. The bay has a small watershed, only 223 square miles, with no major rivers draining directly into it. As such, the input of freshwater is small, and circulation within the unstratified marine water within the bay is tidally dominated. The tide within Humboldt Bay is mixed semi-diurnal with a mean range at the entrance of 4.97 feet and a diurnal range of 6.93 feet (Costa and Glatzel, 2002). Entering Humboldt Bay can be quite hazardous, especially during winter storms when wave shoaling and strong currents are common in the entrance channel.

Two narrow sand spits, from one-eighth- to one-mile in width, separate Humboldt Bay from the Pacific Ocean on both sides of the tidal inlet serving as the entrance to

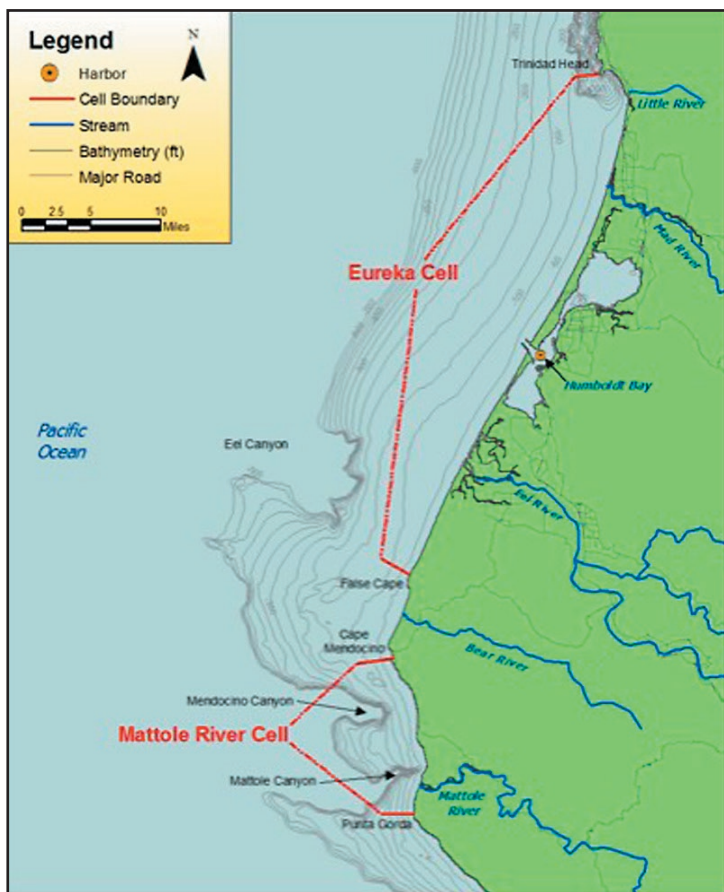


Fig 2.1: Location Map for the Eureka and Mattole littoral cells.



Fig 2.3: False Cape. Copyright © 2002 Kenneth & Gabrielle Adelman



Fig 2.4: Humboldt Bay, 1971

Humboldt Bay consists of three basins: Entrance Bay, South Bay, and North (or Arcata) Bay. Entrance Bay is a dynamic feature located directly east of the entrance channel. Much of this shoreline is armored to protect against damage by waves propagating through the entrance channel. South Bay is just south of Entrance Bay, and is more of a constriction between two features than a defined channel. North Bay (or Arcata Bay) is connected to the entrance channel by a long, narrow, maintained channel called the North Bay Channel. North Bay splits off into two smaller channels, Samoa and Eureka channels.

Entrance Stabilization: Before the entrance to Humboldt Bay was stabilized, there was an 3,000 to 5,000 foot wide opening through the north and south sand spits



Fig 2.2: Trinidad Head, Copyright © 2002 Kenneth & Gabrielle Adelman

the bay. The north spit is relatively flat with low dunes near the southerly end rising gradually to the north into higher, heavily wooded sand dunes. Along an approximately three-mile stretch from the entrance of Humboldt Bay along the north spit, the shoreline has advanced seaward and varied as much as 3,400 feet adjacent to the north jetty to no change three miles north of the jetty since jetty construction (USACOE, 1973). In contrast to the wide north spit, the south spit is narrow, low, and mostly unvegetated and extends approximately four miles to Table Bluff, a high headland separating Humboldt Bay from the Eel River delta.

forming a natural entrance with a bar located offshore in about 18 feet of water. In five-year cycles this inlet would migrate north to south along the length of the bay returning to the northern end once it reached the southern end (Noble, 1971).

Improvements to the interior of the harbor began in 1881; however, it wasn't until 1889 that the first attempt to stabilize the entrance to Humboldt Bay occurred. Due to the high-energy environment and the dynamic behavior of the spits, attempts to stabilize the entrance with jetties proved to be a challenging undertaking. Approval of the first engineering project, twin jetties, occurred in 1888, but the construction and heavy maintenance that was required for these jetties lasted until the early 1930's. Improvements and additional repair of the jetties were still required until the 1970's. Finally, in the late 1970's a more extreme engineering approach was undertaken. Massive artificial armor units, or dolos, were placed on the jetties to offer additional protection against the extreme wave conditions common in this area (Costa and Glatzel, 2002). Currently, two rubble mound jetties extending from the end of the two sand spits are in place to stabilize the inlet, or entrance channel. At their seaward end, 2,100 feet separate the 4,500 foot-long north jetty from the 5,100 foot-long south jetty.

Entrance Channel Maintenance Dredging: Originally, the bar and entrance channel to Humboldt Bay were dredged to a depth of 30 feet. In 1934, the channel was deepened to 35 feet in order to accommodate larger vessels, which required the removal of about 200,000 yds³ of material (Noble, 1971). Subsequent to this deepening operation the bar became relatively stable. According to O'Brien's Ratio, the entrance channel depth for a harbor this size (with a tidal prism equal to 4.38×10^9 cubic feet) and a distance between the two stabilizing jetties of 2,100 feet is 35.2 feet (Noble, 1971); thus, the entrance channel was in equilibrium. This equilibrium was disrupted however in 1952 when the bar and entrance channel was deepened to 40 feet. Following this deepening, routine maintenance dredging has been required annually (Figure 2.5). Between 1955 and 2000, the long-term average volume of sand dredged from the bar and entrance channel was ~465,000 yds³/yr. The last alteration of the entrance channel occurred in 1999, when the 40-foot channel was deepened to 48 feet (Winkelman et al., 1999).

Dredge Disposal: Between the 1940's and 1988, dredged material was deposited southwest of the south jetty in 60 to 90 feet of water in a disposal site named SDF3 (Kendall et al., 1991). Heavy use of this disposal site decreased the water depth in this location to 40 feet causing waves to shoal and break and the area to become a navigational concern. As a result, SDF3 was abandoned in 1988.

Between 1988 and 1989 a temporary disposal site, NDS,

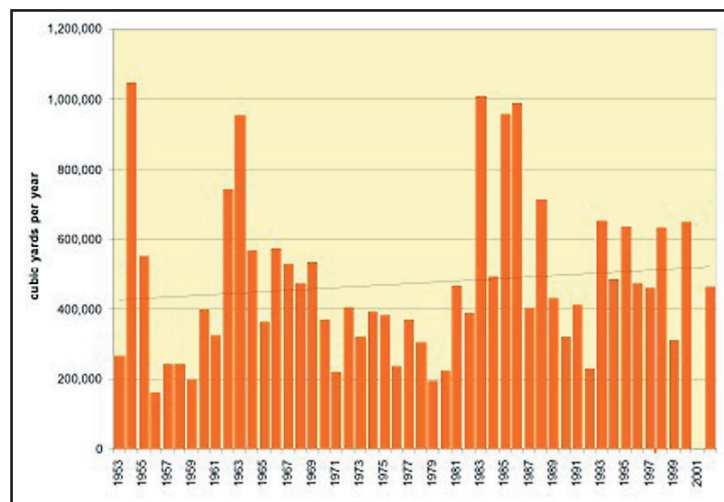


Fig 2.5: Dredging volumes for Humboldt Bay's bar and entrance channel from 1953-2000

was used, which was also located south of the jetty in 56 feet of water; this site was ultimately terminated (Kendall et al., 1991). Since 1990, dredged material has been taken offshore to the Humboldt Open Ocean Disposal Site (HOODS), which is located three miles offshore in 180 feet of water. At this depth, the sand is effectively removed from the littoral system (Winkelman et al., 1999). It is estimated that annual dredging removes ~25% of the sand from the littoral system in this cell (Kendall et al., 1991; Winkelman et al., 1999).

BEACHES

The shoreline in this cell is comprised of beaches backed by large dunes from the Little River to the entrance of Humboldt Bay, continuing down-coast with narrow beaches to just north of False Cape. Around the False Cape area and southward, sandy beaches are non-existent and the coast becomes very rocky (Figure 2.3). Where they exist, the beaches tend to be wide and flat composed of fine to medium-grained sand (USACOE, 1973). Glogoczowski and Wilde (1971) found that the littoral cut-off diameter (the diameter which less than 1% of the sand on the beaches is finer than) for beaches in this cell is 0.125mm.

DUNES

Sand dunes along the north and south spit of Humboldt Bay serve as both sources and sinks of beach sand in the Eureka littoral cell. Extensive dune fields exist between the Little River to the north and the Eel River to the south with an interruption in this field at the entrance to Humboldt Bay. Between the Little and Mad rivers there is a narrow dune field that has been described by Cooper (1967) as having two distinct ridges. The outer dune ridge is approximately 20 ft above the high tide and is covered mostly by pioneer vegetation. The inner, more substantial ridge reaches a maximum height of 50 ft and is more densely vegetated with portions of the dune remaining active and unvegetated. The dunes extend for eight miles south of the Mad River and are massive

with the height of dune crests reaching 35 to 45 ft (Cooper, 1967). On the south spit, the dunes are narrow, low, and sparsely vegetated.

An extensive monitoring project of the beaches and dunes on the north and south spit was undertaken by Winkelman, et al (1999) analyzing changes in sand volume on the beaches and dunes from 1992-1998 using digital terrain maps (DTMs) in a Geographical Information System (GIS). During this 6-year period the south spit's subaerial beach and dune system gained a total of 1.6 million cubic yards of sand, or ~270,000 yds³/yr (Winkelman et al., 1999). The dune line along the south spit remained stationary or moved seaward during the course of the study. The majority of the beaches and dunes along the north spit, however, decreased in both volume and width, losing a total of 1.05 million yds³, or ~175,000 yds³/yr over the 6-year period (Winkelman et al., 1999).

LITTLE RIVER

The Little River (Figure 2.1; Figure 2.6), located four miles south of Trinidad Head and eight miles north of the Mad River mouth, is the northernmost source of sand for the Eureka littoral cell. Between Trinidad Head and Little River, the beaches are narrow to nonexistent. South of the river mouth the beaches become wider and begin to be backed by extensive dune fields. The Little River has a total drainage area of 40.5 square miles, and currently no dams or diversions on this river exist. The present annual sand flux (sediment coarser than 0.0625 mm) from the Little River is ~53,000 yds³/yr. This is an over-estimation of the sand input to the regional sand budget in this cell, however, because the finest sand that will remain on the beaches and will not be carried offshore (the littoral-cut-off diameter) is 0.125 mm (Glogoczowski and Wilde, 1971). Little River, however, does not have a detailed grain-size analysis of the sediment load, which could allow for a more accurate calculation of the sand supplied to the beaches by this river.



Fig 2.6: Mouth of the Little River. Copyright © 2002 Kenneth & Gabrielle Adelman



Fig 2.7: Mouth of the Mad River. Copyright © 2002 Kenneth & Gabrielle Adelman

MAD RIVER

The Mad River (Figure 2.1; Figure 2.7) is located 11 miles south of Trinidad Head and 13 miles north of the entrance to Humboldt Bay. This river has a drainage area of approximately 494 square miles. For most of its reach, the Mad River flows through a steep canyon. Upon entering the Blue Lake area, the valley becomes wider and the river emerges onto a relatively flat flood plain. Humboldt Bay was once an estuary of the Mad River; today the river only spills into the bay during major flood events.

Two dams have been built on the Mad River: Ruth Dam and Sweasy Dam. Ruth Dam is located east of Forest Glen with the reservoir having a total capacity of 48,000 acre-feet. Water is released down the Mad River for municipal use. Sweasy Dam, constructed in 1938, impounded a 3,000 acre-foot reservoir.

	Natural Discharge (yd ³ /yr > 0.0625mm)	Post-Dam Discharge (yd ³ /yr > 0.0625mm)	Reduction (yd ³ /yr)	Reduction (Percent)
Little River	53,207	53,207	0	0
Mad River	752,072	687,340	64,732	9%
Eel River	3,793,057	3,753,105	39,951	1%
Total	4,598,336	4,493,653	104,683	2%

Table 2.1: Sand Reduction by Dams (Willis 2003)

It ultimately filled with sediment and was removed by dynamiting in August of 1970. A third dam, Butler Dam, was proposed at a site located about half-a-mile downstream from the north end of the valley that would have provided 460,000 acre-feet of storage, but this dam was never constructed. The present annual sand flux (sediment coarser than 0.0625 mm) from the Mad River is ~690,000 yds³/yr; this is a reduction of 9% (Table 2.1) from the natural sand flux due to the damming of this

river (Willis and Griggs, 2003; Willis et al., 2002). Using the littoral-cut-off diameter for this cell of 0.125 mm, the Mad River contributes $\sim 486,000$ yds³/yr of sand that is coarse enough to remain on the beaches.

EEL RIVER

The Eel River (Figure 2.1; Figure 2.8) discharges, on average, more suspended sediment than any river in the lower 48 states after the Mississippi (Meade and Parker, 1984), and has the highest recorded average annual suspended sediment yield of any river its size in the United States (Brown and Ritter, 1971). The Eel River basin has one of the largest sediment yields per unit area in the world (Brown and Ritter, 1971; Holeman, 1968; Judson et al., 1964). In addition, this river has the longest continuous record of water and sediment discharge in California.

Willis (2003) compiled all current USGS water and sediment data through the 2000 water year at the USGS gauging station at Scotia located ~ 21 miles from the coast. According to these data, the annual sediment load is highly variable for the Eel River ranging from ~ 130 million yds³ of sediment in the 1965 water year to 15,500 yds³ in 1977. Currently two major dams, the Scott and Van Arsdale dams impound the flow of the Eel River. Both dams are located on the upper portion of the Eel River and together impound more than 344 square miles (11%) of the basin. Van Arsdale Dam, the lower of the two, functions as a diversion dam facilitating Pacific Gas and Electric's (PG&E) Potter Valley project for hydroelectric power generation and irrigation in the Russian river basin.

The diversion has not significantly reduced the flows at Scotia that transport the bulk of sediment, and as such does not significantly affect sediment transport. In contrast, Scott Dam impounds Lake Pillsbury, an 80,000 acre-ft reservoir, and impacts flows on the Eel River. According to Willis (2003) the annual sand discharge (coarser than 0.0625 mm) averaged over 89 years (from 1911-2000) is 4.9 million tons or 3.6 million yds³ of sand annually when a mean bulk density of 1.35 tons/cubic yard is assumed; however the yearly sand discharge ranges from nearly 35.5 million yds³ in 1965 to 4,200 yds³ in 1977. Sand-sized material (coarser than 0.0625 mm) constitutes $\sim 25\%$ of the sediment yield and bed load was taken to be $\sim 4\%$ of the total load (Hawley and Jones, 1969; Willis and Griggs, 2003). The long-term annual sand discharge (3.6 million cubic yards of sand) is consistent with that found by Ritter (1972) and Griggs (1987a) of 2.9 million cubic yards and 3.3 million cubic yards respectively.

In addition, sand from the Van Duzen River, a tributary to the Eel River, adds an estimated 179,000 cubic yards of sand each year (Brown and Ritter, 1971; Willis et al., 2002). The combined impact of the Scott and Van Arsdale dams, which impound 11% of the Eel River basin,



Fig 2.8: Mouth of the Eel River. Copyright © 2002 Kenneth & Gabrielle Adelman

only reduces the sand discharged by the Eel River by 1.1% (Willis and Griggs, 2003).

In terms of a sand budget, it is important to consider the sediment that will actually remain on the beach and be carried alongshore as littoral drift—sand that is coarser than the littoral-cut-off diameter of 0.125mm. The Eel River contributes ~ 2.3 million cubic yards of beach-size sand annually.

DEPOSITION OF SAND SUPPLIED BY THE EEL RIVER

Where in the littoral system the 2.3 million cubic yards of beach sand discharged on average annually by the Eel River ends up is a debatable issue. The lack of sandy beaches south of the Eel River and the minimal sand accumulation against Humboldt Bay's south jetty north of the Eel River offer few clues as to the direction of transport. As discussed in the subsequent section concerning littoral drift direction, it is unclear whether this sand moves north or south, and it seems quite evident that although the Eel River is the main contributor of sand to this cell, most of the sand is not ending up on the beaches. Ritter (1972) proposed three sinks for this sand: 1. Deposition in the estuary at the mouth of the Eel River; 2. Deposition on the continental margin and loss into the Eel Canyon; and 3. Deposition on the nearby beaches.

Near the mouth of the Eel River, which is tidal for about four miles inland (Evenson, 1959), several islands, channels, and sloughs show evidence of deposition in the estuary (Shepard and Wanless, 1971). Using a surface area for the estuary at high water of 2.6 square miles (Johnson, 1972) and an average long-term sand load of 2.3 million yds³/yr, the estuary would be infilling at an average rate of 1.3 feet per year. This rapid rate of deposition is not observed. Although the actual rates of deposition are unknown, it seems highly improbable that this is a major sink for sand emanating from the Eel River. It is concluded that most of the sand transported by the Eel River makes it to the ocean, passing through

the estuary without much deposition.

To determine if sand was being deposited along the continental margin, Ritter (1972) studied the bottom contours off the mouth of the Eel River. He determined that "although the 30- and 60-foot contours parallel the shoreline, the contours from 120 to 240 feet show a convex bulge." Ritter (1972) used this as evidence that much of the sediment discharged from the Eel River is spread over the continental margin as a blanket deposit or submarine fan. Nittrouer (1999) also concluded that sand accumulates on the inner shelf (<180 feet water depth) offshore of the Eel River. A model developed by Morehead and Syvitski (1999) indicates that under modern geologic conditions, the majority of deposition for sediment discharged from the Eel River occurs up to 12 miles north of the river mouth and is confined to within 6 miles of the coastline.

Submarine canyons located close to shore along the California coast often serve as major sinks for littoral sand. Although Eel Canyon, reaching to within seven miles of the mouth of the Eel River, is located a considerable distance from the shore, it may serve as a sink for sand discharged from the Eel River. As with many issues in this littoral cell however, this is still highly debated. Silver (1971) concluded that the submarine alluvial fan at the mouth of the canyon is far too small considering the large sediment loads that theoretically would be making their way down the canyon. However, by interpreting seismic records, Greene and Conrey (1966) discovered a buried canyon extending shoreward from the present-day canyon, and concluded that sediment deposited by the Eel River must have filled this shoreward part of the canyon and now the sediment is filling the head of the present canyon. More research is needed to determine if Eel Canyon serves as a major sink for sand (coarser than 0.125mm) discharged by the Eel River.

If the sand discharged from the Eel River is not filling the estuary, and it is not ending up in the Eel Canyon or on the continental margin, then the only other logical place it could be is on the beaches along the coast north and south of the Eel River mouth, or perhaps deposited in Humboldt Bay. The beaches north of the river are quite narrow, and the beaches south of the river are non-existent except for the occasional pocket beach. These small beaches are not what would be expected around the mouth of a river discharging an average of over 2 million cubic yards of beach-sand-sized sediment annually.

Ritter (1972) collected sand samples along the entire littoral cell, from Trinidad Head to Centerville Beach, and performed a grain-size and mineral analysis to determine the source of sand. He determined that mean grain size became finer as the distance from the mouth of the Eel River increased. Ritter (1972) supported a southward littoral drift, and his grain size statistics demonstrated a significant difference between mean grain sizes north

and south of the entrance to Humboldt Bay, indicating different source material. Ritter (1972) concluded that sand north of Humboldt Bay is supplied by the Mad and Little rivers and sand south of Humboldt Bay is supplied by the Eel River. This conclusion was consistent with his heavy mineral analysis. Ritter (1972) could not explain, however, why the beaches between Humboldt Bay and False Cape are so small and narrow with a supply of sand as great as the Eel's. It is not likely that Humboldt Bay is a significant sink for the sand discharged from the Eel either due to the theoretical rate of infilling that would result from such a large sand load (Ritter, 1972).

DIRECTION OF LITTORAL DRIFT OR LONGSHORE TRANSPORT

Understanding the predominant direction of sand movement, or the direction of littoral drift, is an essential component in the development of a robust regional sand budget. In the Eureka littoral cell, the direction of longshore transport is still a contentious issue, and one that has not been fully resolved. Ideally, the northerly and southerly movement of sand can be assessed to provide both net and gross longshore transport rates; however, in the Eureka cell there has been no confident assessment made for the quantities of sand involved in this movement.

The most notable study on the direction of littoral drift in this area was done by Noble (1971) using unpublished U.S. Army Corps of Engineers reports focusing on the construction of the Humboldt Bay jetties and the resulting impact to the shoreline. Noble argues for a dominant north to south transport, stating that the natural condition of Humboldt Bay's entrance inlet, before the jetties were emplaced, cycled from north to south over a five-year interval. Over the five-year cycle the inlet would migrate 1.5 miles from north to south only to open again at the northern end and repeat the cycle. Additionally, the waves along this stretch of coast are predominantly from WNW and to the north of WNW, which will produce a southerly drift; thus, this evidence indicates a predominant direction of drift to the south (Noble 1971). Following the initial phase of construction of the Humboldt jetties (1870 to 1899), the shoreline advanced along both the north and south spits; the north spit shifting seaward 2,600 ft and the south spit shifting seaward 2,200 ft. Noble cited this as additional evidence for a north to south drift. He also noted that the Army Corps of Engineers estimated the net longshore transport in the vicinity of Humboldt Bay to be on the order of 500,000 yds³/yr to the south. Habel and Armstrong (1978) also indicate net transport to be to the south in this cell; however, they do not give any evidence in support of their conclusion.

Borgeld et al. (1993) believe that Noble (1971) was incorrect in his assessment of the evidence supporting a north to south transport, and instead proposed that the dominant transport direction is from south to north. By

assessing the bar and channel configuration of Humboldt Bay they suggest a south to north transport both prior to and following jetty construction. Additional indication of a south to north transport direction is given by the fact that between completion of the jetties in 1899 until 1903, a time during which no maintenance of the jetties was undertaken, allowing for the ends of the jetties to severely deteriorate and fall below mean lower low water, the south spit adjacent to the jetty advanced seaward by 1,000 ft and the north spit eroded. However, by 1912, the south spit had eroded 800 ft and the north spit was continuing to retreat. Reconstruction of the Humboldt jetties occurred between 1912 and 1916. During this time, the north spit once again advanced seaward 2,300 ft while the south spit advanced seaward by only 450 ft. Once again, Noble (1971) saw this as evidence for a dominant north to south littoral drift. Borgeld et al (1993) however, do not agree with this interpretation and maintain that the drift is from the south to north.

Also of notable interest in the debate on transport direction, is the longshore sorting of sand on the beaches. Snow (1962) found that the mean grain size of sand on the beaches decreased from south to north, once again indicating a south to north transport direction. However, as discussed earlier, Ritter (1972) concluded that mean grain size and heavy mineral tracers such as garnet indicate that the Eel River is the main contributor to the beaches in the southern end of the cell, while the Mad and Little river are the main sources of sand to the beaches north of Humboldt Bay, thus arguing a dominant north to south transport in the northern reach of the cell (from Trinidad head to the Humboldt Bay), and a south to north littoral drift in the southern reach of the cell (from False Cape to Humboldt Bay). However, Bodin (1982) found that there was a systematic south to north decrease in the mean grain size of the beach sand throughout the full length of the cell, and his heavy mineral analysis concluded that Eel River sand was the primary source of sand throughout the cell indicating a dominant south to north transport direction throughout the Eureka Cell.

The Eel River, located in the southern portion of the cell, contributes most (77%) of the sand to the Eureka Cell. Significantly smaller volumes of sand are provided by the Mad and Little rivers, which are both located in the northern region of the cell. Borgeld et al. (1993) argue that this fact alone, the extremely large volume of sand emanating from the Eel River, is evidence for a south to north transport. However, if such a large volume of sand is discharged from the Eel River and travels north, it would be expected that the south spit of Humboldt Bay would be accreting significantly next to the southern jetty and be offset a great deal more seaward than the north spit; this is not the case, however.

If a southward transport direction is supported, one would expect wide sandy beaches south of the Eel River.

However, there are no sandy beaches in this area, nor is sand accumulating on the north side of False Cape, the proposed terminus of the Eureka littoral cell. There are also no submarine canyons between Eel River and False Cape reaching close enough to shore to serve as a sink for the sand. One possibility is that False Cape is not acting as a complete barrier to littoral transport. Sand may be making its way around False Cape, continuing along the shoreline around Cape Mendocino, and ultimately end up flowing into the Mendocino and Mattole canyons. This theory would require that the long accepted southern boundary for the Eureka littoral cell, False Cape, needs to be extended southward to include Mendocino and Mattole canyons.

Overall, the issue concerning the direction of longshore drift in the Eureka Cell is unresolved. Convincing evidence is presented for both a north to south transport as well as a south to north transport. In this cell, what may be more important to realize when developing a regional sand budget than the dominant direction of littoral drift, or considering alterations to the coastline, is that the quantities and direction of littoral drift in this cell may change from year to year, and engineering activities along the coastline may have far reaching consequences. In the most recent studies, sand transport in the Eureka Cell is characterized by a large gross movement with a small net movement of sand to the north (Madalon and Kendall, 1993; Winkelman et al., 1999).

The sand budget developed for this cell should be used with caution because of the inconclusive nature of the transport direction studies. After assessing the literature concerning the longshore transport direction, the evidence appears to be stronger in supporting a dominant north to south transport direction north of Humboldt Bay, and a bidirectional transport direction south of Humboldt Bay.

DISCUSSION

Development of a regional sand budget for the Eureka Cell is challenging due to the uncertain direction of littoral drift and the undefined sink for the extremely large volume of sand discharged annually from the Eel River. What is known is that the Little and Mad rivers contribute ~53,000 and ~486,000 cubic yards of beach-size (>0.125 mm) material annually north of Humboldt Bay. Eighty-nine percent of the total sand discharge from these river occurs between December and February (DeGraca and Ecker, 1974), making most of this beach compatible material available within a very short time, thus exceeding potential littoral transport and producing a surplus of sand north of Humboldt Bay. As a result, extensive sand dunes exist north of the bay. It has been estimated by the Army Corps of Engineers that the net littoral drift for this cell in the vicinity of Humboldt Bay is ~500,000 cubic yards of sand annually (Noble, 1971). This volume is consistent with the long-term average

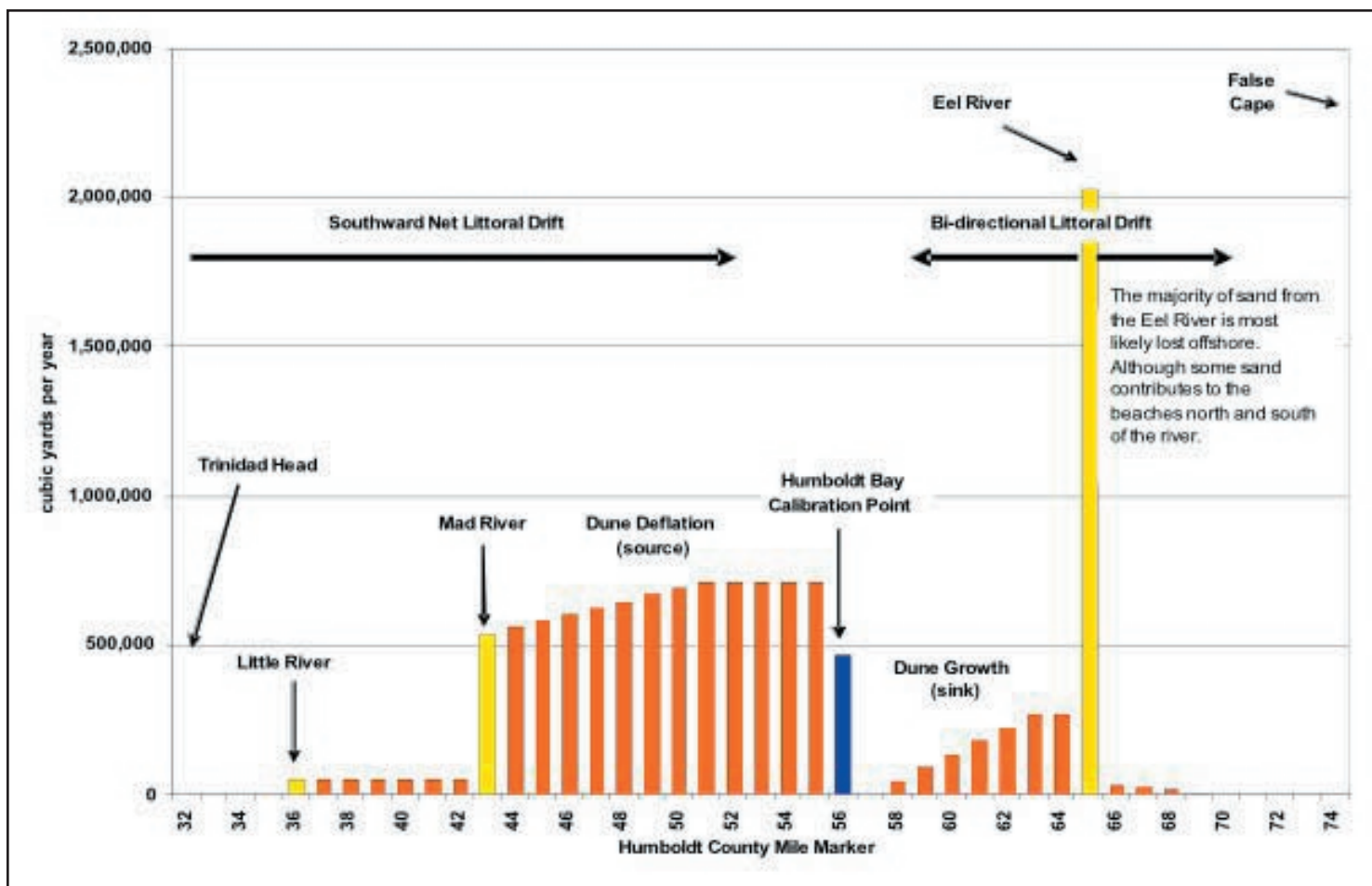


Fig 2.9: Running, mile-by-mile sand budget for the Eureka littoral cell

annual entrance channel and bar dredging for Humboldt Bay (~465,000 cubic yards annually).

It is not clearly understood why the sand on the beaches around the mouth of the Eel River is so sparse considering it is discharging ~2,300,000 yds³/yr. The sand supply from the Eel River should make the surrounding beaches wider and the dunes higher. However, the beaches north of the mouth are narrow and the dune sizes do not reflect an extremely large supply of sand. Beaches south of the mouth are practically nonexistent, narrow, pocket beaches. The dimensions of the estuary around

the Eel River and Humboldt Bay are not large enough to accommodate the heavy sand load from the Eel without rapidly infilling, and Eel canyon appears to be located too far offshore to serve as an adequate sink for littoral-sized sand. Ritter (1972) concludes that "the Eel River, although undoubtedly contributing sand to all the places mentioned above, clearly deposits most of its sand load on the continental shelf." This conclusion is consistent with findings by Nittrouer (1999) and Morehead and Syvitski (1999). An additional possibility is that littoral drift moving south is deflected offshore into deeper water, makes its way around Cape Mendocino, and is eventually lost to Mattole and Mendocino submarine canyons; this theory would necessitate changing the southern boundary of the Eureka Cell. Based on grain size analyses and mineralogy (Bodin, 1982; Ritter, 1972; Snow, 1962), the Eel River is thought to be the chief contributor of sand to the beaches between Humboldt Bay and its mouth.

CONCLUSION

In order to create a definitive sand budget for the Eureka Littoral Cell, more research will need to be completed to determine the littoral transport direction(s) for the cell and the sinks for sand discharged from the Eel River. A detailed multibeam bathymetric study from the shoreline to the head of Eel Canyon is highly recommended and may

Sources	Cubic Yards per Year
Little River	53,000
Mad River	486,000
Eel River	2,300,000
Dunes	175,000
Total	3,014,000
Sinks	Cubic Yards per Year
Dunes	270,000
Humboldt Bay (offshore)	465,000
Offshore Losses (estimated in order to balance the sand budget)	2,279,000
Total	3,014,000

Table 2.2: Sources and Sinks for the Eureka Littoral Cell

help resolve the uncertainties and debates. With the current state of knowledge, it is assumed that the $\sim 540,000$ yds³ of sand discharged by the combined Mad and Little rivers travels south as littoral drift, gains and loses sand from the immense dune fields on the north spit, and is eventually deposited in the bar and entrance channel to Humboldt Bay, where $\sim 465,000$ yds³ of sand is dredged annually and deposited offshore, effectively removing it from the littoral system (Figure 2.9; Table 2.2). South of Humboldt Bay, $\sim 2,300,000$ yds³ of sand is discharged annually from the Eel River, the majority of which is lost offshore along the continental shelf or deposited into Eel Canyon. Some of this sand travels north to feed the beaches along the south spit between the mouth of the Eel River and Humboldt Bay, and some of the sand travels south along the rugged coast to False Cape (Figure 2.9; Table 2.2). Sand from the Eel River may in fact make its way around Cape Mendocino with an eventual sink at Mendocino and Mattole submarine canyons.

CHAPTER 3

SANTA CRUZ LITTORAL CELL SAND BUDGET

The Santa Cruz littoral cell (Figure 3.1) extends, for the purpose of this study, approximately 75 miles from Pillar Point to the Monterey Submarine Canyon at Moss Landing in central Monterey Bay (Griggs, 1987b; Limber, 2005; Perg et al., 2003; Weber et al., 1979; Yancey and Lee, 1972). This stretch of coast is morphologically diverse with broad continuous marine terraces fronted by beaches in Monterey Bay and Half Moon Bay. North of Monterey Bay, resistant headlands punctuate the coastline creating pocket beaches.

The Santa Cruz littoral cell has a Mediterranean climate moderated by the California Current. The Santa Cruz Mountains, backing nearly the entire coastline, have pronounced orographic effects on the climate in the region with 90% of the annual precipitation occurring between the months of November and March (Rantz, 1971). The average yearly rainfall is ~31 inches near Santa Cruz and decreases to ~22 inches in the northern portion of the cell (Rantz, 1971).

PHYSICAL SETTING

Pillar Point to Año Nuevo: Pillar Point appears to be the northern boundary of the Santa Cruz littoral cell (Figure 3.1). It is believed that little to no sand is transported around Point San Pedro (Limber, 2005). As evidence of the cell boundary, Half Moon Bay Harbor, located just south of Pillar Point (Figures 3.1 and 3.2) has never required maintenance dredging as a result of sediment entering the channel entrance, nor is there a significant build-up of sand against the breakwater. There is, however, a considerable amount of sand immediately south of Half Moon Bay, indicating sand may be leaking into the cell from upcoast. Seafloor rock outcrops off of Pillar Point, responsible for creating large waves at the popular big-wave surf spot, Mavericks, may steer sand around the harbor to the downcoast shore. For the purpose of this study, Pillar Point will be used as the northern boundary for the Santa Cruz littoral cell, however, this boundary may not be definitive; sand may leak into the cell from north of Pillar Point.

Half Moon Bay, located between Pillar Point to the north (Figure 3.2) and Miramontes Point to the south, is a 6.5-mile long, hook-shaped bay consisting of sandy beaches backed by low, eroding bluffs. In 1959, a long breakwater was constructed across the northern portion of Half Moon Bay to create a protected harbor. Construction of this breakwater caused a change in wave refraction in the bay and resulted in the increased erosion (from 3 inches per year to as high as 80 inches per year) of the low, weak bluffs at the eastern end of the breakwater (Griggs et al., 2005).

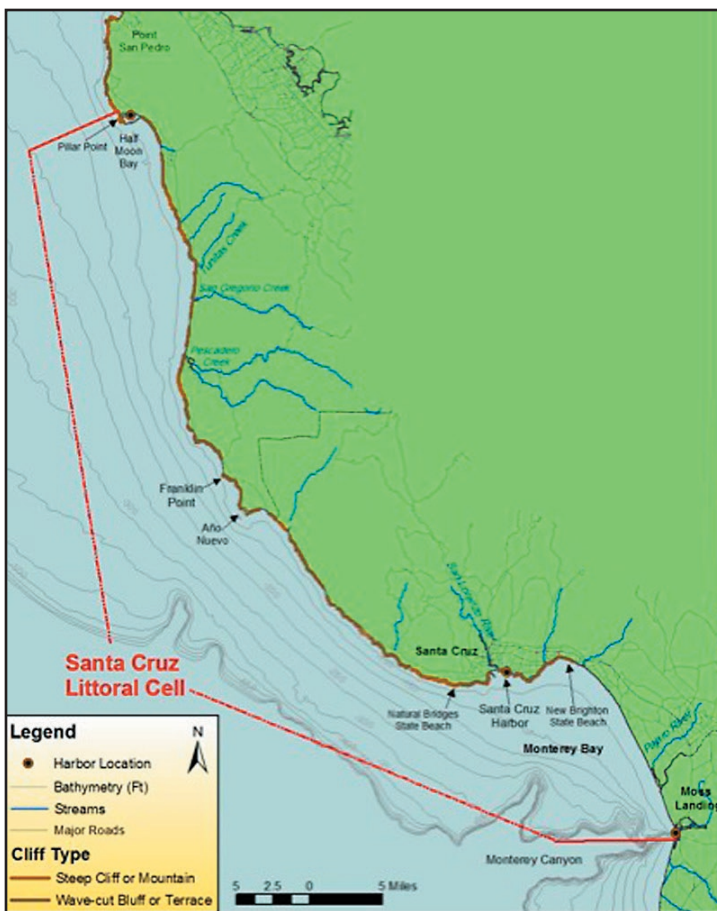


Fig 3.1: The Santa Cruz littoral cell

South of Miramontes Point, the ~6 mile coastline to Tunitas Creek (Figure 3.3) consists of steep, irregular cliffs ranging from 70- to 160-feet high fronted by narrow and/or pocket beaches. While the rates of seacliff erosion in this vicinity are quite variable, the majority of these cliffs are relatively stable (Griggs et al., 2005).



Fig 3.2: View west from Maverick's, showing the tail-end of Pillar Point and Half Moon Bay Harbor, California. Copyright © 2004 Kenneth & Gabrielle Adelman

From Tunitas Creek (Figure 3.3) south to Pescadero Creek (Figure 3.4), the coastline consists of sandstone and mudstone coastal cliffs interrupted by coastal streams. Narrow, sandy beaches often front these

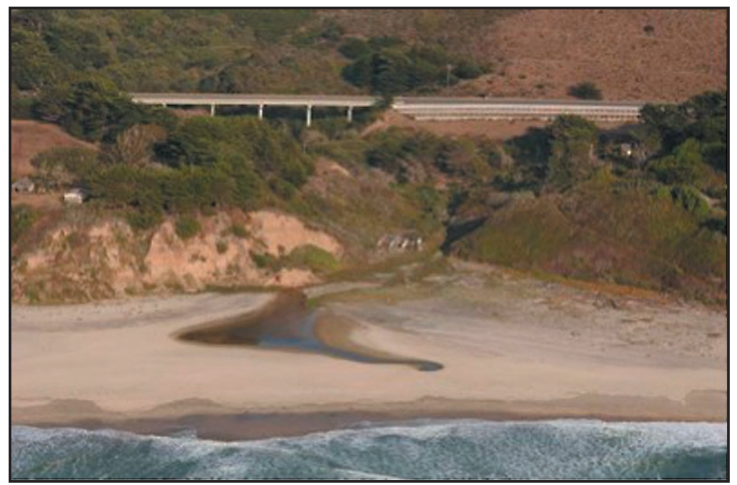


Fig 3.3: Tunitas Creek. Copyright © 2002 Kenneth & Gabrielle Adelman

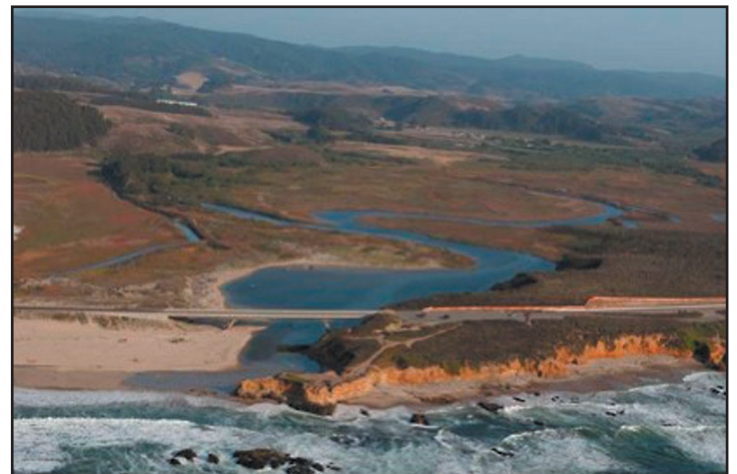


Fig 3.4: Pescadero Creek. Copyright © 2002 Kenneth & Gabrielle Adelman

relatively stable seacliffs during the summer months.

Low, rocky cliffs and bluffs with small pocket beaches mark the coastline from Pescadero Creek to Franklin Point (Figure 3.1). Resistant sandstones, mudstones and conglomerates are exposed to wave erosion along this stretch of coast. Stabilized sand dunes characterize Franklin Point. Seacliff erosion along this stretch of coast is minor because of the resistance of the rocks to wave attack (Griggs et al., 2005).

Point Año Nuevo is a low-lying headland near the southern boundary of San Mateo County (Figure 3.1). The nearly flat, broad marine terrace exposed at this point is comprised of a resistant sandstone and mudstone bedrock overlain by a 5- to 30-feet thick layer of easily eroded sand, gravel, and silt (Griggs et al., 2005). On its seaward half, this headland, or point, is topped by a 5,000-to 6,000-year-old dune field that has been stabilized and vegetated over the past 110 years (Griggs et al., 2005). The northern portion of the shoreline at Point Año Nuevo is nearly linear with sand and gravel beaches backed by low bluffs. The southwest-facing shoreline is essentially a curved, pocket beach formed between

two rocky points, while the southern portion of the point consists of irregular, low vertical- to overhanging-cliffs.

Año Nuevo Island, lying 2,300 feet offshore from the southern point of the headland, probably formed in the time between the late seventeenth to mid-eighteenth century (Griggs et al., 2005; Seals, 2005). When first discovered in 1603, the Año Nuevo area was named Point Año Nuevo and was presumably a peninsula. Continued sea level rise and coastal erosion, possibly in connection with movement related to prehistoric earthquakes along the San Gregorio Fault Zone, eventually led to the formation of an island separated from the mainland by a channel (Griggs et al., 2005).

Point Año Nuevo once formed a barrier, or trap, for sand traveling south as littoral drift, which impounded sand and formed wide, sandy beaches north of the point. Littoral sand blew up onto the low marine terrace and moved across the point as dunes, eventually cascading over the southern portion of the headland where it once again entered the littoral cell. Once Año Nuevo Island separated from the mainland, the point was no longer an effective littoral barrier; thus, the wide, sandy beach supplying the dunes disappeared on the north side of the headland. The formation of the channel resulted in as much as 12 to 18 million yds³ of sand that had previously been trapped by the headland, to again enter the sand budget over the past 200 to 330 years (Griggs et al., 2005). Tens of thousands of cubic yards were added to the sand budget annually from this reserve of sand. However, the large source of sand is now depleted. As the end of the wave of extra sand migrates down the coast, beaches in this littoral cell, south of Point Año Nuevo may return to a natural, narrower width (Griggs et al., 2005).

Año Nuevo to Natural Bridges State Park: From Año Nuevo to Natural Bridges State Park (Figure 3.1) the coastline is predominantly undeveloped. Agricultural fields are situated atop the lowest and youngest of a sequence of up to five marine terraces (Figure 3.5). The seacliffs along this stretch of coast range from 30- to 200-feet high and consist of moderately resistant mudstone. Beaches exist where coastal streams have incised the marine terrace to reach the ocean. Average long-term seacliff erosion rates in this vicinity are relatively low (3 to 6 in/yr or less) due to the resistance of the Santa Cruz Mudstone to wave attack and the protection offered by low mudstone benches, or shore platforms, commonly extending seaward at the base of the cliffs (Griggs et al., 2005).

Natural Bridges to New Brighton State Beach: From Natural Bridges State Park to New Brighton Beach (Figure 3.1) the coastline is almost continuously developed. This 10-mile stretch of coast consists off narrow to wide beaches backed by seacliffs ranging from 25- to 75-feet-high. Wider beaches exist at stream mouths and north of natural and artificial retention structures such



Fig 3.5: Marine terrace at Sand Hill Bluff located just north of Santa Cruz Copyright © 2002 Kenneth & Gabrielle Adelman

as headlands, jetties and groins. As you move from west to east along this stretch of coast, the more resistant Santa Cruz Mudstone dips below the younger, less resistant Purisima Formation about a mile east of Natural Bridges where cliff erosion begins to proceed more rapidly. Much of this section of coast has been armored in the last 30 to 40 years, predominantly with riprap (Griggs et al., 2005). In this 10-mile stretch of coast, 5 miles of shoreline, or 50%, are protected by armor.



Fig 3.6: Santa Cruz Small Craft Harbor, California. Copyright © 2004 Kenneth & Gabrielle Adelman

Construction of the Santa Cruz Small Craft Harbor (Figure 3.6), located in the southern reach of the littoral cell, was initiated in 1963 by dredging a coastal lagoon and stabilizing an entrance channel with two parallel rubblemound jetties (completed in 1965) (Griggs et al., 2005; Wiegel, 1994). The west jetty is 1,200-feet-long with the ocean-end formed into a 300-foot-long dogleg angling toward the entrance. The east jetty is 810 feet long. The harbor was initially dredged to a depth of 20 feet and is 125 feet wide at the end of the jetties. Since 1986, routine dredging has been done with the harbor's own dredge (the Seabright), which operates nearly continuously during the winter and spring seasons at a cost

of ~\$500,000 annually (Wiegel, 1994). Following construction of the harbor, Seabright Beach, located west of the entrance and adjacent to the upcoast jetty, accreted rapidly, while beaches downdrift, or east of the entrance, experienced significant erosion. Capitola Beach, located approximately 3.5 miles downdrift of the harbor, disappeared within several years after completion of the harbor. A 250-foot-long groin was constructed at the downcoast end of Capitola beach in an attempt to stabilize the beach (Griggs, 1990). Beginning in 1965, dredging of the harbor entrance has provided sand to feed the downcoast or eastern beaches, including Capitola Beach, resulting in essentially equilibrium conditions in the area since the 1970's (Wiegel, 1994). Approximately five miles east of the harbor, at New Brighton State Beach, beach profiles indicate no long-term changes in the shoreline position since the 1970's (Wiegel, 1994).

Immediately up- and downcoast of Capitola, the irregular shoreline is backed by 50- to 75-feet high bluffs. Most of this area is devoid of beaches, with the exception of beaches in Capitola at the mouth of Soquel Creek, which has been widened due to a groin.

New Brighton State Beach to Monterey Submarine Canyon: South of New Brighton State Beach, in the southern portion of Santa Cruz County, the remaining shoreline of the Santa Cruz littoral cell is within the protected inner portion of Monterey Bay. Wide, sandy beaches provide a buffer for the bluffs from wave attack. From New Brighton Beach to La Selva Beach, seacliffs forming the seaward edge of a marine terrace reach to ~100 feet in elevation. From Manresa Beach to the Pajaro River, the terrace disappears and the coastline is dominated by Pleistocene-aged and recent sand dunes. During severe storms, these dunes undergo significant erosion. This erosion is subsequently followed by a period of dune accretion and growth (Griggs et al., 2005). South of the Pajaro River, wide sand dunes, reaching as high as 100 feet, back the beaches.

LONGSHORE TRANSPORT AND LITTORAL CUT-OFF DIAMETER

The dominant waves from the northwest drive net littoral drift to the south along the entire cell (Best and Griggs, 1991a; Habel and Armstrong, 1978). Potential littoral drift rates have been calculated in the vicinity of Santa Cruz Small Craft Harbor (Anderson, 1971; Walker and Dunham, 1978). Moore (1972) and Walker and Dunham (1978) estimated the littoral drift in the vicinity of the Santa Cruz Small Craft Harbor to be ~250,000 and ~300,000 yd³/yr respectively, based on the accretion rates against the upcoast jetty of the harbor. Walker and Williams (1980) suggest that ~175,000 to 375,000 yd³/yr bypass the harbor mouth. Seymour et al. (1980), however, concluded that bypassing of the harbor mouth is minimal.

Best and Griggs (1991a; 1991b) determined that the littoral cut-off-diameter, or the smallest grain size that will

remain on the beach, for the Santa Cruz littoral cell is 0.18 mm. Sand finer than 0.18 mm will be transported and ultimately lost offshore, and thus is not a component of the sand budget. Fluvial transport in this cell is low relative to other littoral cells in California due to the small number of coastal streams delivering only minimal amounts of littoral-sized sand to the shoreline. In addition, resistant bluffs and cliffs consisting of Santa Cruz Mudstone and the Purisma Formation do not provide a great deal of sand that is sufficiently coarse to remain on the beaches (Best and Griggs, 1991b; Best and Griggs, 1991a). Headlands also hinder littoral transport by trapping sand in pocket beaches and preventing the continuous downdrift movement of the sand.

Harbor dredging can be used as an indicator of littoral drift assuming that the mouth of the harbor is an effective and efficient trap for littoral sand. From 1965 to 2004, an average of ~160,000 yd³/yr of sand has been dredged from the entrance to the Santa Cruz Small Craft Harbor (Table 3.1).

Year	Yd ³ /Yr	Year	Yd ³ /Yr
1965	70,000	1985	145,200
1966	34,000	1986	207,000
1967	57,000	1987	206,400
1968	60,000	1988	230,400
1969	79,000	1989	214,500
1970	94,700	1990	173,600
1971	108,300	1991	163,300
1972	90,000	1992	220,600
1973	109,000	1993	124,300
1974	60,000	1994	234,400
1975	91,000	1995	170,700
1976	98,000	1996	101,900
1977	199,000	1997	118,200
1978	55,000	1998	399,300
1979	162,000	1999	317,900
1980	190,300	2000	262,300
1981	187,000	2001	242,000
1982	138,200	2002	348,000
1983	154,500	2003	220,000
1984	79,500	2004	180,000

Table 3.1: Annual dredging volumes in the entrance channel of the Santa Cruz Small Craft Harbor

Following harbor construction the beach west of the entrance, Seabright Beach, accreted quickly, eventually approaching a near equilibrium width around 1977 (Wiegel, 1994). With an equilibrium upcoast beach, littoral drift moves sand around the west jetty where it is trapped in the harbor mouth until it is dredged and placed on the downdrift beach. From 1977-2004, after Seabright Beach reached a point of near equilibrium, the Santa Cruz Small Craft Harbor has dredged an average of ~194,500 yd³/yr of sand from the entrance channel and placed it on the beaches downdrift (easterly) (Table 3.1). Seabright Beach did continue to widen slightly

for about the next decade, but over the past 20 years appears to have stabilized; the annual dredging volume over this last 20-year period, therefore is higher and has averaged $\sim 214,000$ yd³. With 40 yrs of history, dredging from the entrance channel of Santa Cruz Small Craft Harbor provides the most reliable indicator of littoral drift in the southern portion of the Santa Cruz littoral cell which is estimated to range from $\sim 180,000$ to $\sim 220,000$ yd³/yr.

SAND SOURCES

River Input: The main fluvial source of sand to this littoral cell is the San Lorenzo River (Figure 3.7), which discharges ~ 1 mile west of the Santa Cruz Small Craft Harbor. Small coastal streams draining the Santa Cruz Mountains in San Mateo and Santa Cruz counties provide additional sand to the Santa Cruz littoral cell. Thirteen streams with basins greater than 5 square miles drain 85% of the 274 square mile region from Tunitas Creek to Santa Cruz Harbor (Best and Griggs, 1991a). The mouths of the majority of these streams have been drowned by Holocene sea level rise resulting in low gradient flood plains and coastal lagoons, which serve as temporary sand storage sites. During the dry summer months, sand bars are commonly observed at the mouths of the streams (Figure 3.2). In addition, the construction of Highway 1 and railroad fill has prevented many coastal streams from reaching the ocean directly, leading to significant sediment impoundment during the past century.



Fig 3.7: Mouth of the San Lorenzo River. Copyright © 2002 Kenneth & Gabrielle Adelman

From Tunitas Creek south to Santa Cruz Harbor, Best and Griggs (1991a) used existing stream discharge and sediment transport data, collected additional data and used drainage basin comparisons to calculate that rivers, creeks, and streams provide an upper limit average of approximately $\sim 114,000$ yd³/yr of littoral-sized sand (0.18 mm). South of Santa Cruz Harbor, the Pajaro River (Figure 3.8) currently contributes an average of $\sim 60,500$

yd³/yr of sand-sized material (coarser than 0.0625 mm) (Willis and Griggs, 2003; Willis et al., 2002). This is an upper limit to the sand supplied to the beaches from the Pajaro River because sand between 0.0625 mm and 0.18 mm will be lost permanently offshore. Damming of the Pajaro River has reduced the sand discharge by 6% from 64,000 yd³/yr under natural conditions (Willis and Griggs, 2003; Willis et al., 2002). Overall, streams currently contribute $\sim 174,500$ yd³/yr to the sand budget in the Santa Cruz littoral cell representing 81% of the present-day littoral budget (Table 3.2).



Fig 3.8: The Pajaro River mouth. Copyright © 2002 Kenneth & Gabrielle Adelman

Gully Erosion: Gully erosion results from soil piping through more permeable subsurface horizons that typically collapse as they enlarge producing gullies and channelized overland flow (Swanson, 1983). Extensive gully erosion is prevalent along the coastal hills in the northern San Mateo County portion of the littoral cell. Gully erosion tends to be confined to the alluvial and colluvial marine terrace deposits overlying the Purisma Formation. Using ground coverage, depth and width of gullies as well as material being eroded, it was determined that gully erosion adds an estimated 38,000 yd³/yr of sediment to the shoreline; however, 80-90% of this material is too fine to remain on the beaches (Best and Griggs, 1991b; Best and Griggs, 1991a). Using the littoral-cut-off diameter (0.18 mm), gully erosion in the northern portion of this cell provides a maximum of $\sim 7,600$ yd³/yr of sand to the budget (Best and Griggs, 1991b; Best and Griggs, 1991a). Overall, gully erosion represents 4% of the present-day sand supplied to the cell (Table 3.2).

Cliff Erosion: Quaternary aged marine terraces fronted by actively eroding, near vertical seacliffs ranging in height from 10- to 165-feet line ~ 63 miles of the 75-mile-long shoreline of the Santa Cruz littoral cell. These cliffs or bluffs are often capped with terrace deposits ranging from 5 to 40 feet in thickness (Best and Griggs, 1991b; Best and Griggs, 1991a; Hapke and Richmond, 2002). Santa Cruz Mudstone, the Pigeon Point Formation (consisting of well indurated silts, sands and grav-

el), and the Purisima Formation (consisting of mudstone, siltstone and very fine-grained sandstone) are exposed in the seacliffs in this littoral cell. Quaternary dunes, terrace deposits and alluvium cap the bluffs at Año Nuevo. Pocket beaches exist where coastal streams and creeks interrupt the cliffed coastline.

Reduction to the Sand Supply in the Santa Cruz Littoral Cell			
Inputs	Natural (cy/yr)	Actual (cy/yr)	Reduction (cy/yr)
Rivers	196,000	190,000	5,000 (3%)
Bluff Erosion	41,000	33,000	8,000 (20%)
Santa Cruz Littoral Cell Sand Budget Components			
Sand Source	Historic: Including Año Nuevo Sand Reserve	Present Day: Excluding Año Nuevo Sand Reserve	
Rivers	174,000 (66%)	174,000 (81%)	
Bluff Erosion	33,000 (12%)	33,000 (15%)	
Gully/Terrace Erosion	8,000 (3%)	8,000 (4%)	
Sand from Año Nuevo Reserve	50,000 (19%)	0 (0%)	
Total Littoral Input	265,000 (100%)	215,000 (100%)	

Table 3.2: Overall sand contributions and reductions to the Santa Cruz littoral cell. Reductions to river sand yields are reported in this table only for the San Lorenzo and Pajaro rivers and San Gregorio, Pescadero and Soquel creeks. In addition, these estimates are for sand coarser than 0.0625 mm or the sand/silt break point. The littoral cut-off diameter for this cell is 0.18 mm; thus the sand contribution to the sand budget in this cell from rivers is somewhat less than reported under the “actual” conditions in this table. “Natural” sand yield refers to the estimated original volume of sand discharged by streams and generated from seacliffs through erosion. “Actual” sand yield refers to the estimated volume of sand reaching the coast under present day conditions taking into account reductions in sand supply from dams and shoreline armoring. Sand contributions to the budget for the Santa Cruz littoral cell, and the subsequent percentages, are shown including the sand from the reserve at Año Nuevo (which is currently depleted) and when excluding it.

Seacliff erosion rates vary in this littoral cell from nearly undetectable along the resistant headlands and cliffs of the Pigeon Point Formation, to moderate in the Purisima Formation (0-8 in/yr), to high (up to ten feet per year) near Año Nuevo Point. The Santa Cruz Mudstone and the Purisima formation are fine-grained and contribute a negligible amount of littoral-sized sand (coarser than 0.18 mm) to the sand budget in this cell. Erosion of the coastal cliffs and bluffs from Tunitas Creek to Santa Cruz Harbor only contribute between 16,000 and 26,000 yd³/yr (an average of 21,000 yd³/yr will be used in this analysis) (Best and Griggs, 1991b; Best and Griggs, 1991a). South of Santa Cruz Harbor, erosion of the bluffs, which are also comprised of the Purisima Formation, contrib-

utes ~10,000 yd³/yr of sand sized material. An additional ~10,000 yd³/yr of littoral-sized sand is produced by the cliffs between Half Moon Bay and Tunitas Creek (Limber, 2005). In total, under natural conditions, seacliff erosion contributes an average of ~41,000 yd³/yr of sand to the Santa Cruz littoral Cell (Table 3.2).



Fig 3.9: Coastal armoring along West Cliff Drive, Santa Cruz Copyright © 2002 Kenneth & Gabrielle Adelman

Shoreline armoring protects 8 miles of seacliffs in the Santa Cruz Littoral Cell. The majority of the shoreline armoring is located in the developed portion of Santa Cruz County (Figure 3.9). Coastal armoring prevents an estimated 8,000 yd³/yr (20% reduction) of sand from entering the littoral cell through seacliff erosion. Thus, by taking shoreline armoring into account, seacliff erosion adds ~33,000 yd³/yr of sand to the Santa Cruz littoral cell, representing 15% of the sand in the present-day overall littoral budget (Table 3.2).

Dunes: Modern sand dunes are found at the mouths of Pescadero, San Gregorio, Waddell and Scott creeks. In addition, sand dunes overlie marine terrace deposits at Año Nuevo, Franklin Point, and Sand Hill Bluff. Best and Griggs (1991a) determined that there is minimal sand transferred today from the beaches in this cell to the dunes and vice versa at Franklin Point and Sand Hill Bluff due to the relatively small size of these dune fields. Thus, these dunes do not significantly impact the sand budget for the Santa Cruz littoral cell.

Once Año Nuevo Island was isolated from the mainland, sand that was previously retained behind the point, which was serving as a natural groin, was now free to flow south as littoral drift. An average of ~50,000 yd³/yr of sand was added to the budget of the Santa Cruz littoral cell from the reserves at Año Nuevo (Griggs et al., 2005; Seals, 2005). However, the 13 to 20 million cubic yards of sand that was estimated to have been retained by the point has now been exhausted. Beaches down-drift or south of Año Nuevo may start to narrow with a reduction in this sand source (Griggs et al., 2005; Seals,

2005). Historically, Año Nuevo sands accounted for 19% of the overall sand in the budget for the Santa Cruz littoral cell, reducing the importance of sand provided by river, seaciffs, and gulying (Table 3.2). Without the sand supplied by Año Nuevo, rivers now represent 81% of the sand budget with seaciffs and gully erosion providing the remaining 15% and 4% of sand respectively. More research needs to be done in this vicinity to determine the potential impact to the downcoast beaches resulting from the loss of this estimated 50,000 yds³ of sand annually from this former sand source.

Beach Nourishment: Harbor bypassing is the only regular form of beach nourishment practiced in the Santa Cruz littoral cell (Wiegel, 1994). As previously stated, bypassing at Santa Cruz Harbor has provided an average of ~160,000 to ~220,000 yd³/yr of sand to beaches down-drift or east of the harbor. In 1969, following the loss of Capitola beach as a result of sand trapping by the jetties at the Santa Cruz Small Craft Harbor, 27,000 yds³ were trucked in to rebuild the beach. There has been no other form of beach nourishment in this littoral cell.

SAND SINKS

Submarine Canyon: Monterey Submarine Canyon is the main sand sink effectively terminating the Santa Cruz littoral cell. The head of the canyon is located at Moss Landing (Figure 3.10), ~20 miles southeast of the Santa Cruz Small Craft Harbor. Three branches of the submarine canyon extend to within 300 feet of shore capturing littoral drift and terminating the littoral cell (Best and Griggs, 1991b; Best and Griggs, 1991a). It is estimated, through budget analysis, that ~265,000 yd³/yr of sand, on average, is lost into the Monterey Submarine Canyon from the Santa Cruz littoral cell.



Fig 3.10: Moss Landing Harbor. The head of Monterey Submarine Canyon reaches nearly to the harbor entrance. Copyright © 2002 Kenneth & Gabrielle Adelman

Offshore Transport: Movement of sand on- and offshore across the shelf is a potentially significant factor in the development of a sand budget for a littoral cell. Storage on the inner shelf is a difficult component to quantify

(Bowen and Inman, 1966). With such large shelf areas typically involved, a small increase in the thickness of the sand veneer can produce a large volume of sand storage. However, there have been no studies addressing this transfer or storage of littoral-sized sand (0.18 mm for the Santa Cruz littoral cell) for the offshore region of the Santa Cruz littoral cell. Due to the research required to evaluate this component, on- and offshore estimates were not attempted in this study. It is assumed that on- and offshore transport is in equilibrium resulting in a zero net gain or loss for this littoral cell. At depths greater than 80 ft, offshore sampling across the shelf revealed that nearly all of the sediment is finer than the littoral-cutoff diameter (0.18 mm) suggesting that there is not a significant transfer of material offshore (Best and Griggs, 1991a; Lee et al., 1970; Yancey et al., 1970). Recent multibeam bathymetry done by the USGS north of Santa Cruz confirms that there is significant movement of sand at depths of 10-20 meters along the inner shelf although not enough work has been done over time to indicate whether or not there is net transport, on or offshore (Curt Storlazzi, personal communication).

SUMMARY OF THE SAND BUDGET FOR THE SANTA CRUZ LITTORAL CELL

The sand budget for the Santa Cruz littoral cell is summarized in Figure 3.11 as a simple box-model and in Figure 3.12 as a running, alongshore, mile-by-mile budget. From Pillar Point to the Santa Cruz Small Craft Harbor, sand is presently supplied to the beaches by streams (~114,000 yd³/yr), gully and terrace degradation (~8,000 yd³/yr), cliff erosion (~23,000 yd³/yr), and formerly supplied by the distribution of sand retained in the sand at Point Año Nuevo (~50,000 yd³/yr). Sand supply in the northern reach of the cell totals ~195,000 yd³/yr.

The surplus of sand that existed on the Año Nuevo peninsula has now been depleted, and the beaches at Año Nuevo point have thinned drastically over the past 150 years (Griggs, Patsch and Savoy, 2005). Rough estimates indicate that as much as 12 to 18 million yds³ of additional sand-sized sediment was made available to littoral drift over the past 200 to 350 years. During that time the normal flow of littoral sand was apparently augmented by many tens of thousands of cubic yards of additional sand on an annual basis. This suggests that the downcoast beaches including the beaches of northern Monterey Bay widened as a result. The most interesting conclusion that can be inferred from the changes at Año Nuevo Point is that once the tail end of this point source of sand moved southward along the coast, the once-wide beaches may begin to slowly thin. This may lead to increased cliff and bluff retreat (Griggs, Patsch and Savoy, 2005). To date, however, there has been no reduction in the annual volumes of sand dredged from the Santa Cruz Harbor (Table 3.1). With all of the other fluctuations and perturbations in the source inputs and littoral transport rates, changes in sand supply on the

order of 50,000 yd³/yr may simply not be observable or recognizable.

The Santa Cruz Small Craft Harbor dredges ~200,000 yd³/yr of sand from its entrance channel which is placed on the downdrift, or eastern, beaches. This sand, in addition to the sand supplied through seacliff erosion (~10,000 yd³/yr) and from the Pajaro River (~60,500 yd³/yr) feeds the beaches in the southern reach of the cell. Littoral drift travels around the northern margin of Monterey Bay until it eventually reaches the head of the Monterey Submarine Canyon where it is funneled offshore and lost permanently to the littoral cell sand budget. It is estimated that ~265,000 yd³/yr of sand is lost into Monterey Submarine Canyon from the Santa Cruz littoral cell.

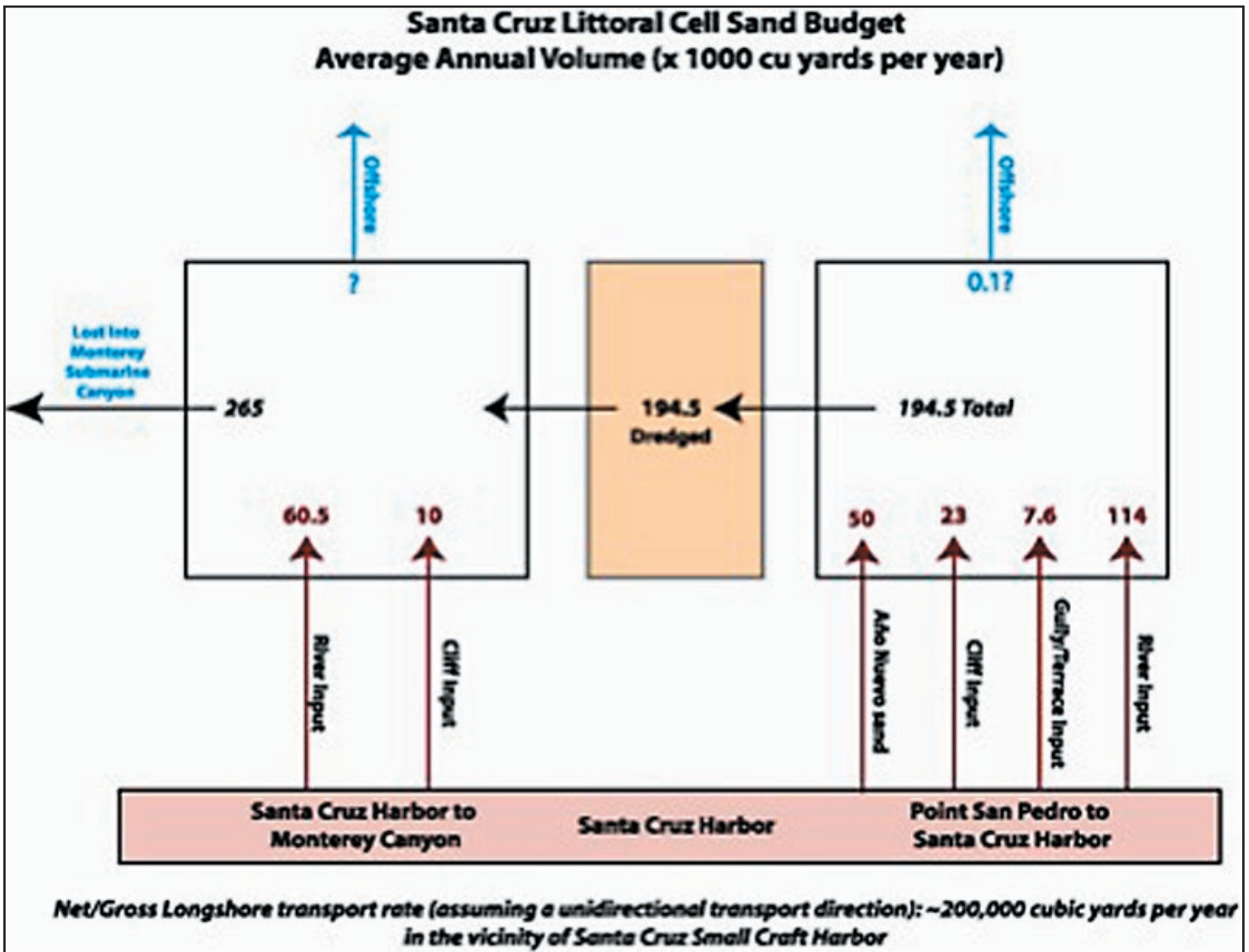


Fig 3.11: Box-model sand budget for the Santa Cruz littoral cell. The 50,000 yd³/yr of sand supplied by Año Nuevo is no longer being added to the littoral budget. Thus, the sand budget is not currently balanced, which may result in the narrowing of beaches downdrift of Año Nuevo.

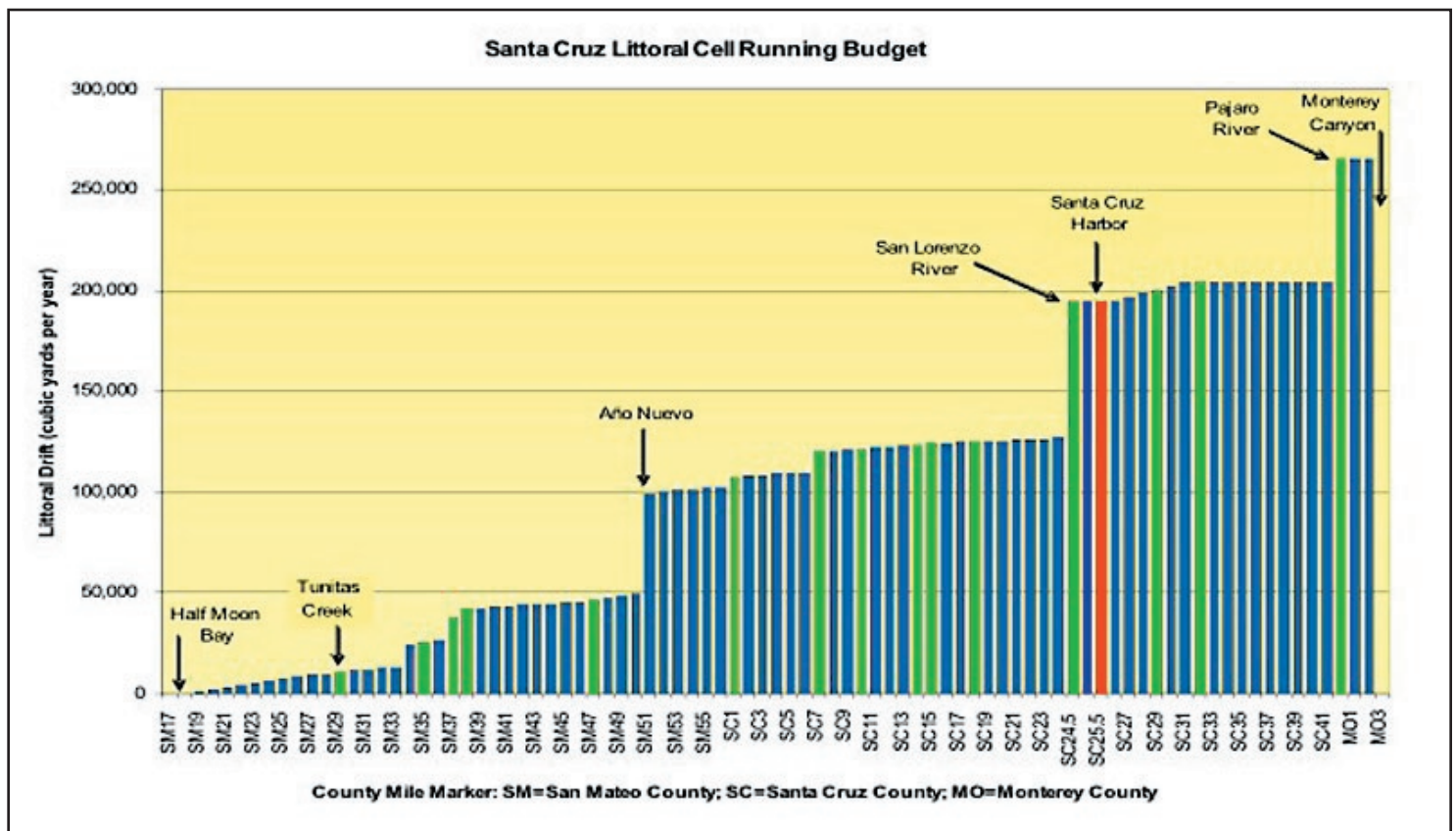


Fig 3.12: Running mile-by-mile sand budget for the Santa Cruz littoral cell. Stream inputs are shown in green. Santa Cruz Small Craft Harbor is shown in red and serves as a check point for the cell budget. Other inputs include cliff erosion both north and south of the harbor, gully degradation north of the harbor, and sand from Año Nuevo's sand reserve, which is now depleted resulting in a negative balance of the budget. If the budget is slightly negative, the beaches in the southeastern portion of the cell may narrow.

CHAPTER 4

SOUTHERN MONTEREY BAY LITTORAL CELL

The 20-mile stretch of coastline, from Moss Landing to the Monterey Peninsula, comprising the Southern Monterey Bay littoral cell (Figure 4.1), consists of wide, sandy beaches backed by broad coastal lowlands and extensive late-Pleistocene sand dunes rising to heights of 150 feet. Over the past several thousand years, the Salinas and Pajaro rivers delivered large volumes of sand to the shoreline along this stretch of coast. The large quantity of sand in combination with a dominant, on-shore wind and a broad, low-lying back beach allowed for the creation of the broad beaches and large dunes seen today (Figure 4.2) from Sunset Beach to Monterey (Griggs et al., 2005).

Southern Monterey Bay's beaches and dunes are in an erosive state meaning that more sand is removed than is being supplied. This is in part due to sea level rise but also to the large beach sand mining operations that were common in this area from the early 1900's until approximately 1990. Dune erosion, which occurs with the recession of the bluff-top edge of the dune, nourishes the beaches throughout the cell. In addition to the sand supplied to the beaches through dune erosion, sand is added to this littoral cell from the Salinas River located near the north end of the cell.

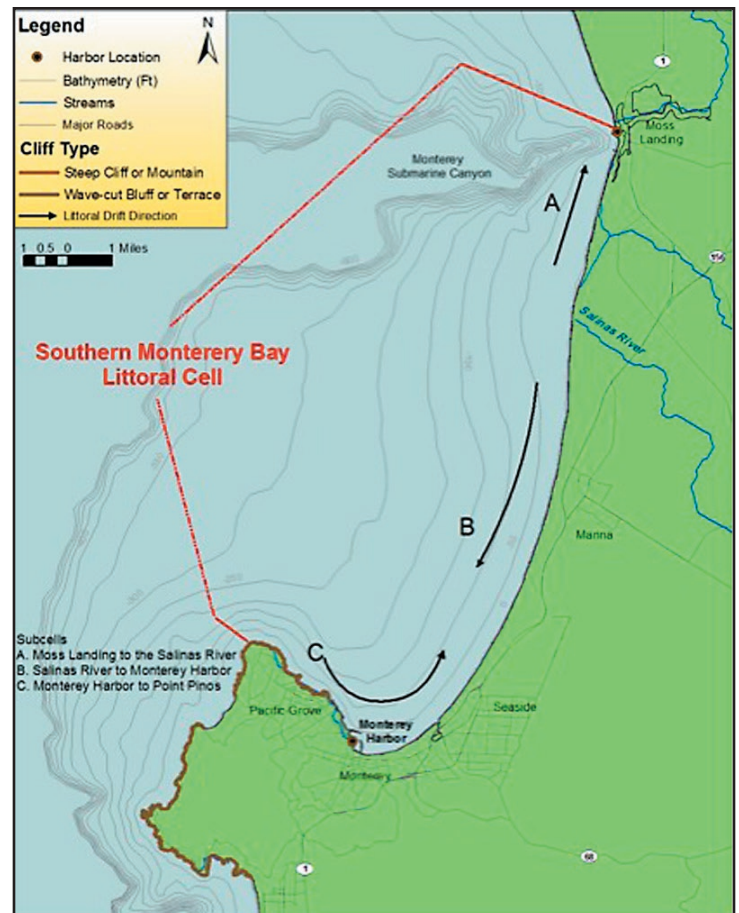


Fig 4.1: Southern Monterey Bay Littoral Cell Location Map



Fig 4.2: South end of the City of Marina. Copyright © 2004 Kenneth & Gabrielle Adelman.

LONGSHORE TRANSPORT

Three sub-cells have been identified within the larger Southern Monterey Bay littoral cell essentially delineated by differing littoral transport directions (Habel and Armstrong, 1978). Due to the refraction of waves as they travel over Monterey Submarine Canyon and the delta offshore of the Salinas River, littoral drift between the Salinas River and Moss Landing is dominantly to the north, creating the northern sub-cell (Figure 4.1) (Habel and Armstrong, 1978; Thornton et al., 2006). South of the Salinas River to Monterey Harbor (Figure 4.1) littoral drift is directed to the north and south (Habel and Armstrong, 1978; Thornton et al., 2006). Where the north and south longshore currents converge, rip currents develop and carry sand offshore. South of Monterey Harbor, waves are refracted around the large granitic promontory of Monterey Peninsula forming the southern sub-cell between Point Piños, the northernmost tip of the peninsula and Monterey Harbor (Figure 4.1) (Habel and Armstrong, 1978).

Since its construction, Monterey Harbor (Figures 4.1 and 4.3) has required no maintenance dredging in its entrance



Fig 4.3: Monterey Municipal Wharf and Marina, Monterey Copyright © 2004 Kenneth & Gabrielle Adelman.

channel. This is a good indication that this is the boundary of a sub-cell within the greater Southern Monterey Bay littoral cell such that no sand is traveling into the cell as littoral drift from the Monterey Peninsula. Evidence for the delineation of the third sub-cell, from Point Piños to the Monterey Harbor includes drastic differences in lithology, coastal orientation and beach mineralogy.

Beaches on the peninsula in the third sub-cell are formed of coarse-grained, angular, granitic materials, while sand on the beaches in the second sub-cell, from Monterey Harbor to the Salinas River are composed of fine-grained, rounded, quartz material derived from the erosion of the southern Monterey Bay dunes (Storlazzi and Field, 2005; Thornton et al., 2006).



Fig 4.4: Mouth of the Salinas River, 2004 Copyright © 2004 Kenneth & Gabrielle Adelman.

RIVER INPUT

Until 1910, the Salinas River, after flowing northwards parallel to the shoreline, discharged into Elkhorn Slough, a large estuary in the center of Monterey Bay, just landward of the head of Monterey Canyon. In 1910, the river broke through the narrow stretch of dunes separating the river from the ocean at approximately its current location (Figure 4.4). At that time, a dike was constructed to hold the channel in its present location and prevent the river from entering its former channel (Griggs et al., 2005). The bathymetric contours of the pre-historic submarine Salinas River delta radiate outward from the present mouth of the river (Figure 4.1), however, suggesting that the present mouth may have been the discharge point for an extended period of time in the Pleistocene.

In its undisturbed (pre-dammed) condition the Salinas River yielded $\sim 726,000 \text{ yd}^3/\text{yr}$ of sand (coarser than 0.0625mm); however, damming of the river has reduced the sand discharge by 33% to $\sim 489,000 \text{ yd}^3/\text{yr}$ (Willis and Griggs, 2003). These sand transport volumes are based on data from the closest gauging station to the mouth (at Spreckels), located 12 miles upstream from

the coast. It is believed that much of the sand may be deposited along the low gradient lower reach of the river with additional sand lost to the floodplain during over-bank flooding, such that these volumes may be too high. Yet these are the best actual data available and will be used in the budget. Currently, the Salinas River contributes 58% of the sand to the overall sand budget in the Southern Monterey Bay littoral cell (Table 4.1). Most of this sand is driven northward by the dominant littoral drift and is eventually carried into one of the active nearshore tributaries of Monterey Submarine Canyon. During major floods in the recent past, however, some Salinas River sand has been traced southward along the shoreline, using heavy mineralogy (Combellick and Osborne, 1977).

Southern Monterey Bay			
Inputs	Natural (cy/yr)	Actual (cy/yr)	Reduction (cy/yr)
Rivers	726,000 (57%)	489,000 (58%)	237,000 (33%)
Dune Erosion (1940-1984)	353,000 (33%)	353,000 (42%)	0 (0%)
Sand Mining (1940-1984)	Na (Na)	Na (Na)	180,000 (Na)
Total Littoral Input	1,079,000 (100%)	842,000 (78%)	417,000 (39%)

Table 4.1: Over-all sand contributions and reductions to the Southern Monterey Bay littoral cell. Reductions in the sand supply are due to the damming of the Salinas River and sand mining operations prevalent in this area from 1940 through the 1990's. "Natural" sand yield refers to the estimated original volume of sand discharged by streams and contributed to the littoral budget through dune erosion or recession. "Actual" sand yield refers to the estimated volume of sand reaching the coast under present day conditions taking into account reductions in sand supply.

SAND DUNES

Large sand dunes, reaching heights of up to 150 feet along the shoreline of the Southern Monterey Bay littoral cell, are geologically young (approximately 3,000 to 5,000 years old), but are now cut-off, for the most part, from their beach sand sources due to coastal erosion associated with sea level rise (Figure 4.2). These dunes were created during the Pleistocene from sand deposited along the exposed continental shelf by the Salinas and Pajaro rivers. Prevailing winds blew this surplus of sand onshore to create the massive sand dunes seen today (Thornton, et al, 2006).

Dune erosion is highly episodic, and occurs when large storm-generated waves coincide with high tides (Dingler and Reiss, 2002). This erosion is exacerbated during El Niño winters when storm waves intensify. Erosion of the dunes occurs more often in the winter months when storms are more powerful and frequent, and when the protective fronting beaches are narrower, thus leaving the dunes exposed and vulnerable to erosion. Dune ero-

sion occurs when wave swash or run-up undercuts the base of the dunes causing the overlying sand to slump onto the beach (McGee, 1987). This sand is washed out with the retreating waves where most of it becomes part of the littoral drift system.

Thornton et al (2006) determined long-term erosion rates for the dunes in this cell to be on the order of 1.6 ft/yr in the south end of the central sub-cell near Monterey, increasing to a maximum of 5 feet/yr around Seaside and subsequently decreasing northwards towards the Salinas River. Overall, from 1940-1984, dune erosion or recession has contributed ~353,000 yd³/yr of sand to the littoral cell, representing 42% of the overall sand budget (Thornton, et al, 2006; Table 4.1). This volume includes the El Niño winters of 1957-1958 and 1982-1983.

The large El Niño winter of 1997-1998 resulted in extensive erosion of the beaches and dunes at Fort Ord, Marina, Sand City and Monterey. Thornton et al. (2006) estimate that a total of ~3,392,000 yds³ of sand was eroded from the dunes and beach during this El Niño winter. Specifically, ~2,380,000 yds³ of sand eroded from the dunes (over 6 times the long-term annual average), and ~1,011,000 yds³ of sand eroded from the beaches in this cell. The majority of the eroded beach sand will be stored in offshore bars that form during the winter and return to the beaches with the summer swell. Some sand, however, is lost permanently from the system during these large storm events due to transport across the inner shelf.

SUBMARINE CANYONS

Monterey Submarine Canyon, one of the world's deepest and largest submarine canyons, is the main sink of sand for the Southern Monterey Bay littoral cell. Three branches of the submarine canyon extend to within 300 feet of shore, capturing littoral drift and terminating the littoral cell. Sand traveling south from the Santa Cruz cell to the north, and from the southern portion of Monterey Bay is carried down the canyon by turbidity currents and deposited miles offshore, effectively removing the sand from the littoral cells.

SAND MINING

The largest anthropogenic sink for sand in the Southern Monterey Bay littoral cell has historically been sand mining. Beach sand mining began in 1906 at the mouth of the Salinas River. By the 1950's, mining operation had expanded to six commercial sites at Marina and Sand City (Habel and Armstrong, 1978; Magoon, 1972). Beach-sand mining operated unregulated until 1968 when leases were issued and managed by the State Lands Commission. In 1974, the U.S. Army Corps of Engineers put additional regulations in place. Leases on all but one beach mining operations expired in the late 1980's. As of 1990, mining of the surf zone was discontinued.

However, one mining operation still exists on the beach at Marina (Figure 4.5) where sand is dredged from the back beach, and therefore, effectively removed from the littoral system. Sand mining from the back dunes was also common in this area and is still underway in Marina, however, dune sand mining does not directly impact the littoral sand budget, and thus, is not included in this report.



Fig 4.5: Back beach sand mining operation in Marina. Copyright © 2004 Kenneth & Gabrielle Adelman.

Between 1940 and 1984, Thornton et al (2006) estimate that on average $\sim 167,000 \text{ yd}^3/\text{yr}$ of sand were mined from the beaches of the cell, resulting in the permanent loss of this sand (Table 4.1). Data released recently by the Army Corps of Engineers on the sand mining history of southern Monterey Bay indicates a slightly higher figure of $180,000 \text{ yd}^3/\text{yr}$ removed during the 50-year period from 1940-1990.

SUMMARY OF THE SAND BUDGET

The Southern Monterey Bay littoral cell is a complicated network of sand sources, littoral transport, and sinks. Due to the lack of a uniform littoral transport direction in this cell, an alongshore, running, mile-by-mile sand budget was not appropriate. Three sub-cells exist within the larger framework of the Southern Monterey Bay cell: Monterey Submarine Canyon to the Salinas River, the Salinas River to Monterey Harbor, and Monterey Harbor to Point Piños, the northernmost tip of the granitic Monterey Peninsula (Figure 4.1).

In the first sub-cell, from the head of Monterey Submarine Canyon to the Salinas River, littoral drift is dominantly to the north. Sand entering the cell from the Salinas River travels upcoast, nourishing the beaches until it is lost into the Monterey Submarine Canyon. Currently, the Salinas River is believed to discharge $\sim 490,000 \text{ yd}^3/\text{yr}$ of sand-sized material (0.0625 mm or coarser) (Willis and Griggs, 2003; Willis et al., 2002). Dams have reduced the original sand yield for the Salinas River by 33%, or $\sim 237,000 \text{ yd}^3/\text{yr}$ (Willis and Griggs, 2003; Willis et al., 2002).

From the Salinas River to Monterey Harbor littoral drift travels both north and south due to the orientation of the coastline and the nearshore bathymetry. Lateral or longshore transport within this sub-cell has been shown to be minimal (Philip Williams & Associates, 2004) with rip currents likely the dominant transport mechanism and sink such that sand moves predominantly offshore instead of alongshore (Thornton et al., 2006). The only significant source of sand in this sub-cell is from the erosion of dunes, which contributes $\sim 353,000 \text{ yd}^3/\text{yr}$ of sand (Thornton et al., in 2006). Sand mining, operating from the early 1900's until 1990, was the main anthropogenic reduction to the sand supply within this sub-cell. From 1940-1990, $\sim 180,000 \text{ yd}^3/\text{yr}$ of sand was permanently removed from the sub-cell. All but one beach sand mining operation have been terminated, thus reducing the importance of this historic sink. As previously stated, the main sink for sand in this sub-cell is believed to be the transport of sand offshore by rip currents. Monterey Harbor has not required significant maintenance dredging in its entrance channel since its construction indicating that sand is not moving alongshore as littoral drift into this area from the north. Sand does move from the Monterey Peninsula eastward towards the harbor as evidenced by the rapid development of the beach west of the harbor since the breakwater was emplaced (Storlazzi and Field, 2000).

From Monterey Harbor to Point Piños, the northern tip of the Monterey Peninsula, beaches are backed by low, resistant granitic cliffs. Beaches in this sub-cell consist of 1) material eroded from the porphyritic granodiorite outcrops or deposited by streams and then carried eastward by waves and currents, and 2) relict sediments originally from the Salinas River to the north that have been transported onshore by northwesterly waves or wind during sea level low stands. Volumetric estimates of sand emanating from seacliff erosion were not made for this sub-cell.

CHAPTER 5

SANTA BARBARA LITTORAL CELL SAND BUDGET

The Santa Barbara littoral cell (Figure 5.1) is the longest littoral cell in southern California, extending 144 miles from the mouth of the Santa Maria River, around Point Conception, and terminating at Point Mugu into the Mugu Submarine Canyon (Patsch, 2004). At Point Conception, the California coastline makes an abrupt 90-degree shift from a north/south orientation to an east/west orientation. It has been concluded by many researchers (Azmon, 1960; Bowen and Inman, 1966; Judge, 1970; Trask, 1952) that Point Conception is only a partial barrier to littoral drift; sand moves around this promontory. From Point Conception to Santa Barbara Harbor, the shoreline generally consists of thin (less than 10 feet thick), narrow beaches backed by vertical cliffs or bluffs (Wiegel, 1994). Significant beach erosion has threatened development in the communities of Isla Vista and Goleta.

SANTA BARBARA LITTORAL CELL BOUNDARIES

Originally, Habel and Armstrong (1978) delineated the northern boundary of the Santa Barbara littoral cell at Point Arguello (south of the Santa Ynez River mouth); however, Patsch (2004) concluded that the boundary needed to be extended to include the Santa Maria River mouth. The large dune fields north of the Santa Maria River mouth suggest that most of the upcoast littoral sand is lost to inland sources at this location. In order to explain the average volume of sand dredged from Santa Barbara Harbor annually ($\sim 314,000 \text{ yd}^3/\text{yr}$), assuming a unidirectional southeastward littoral drift in this reach of coast, sand contributions from the Santa Maria and Santa Ynez rivers and San Antonio Creek must be included. The small, ephemeral, Santa Ynez mountain streams, east of Point Conception, which are the only significant sources of sand to this stretch of shoreline, do not provide enough sand annually ($\sim 195,000 \text{ yd}^3/\text{yr}$) to explain the volume of sand dredged from Santa Barbara Harbor. This sand deficiency as well as a number of historic studies that have argued for a more northerly boundary for the Santa Barbara cell that will be discussed below led us to use the mouth of the Santa Maria River as the upcoast boundary of the cell.

LITTORAL DRIFT

There are four harbors within this littoral cell (Santa Barbara, Ventura, Channel Islands and Port Hueneme harbors), which serve as constraints, or check points, for littoral drift rates when constructing a sand budget. Because these harbors essentially serve as nearly complete traps for littoral transport, the yearly dredging numbers from the harbors are believed to provide a reasonable proxy for annual littoral drift rates. Because

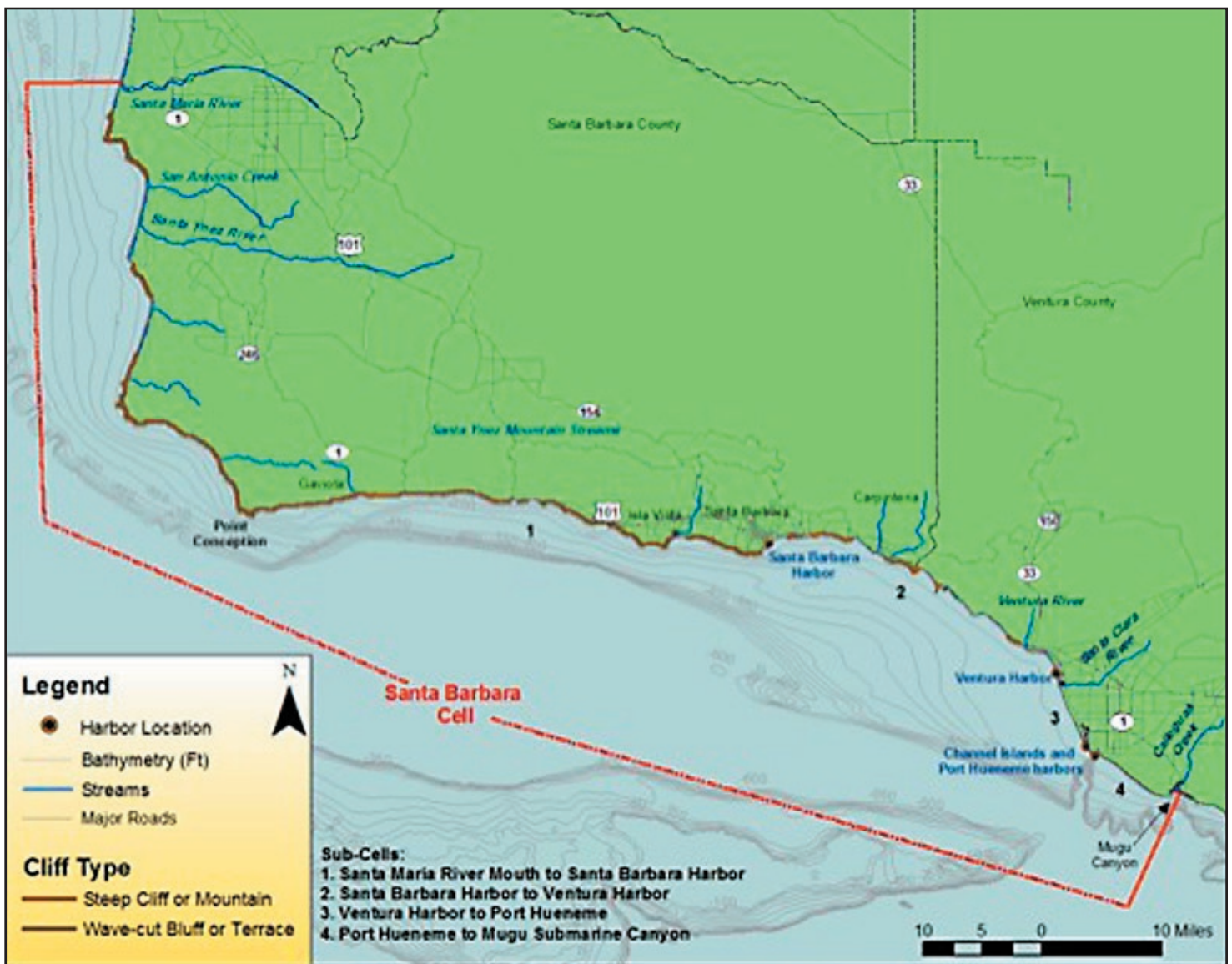


Fig 5.1: Location map for the Santa Barbara Littoral Cell

of the coastal orientation and essentially unidirectional trend of littoral drift in the southeastward direction, these drift rates are considered to represent both the net and gross transport rates. This cell is divided into four sections, with each harbor acting as a terminus: (1) Santa Maria River to Santa Barbara Harbor, (2) Santa Barbara Harbor to Ventura Harbor, (3) Ventura Harbor to Channel Islands Harbor/Hueneme Submarine Canyon, and (4) Hueneme Submarine Canyon to Mugu Submarine Canyon (Figure 5.1).

SAND SOURCES

Fluvial Inputs: The Santa Barbara littoral cell has four main rivers (Santa Maria, Santa Ynez, Ventura, and Santa Clara rivers) and a number of smaller streams (San Antonio Creek, Santa Ynez mountain streams, and Calleguas Creek (Figure 5.1), which together, currently contribute 99.5% (or an average of $\sim 2,167,000 \text{ yd}^3/\text{yr}$) of sand to this littoral cell (Willis and Griggs, 2003; Willis et al., 2002). Before dam construction these rivers contributed $\sim 3,643,000 \text{ yd}^3/\text{yr}$ of sand to the cell (Table

5.1). Thus, dams have reduced the sand yield of these rivers by 40% or $\sim 1,476,000 \text{ yd}^3/\text{yr}$ (Willis and Griggs, 2003; Willis et al., 2002).

SEACLIFF/BLUFF EROSION

The seacliffs or bluffs in the Santa Barbara littoral cell are 10- to 100-feet high and are cut into uplifted marine terraces. The seacliffs expose a basal bedrock unit (either the Monterey Shale, which is a Miocene marine diatomaceous shale, or the Sisquoc Formation, a diatomaceous silty shale) and an overlying sequence of unlithified marine terrace deposits and soils, ranging in thickness from 5- to 50- feet. By sampling the Monterey and Sisquoc formations it was found that no beach-size material (0.125 mm or coarser in this cell) resulted from the breakdown and analysis of bedrock samples. Thus, the bedrock material exposed in the cliffs is not a significant contributor to the sand budget in this cell (Patsch, 2004; Runyan, 2001; Runyan and Griggs, 2003; Runyan and Griggs, 2002). Terrace deposit samples were also analyzed and found to contain an average of 60% littoral or beach-size sand (coarser than 0.125 mm).

Erosion rates for the seacliffs in the Santa Barbara cell are not well documented. In *Living with the Changing California Coast* (Griggs, Patsch and Savoy, 2005), fifteen erosion rates throughout the length of the cell were reported. These rates range from 3-inches to 20-inches per year, overall a relatively narrow range. Based on these erosion rates and the littoral sand content of the cliffs, the overall “natural” sand contribution from seacliff erosion for the entire Santa Barbara Littoral Cell is estimated to be ~14,000 cubic yards per year (Table 5.1) (Patsch, 2004; Runyan, 2001; Runyan and Griggs, 2003; Runyan and Griggs, 2002).

Seacliff failures have been devastating to many cliff-top developments in the Santa Barbara Cell. Seawalls, revetments or other armoring, including breakwaters, now protect 33 miles of the coastline in the Santa Barbara cell. Only 11 miles of this armoring is protecting seacliffs, however; the remaining armor is protecting back-beach development and harbors and is not impacting the natural sand supply to the coast from cliff erosion. The shore-parallel armor is estimated to be preventing approximately 3,000 cubic yards per year of sand from ending up on the beaches of the cell (Table 5.1). This represents almost 20% of the original or “natural” contribution to the littoral budget from seacliff erosion, although still a very small amount of sand (Patsch, 2004; Runyan, 2001; Runyan and Griggs, 2003; Runyan and Griggs, 2002).

Santa Barbara Littoral Cell			
Inputs	Natural (cy/yr)	Actual (cy/yr)	Reduction (cy/yr)
Rivers	3,643,000 (99.6%)	2,167,000 (99.5%)	1,476,000 (40.5%)
Bluff/Cliff Erosion	14,000 (0.4%)	11,000 (0.5%)	3,000 (19.4%)
Total Littoral Input	3,657,000 (100%)	2,178,000 (100%)	1,479,000 (40.4%)

Table 5.1: Overall sand contributions and reductions to the Santa Barbara littoral cell. Reductions are due to the damming of rivers and the armoring of seacliffs. “Natural” sand yield refers to the estimated original volume of sand discharged by streams and contributed to the littoral budget through seacliff or bluff erosion. “Actual” sand yield refers to the estimated volume of sand reaching the coast under present day conditions taking into account reductions in sand supply from dams and seacliff armoring as well as additions to the budget from beach nourishment.

Total natural input from seacliff erosion was ~14,000 cubic yards per year, which has been reduced to ~11,000 cubic yards annually due to construction of coastal armoring structures (Table 5.1). Thus, littoral sand inputs to the Santa Barbara cell at present total 2,178,000 cubic yards per year, of which stream input contributes 99.5% with seacliff erosion contributing the remaining 0.5% (Table 4.1). Prior to armoring, the cliffs

contributed 0.4% of the entire sand supply to the cell. Cliff armoring has reduced the total sand input from seacliff erosion to the Santa Barbara cell by 3,000 cubic yards annually, or 0.1% of the total budget; however due to the increase in sand blocked by dams, the importance of seacliff erosion to the littoral budget is slightly increased.

BEACH NOURISHMENT

Harbor bypassing has been a significant form of beach nourishment in this sub-cell, and will be discussed in the subsequent sections. Bypassing does not introduce “new” sand to the system; thus, it is not considered a sand source with respect to the sand budget.

SAND SINKS

Submarine Canyons: Like most littoral cells in southern California, the major sinks for the Santa Barbara littoral cell are submarine canyons. Hueneme Submarine Canyon, located at the entrance to Port Hueneme, and Mugu Submarine Canyon both act as sand sinks. Before sand reaches Hueneme Canyon however, it is trapped in Channel Islands Harbor where it is dredged every other year (Table 5.2). The majority of this sand is placed downcoast of Port Hueneme, thus bypassing Hueneme Canyon. Dredged sand deposited downcoast of Hueneme Harbor travels as littoral drift until it eventually is intercepted and funneled into Mugu Submarine Canyon where it is permanently lost to the littoral cell. Mugu Canyon is a nearly complete littoral barrier and terminates the Santa Barbara littoral cell.

DUNES

Dune fields can be a source and sink of sand for a littoral cell sand budget. Where applicable, sand lost or gained from dunes will be discussed in the appropriate section, or sub-cell. Overall, losses to dunes remove ~100,000 yd³/yr of sand from this littoral cell (Bowen and Inman, 1966).

SAND BUDGET FOR THE SANTA BARBARA LITTORAL CELL

Santa Maria River to Santa Barbara Harbor: Willis et al. (2002), using stream flow, sediment discharge and reservoir filling data, calculated the input of sand-sized material from the Santa Maria River, San Antonio Creek, Santa Ynez River, and also the streams draining the Santa Ynez Mountains between Point Conception and Santa Barbara. These streams provide approximately 260,000, 60,000, 345,000, and 195,000 yds³/yr respectively, on average, for at a total of ~860,000 yds³/yr from fluvial sources along this coastal segment (Willis and Griggs, 2003; Willis et al., 2002).

As discussed previously Runyan and Griggs (2003; 2002) determined that seacliff erosion from this stretch of coast presently contributes ~11,000 yds³/yr of beach size material.

Bowen and Inman (1966) developed a sand budget along California's coast from just north of the Santa Maria River to Santa Barbara. Although the values for the river and seacliff erosion contributions have been updated, their estimates for sand lost to the dune systems between the Santa Maria River mouth and Point Arguello are still the best available data. Utilizing migration rates of sand dunes and their cross-sectional areas, Bowen and Inman (1966) estimated that $\sim 100,000 \text{ yds}^3/\text{yr}$ of sand are lost from this littoral cell due to wind transport onshore with storage in dune complexes.

A 1,425-foot long shore-parallel breakwater was completed in 1929 to establish Santa Barbara's small craft harbor (Figures 5.2 and 5.3). Originally, a 600-ft gap was left between the breakwater and the coastline to allow sand to move along the shore from the west, bypass the harbor, and maintain the beach on the downdrift side of the harbor. The plan, however, did not work as anticipated. Because of the wave shadow created behind the breakwater, sand began to fill in the harbor and became a navigational hazard. In order to remedy this situation, the breakwater was extended, on its westward side, to the shore in 1930.

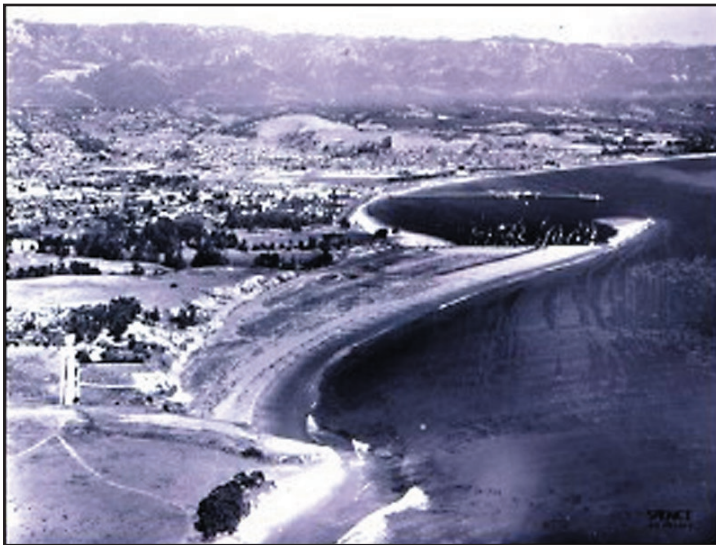


Fig 5.2: Santa Barbara Harbor: 1930's

The extension of the breakwater came with its own suite of problems, however. Sand began to accumulate on the upcoast side of the breakwater, pushing the shoreline seaward along the breakwater. The trapping of littoral drift on the western side of the breakwater essentially starved the beaches of sand on the downdrift side of the harbor. Sand also began to travel around the end of the breakwater and form a spit extending towards the shore (Figure 5.3); this soon became a navigational hazard. Consequently, in 1933, a sand-bypass system was developed that required sand to be dredged from the entrance channel of the harbor and used to nourish the downdrift beaches. Originally, the harbor was dredged every few years, however, in 1959, dredging became an annual procedure (Table 5.2). Santa Barbara

Harbor's sand bypass/beach nourishment system has been operating for 72 years, and has set the precedent for all other sand bypass operations in California (Wiegel, 1965).



Fig 5.3: Santa Barbara breakwater and sand spit, 1989

Santa Barbara Harbor has dredged an average of $\sim 314,000$ cubic yards per year (1933-2004) of sand from its entrance channel and placed it on the downdrift beaches (Chang, 2001; 2005; Chang and Evans, 1992; Griggs, 1987b; Noble Consultants, 1989; Wiegel, 1994). The configuration of the breakwater and associated sand spit (Figure 5.3), and the distance between the beach and the sand spit make littoral drift reversal and transport back to the dredging area very unlikely. It can be assumed then, that the average net longshore transport for this stretch of coast is $\sim 314,000$ cubic yards per year, equivalent to the average annual dredging volume.

Table 5.2 (Found on the following page): Dredging history for harbors in the Santa Barbara Littoral Cell (Chang, 2001; 2005; Chang and Evans, 1992; Griggs, 1987b; Wiegel, 1994)

In order to balance the sand sources ($+870,000 \text{ yd}^3/\text{yr}$) and sinks ($-100,000 \text{ yd}^3/\text{yr}$) within this sub-cell (totaling $\sim 770,000 \text{ yd}^3/\text{yr}$) with the known average annual rate of dredging in the Santa Barbara Harbor ($\sim 300,000 \text{ yd}^3/\text{yr}$), $\sim 470,000$ cubic yards of sand has to be lost from the system in one form or another from the reach of coast between the Santa Maria River mouth and the Santa Barbara Harbor (Figures 5.4 and 5.5). The $870,000 \text{ yd}^3/\text{yr}$ includes $\sim 665,000 \text{ yd}^3/\text{yr}$ of sand from the rivers and streams north of Point Conception (reduced by losses to the dunes of $100,000 \text{ yd}^3/\text{yr}$) and an additional $\sim 200,000 \text{ yd}^3/\text{yr}$ from the streams draining the Santa Ynez Mountains southeast of Point Conception as well as inputs from cliff erosion. It appears that a little over $100,000 \text{ yd}^3/\text{yr}$ of sand must be moving around Point Conception. Bowen and Inman in their classic 1966 littoral sediment budget for the Santa Barbara littoral cell also estimated that approximately $100,000 \text{ yd}^3/\text{yr}$ of sand enters the cell by longshore transport around Point Conception.

While a minor amount of sand discharged by the Santa

Year	Santa Barbara (cy/yr)	Ventura Harbor (cy/yr)	Channel Islands (cy/yr)	Port Hueneme (cy/yr)
1933	606,400			
1935	202,000			
1938	584,700			
1940	697,700			
1942	600,100			
1945	717,800			
1947	643,000			
1949	838,200			
1952	1,174,000			
1954	1,070,000			
1959	85,100			
1960	522,300		5,335,450	
1961	321,200		0	
1962	269,100		0	
1963	462,900		2,000,000	
1964	368,830	191,000	0	
1965	311,200	180,000	3,526,668	
1966	387,610	143,000	0	
1967	355,285	239,000	0	
1968	385,140	257,000	1,620,000	
1969	274,190	1,883,000	2,824,000	
1970	484,700	325,000	0	
1971	242,820	1,113,000	2,407,000	
1972	401,240	17,000	0	
1973	365,000	1,193,820	2,500,000	
1974	383,300	420,000	0	
1975	46,600	160,000	1,809,523	
1976	395,460	152,000	0	
1977	465,800	911,000	2,370,000	
1978	618,400	496,000	0	
1979	214,800	1,021,500	1,980,244	
1980	310,000	320,000	0	
1981	183,079	812,900	1,522,699	
1982	367,800	1,186,000	0	
1983	405,000	1,427,000	1,260,553	281,718
1984	222,595	1,332,900	0	0
1985	207,466	0	1,850,000	0
1986	292,183	910,000	0	0
1987	223,480	363,100	1,993,956	32,608
1988	112,175	800,000	0	0
1989	134,600	230,314	1,720,000	0
1990	90,281	217,913	0	0
1991	287,781	377,183	1,429,157	199,504
1992	240,500	524,702	0	0
1993	548,823	486,478	1,100,000	0
1994	345,269	470,000	0	0
1995	615,540	271,357	876,666	0
1996	442,347	833,000	0	0
1997	446,819	449,128	1,309,000	0
1998	591,030	741,975	1,638,018	0
1999	376,930	639,173	1,117,406	68,333
2000	376,490	818,477	0	0
2001	261,556	624,931	1,222,934	0
2002	336,375	669,749	0	0
2003	418,088	669,566	2,050,116	0
2004	306,279	578,357	0	0
Average	314,408	596,501	1,010,298	26,462

Maria River may travel upcoast, or northward along the shore, and eventually be lost to the dune complex in the southern region of San Luis Obispo (Everts, 2002), this northward traveling littoral drift is considered to be an insignificant component to the long-term annual sand budget, which has a net southerly littoral drift direction. In addition, sand loads reported for the rivers in this sub-cell may not in fact reach the ocean. There may be losses to the alluvial lowlands or flood plains between the gauging stations and the river mouths; as a result, the calculated river input into the littoral system may be too high. Without a way to quantify the volume of sand lost to the alluvial lowlands and flood plains, which is assumed to be minor, and due to the shoreline configuration and the dominant wave approach from the northwest, we believe a large volume of sand is being lost offshore as it moves around Point Conception (Figures 5.4 and 5.5).

As discussed previously, it has been concluded by many researchers (Azmon, 1960; Bowen and Inman, 1966; Judge, 1970; Trask, 1952) that Point Conception is only a partial barrier to littoral drift. In addition, an offshore geology map developed for the California Division of Mines and Geology (Greene and Kennedy, 1986a,b, 1987a,b, 1989, 1990) using side scan sonar, depicts a large sand deposit ~4.5 miles long and ~1.5 miles wide located ~0.5 miles offshore of Point Conception. If ~470,000 yd³/yr of sand were lost to this offshore sand bar the accumulation rate (0.07 feet/yr) would result in the sand bar growing in height by ~7 feet over a 100 year period. This is a reasonable scenario, and supports the permanent loss to the littoral budget of a significant amount of sand traveling as littoral drift around Point Conception.

Because of the significance of this probable offshore transport and storage of such a huge volume of beach sand relatively close to shore, in a littoral cell with significant beach sand deficiencies and cliff erosion problems, we strongly recommend that the area offshore from Point Conception be the focus of a detailed multi-beam bathymetric study to evaluate the distribution of sea floor sand deposits.

SANTA BARBARA HARBOR TO VENTURA HARBOR

The section of coast from Santa Barbara Harbor to Ventura Harbor does not have many sand sources or sinks. There is only one river contributing sand to this sub-cell, and armored seacliffs back approximately four miles of this shoreline. Sand bypassed from the Santa Barbara harbor introduces an average of ~300,000 yd³/yr of sand to this reach. This combined with the reported ~100,000 yd³/yr of sand presently contributed by the Ventura River (Willis et al., 2002), and the negligible amount of sand resulting from seacliff erosion (Runyan and Griggs, 2003), results in total littoral drift of ~400,000 yd³/yr of sand (Figures 5.4 and 5.5).

The next check-point, Ventura Harbor (Figure 5.6), dredges an average of ~600,000 yd³/yr (Table 5.2). One factor not yet accounted for, and shown to be an important component to this sub-cell, is long-term beach erosion. Using beach profile comparisons, Noble Consultants (1989) found that the beaches between the Ventura River and the Ventura Harbor have been eroding at a rate equal to approximately 200,000 cubic yards per year. This brings the total longshore transport to ~600,000 cubic yards per year. This balances the average volume of sand, 600,000 cubic yards per year, dredged annually from Ventura Harbor (Table 5.2) (Chang, 2001; 2005; Chang and Evans, 1992; Griggs, 1987b; Wiegel, 1994). Due to the entrance channel configuration at this harbor, the lack of sand accumulation against the downcoast jetty, and the wave protection offered by the Channel Islands, it is probable that for this harbor, net transport is synonymous with gross transport.

It does not appear that a significant amount of sand is moving upcoast and back into Ventura Harbor; although a small groin was built on the downdrift end of this harbor to prevent sand moving upcoast into the harbor entrance (Figure 5.6).

Ventura Harbor, constructed in 1964, is located on an alluvial plain between the Ventura and the Santa Clara rivers (Figure 5.1). Currently, there are seven groins updrift from the harbor entrance, two jetties fixing the entrance to Ventura Harbor, and a detached breakwater, added in 1972, offset and updrift from the harbor entrance. Sand removed when excavating Ventura Harbor was placed between the groins updrift from the harbor (Wiegel, 1994). Similar to Santa Barbara Harbor, upon completion of the Ventura Harbor, sand began to accumulate updrift of the west jetty, and beaches began to erode on the downdrift side. Consequently, the offshore breakwater was built, and a system of dredging in the lee of the breakwater along with sand bypassing was initiated to nourish the downcoast beaches affected by the harbor. Sand is typically discharged onto beaches south of the harbor; however, in the past, dredged material has been placed updrift of the harbor within the groin field (Wiegel, 1994). In recent years however, the cost of re-dredging this sand from Ventura Harbor has eliminated the placement of dredged sand up-drift of the harbor in the groin field.

This rate of littoral drift (~600,000 yd³/yr) at the Ventura Harbor is consistent with that estimated by Noble Consultants (1989) of ~640,000 yd³/yr. However, in their analysis, this value includes ~100,000 cubic yards per year of reverse transport emanating from beaches south of Ventura Harbor. Thus, Noble Consultants report a net drift of ~540,000 cubic yards per year, and a gross drift of ~640,000 cubic yards per year. In the present study, the budget appears to be balanced with net and gross drift rates of ~600,000 cubic yards per year to the south.

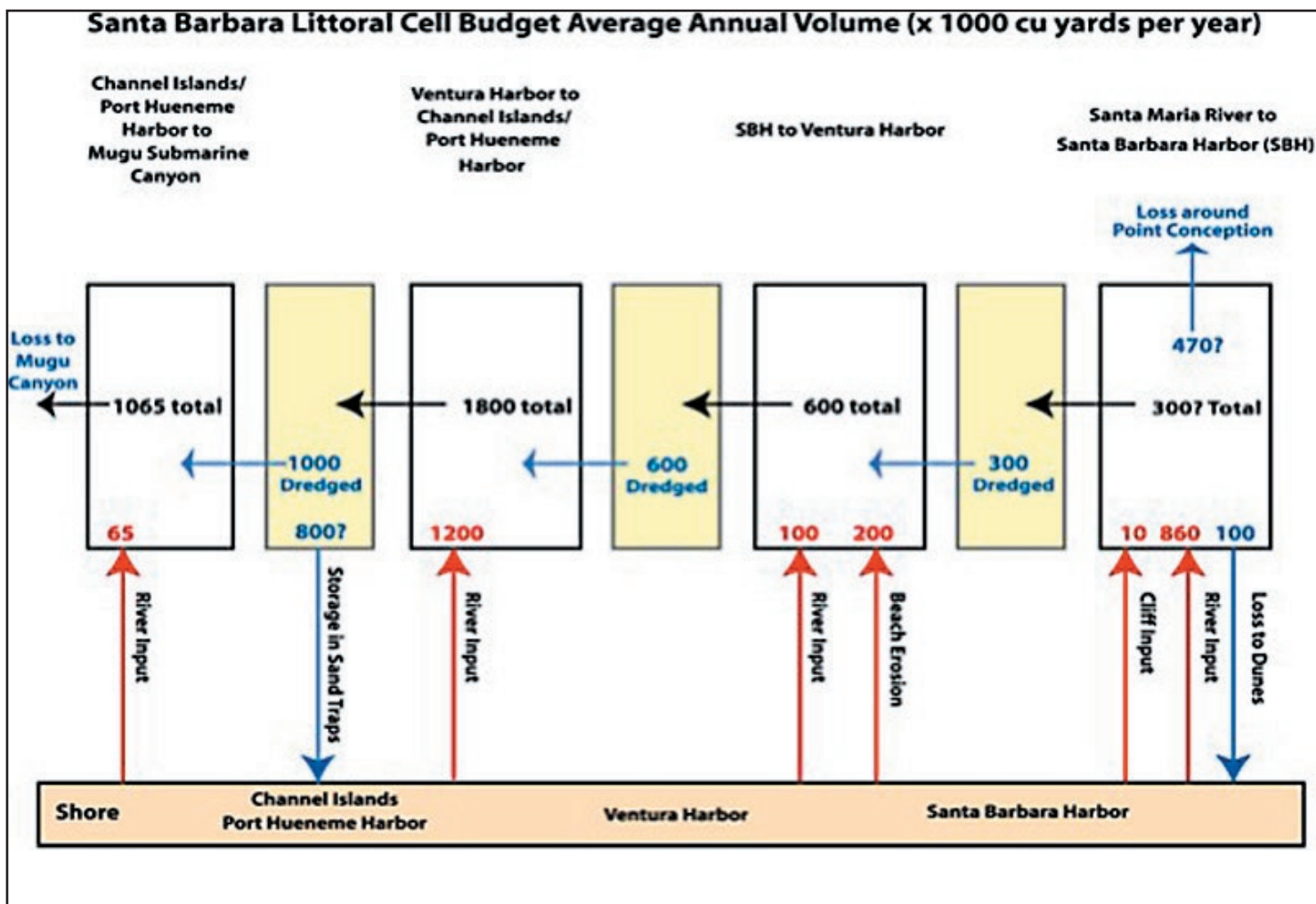


Fig 5.4: Sand Budget for the Santa Barbara Littoral Cell

Santa Barbara Littoral Cell: Running Budget

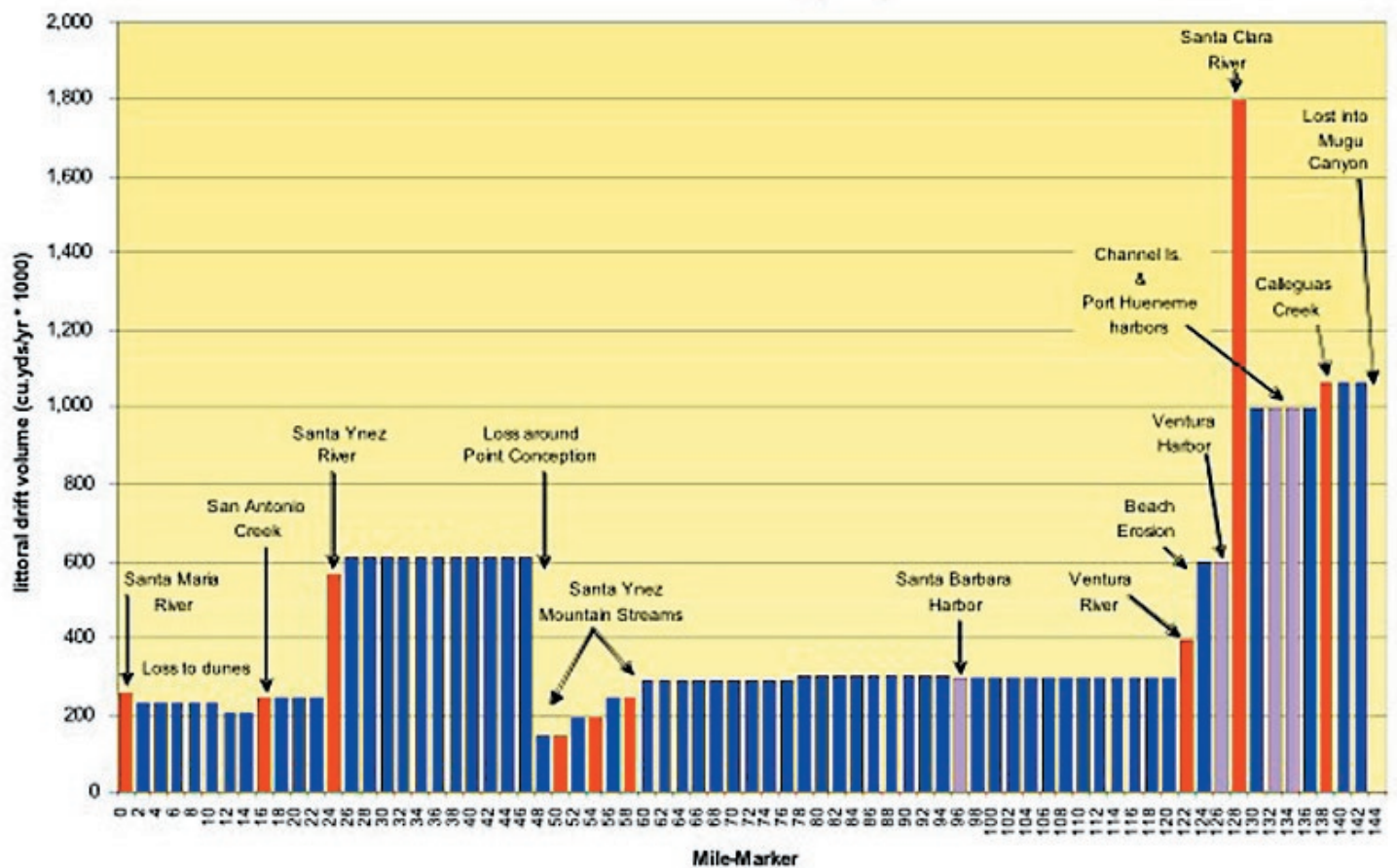


Fig 5.5: Santa Barbara Littoral Cell alongshore, mile-by-mile running sand budget



Fig 5.6: Ventura Harbor: maintenance dredging in 1997

VENTURA HARBOR TO CHANNEL ISLANDS/HUENEME SUBMARINE CANYON

The stretch of coast between Ventura Harbor and Channel Islands Harbor (Figures 5.4 and 5.5) has only one additional source of sand, the Santa Clara River, added to the sand bypassed from the Ventura Harbor traveling along the coast as littoral drift. As previously discussed, approximately 600,000 cubic yards per year of sand is dredged from Ventura Harbor and discharged onto the downdrift beaches. This volume added to the $\sim 1,200,000$ cubic yards per year of sand transported by the Santa Clara River (Willis et al., 2002) totals $\sim 1,800,000$ cubic yards per year, on average.

Today, Channel Islands and Port Hueneme harbors (Figures 5.7, 5.8 and 5.9) act as a unified sand bypass operation with Silver Strand Beach in between. Port Hueneme Harbor was built in 1940, 20 years before Channel Islands Harbor, as a deep-draft commercial and Navy port. The two jetties stabilizing the entrance to Port Hueneme extend almost to the head of Hueneme Submarine Canyon, which reaches inshore to within 1,000 ft of the beach. Initially, sand moving along the coast as littoral drift was funneled into Hueneme submarine canyon from the updrift entrance jetty, resulting in the calculated loss of ~ 1.2 million yd^3/yr from the littoral system (Herron et al., 1966). This loss of sand had serious implication to the downdrift beaches.

In an attempt to mitigate the downdrift erosion and to provide additional recreational boat anchorage, Channel Islands Harbor was built in 1960 one-mile updrift from Port Hueneme (Figures 5.7 and 5.8). Sand is dredged from Channel Islands Harbor, pumped under the entrance to Port Hueneme, and is ultimately discharged onto the downdrift beaches. Since its construction, Channel Islands Harbor has been dredged once every two years; with an average dredge volume of $\sim 1,000,000$ cubic yards per year. Because Channel Islands Harbor was built primarily as a sand trap to impound and store sand before it was lost into Hueneme Canyon, the amount of annual dredging of this harbor is based on congressional

appropriations. Essentially, the amount of sand dredged from the sand trap at Channel Islands harbor is determined by the amount of money left over after the rest of the federally controlled harbors have been dredged to the appropriate navigational depth (typically between 30 and 40 ft). With $\sim 1,800,000$ cubic yards per year of sand supplied to this sub-cell and only $\sim 1,000,000$ cubic yards per year dredged from Channel Islands Harbor, there appears to be a surplus of sand on the order of $\sim 800,000$ cubic yards per year. Again it should be noted that Channel Islands Harbor is not dredged to a consistent depth; thus the average annual dredging volume is only an indicator of the minimum amount of littoral drift moving along this stretch of shoreline. Some of the surplus of sand that appears to exist may be stored in the sand trap at this harbor until there is enough money to dredge it.

The shoreline between the Santa Clara River and the Channel Islands Harbor (including present day Mandalay Beach, Hollywood Beach and the oceanfront residential development at Oxnard Shores) moved seaward from the earliest surveys in the 1850s until the late 1950's and then began to retreat (Inman, 1976). Historical records show that this area was nourished by sand from large floods on the Santa Clara River, and had greater sediment input than waves could remove. This area underwent retreat between 1969 and 1973, however, perhaps a delayed response to diminished littoral drift during the relatively dry years between 1938 and 1969 floods, aggravated by dam construction on the Ventura and Santa Clara rivers (Griggs, Patsch and Savoy, 2005). This may have also reflected changing near-shore bathymetry and wave refraction patterns resulting from the sediments discharged by the large 1969 floods. In the 1990's, however, sand surpluses led to widespread coastal accretion, which encouraged construction of more coastal homes. The calculated excess sand in the budget of the cell at this location may have gone into beach widening over the past 10 or 15 years.

Another possible explanation for this surplus of sand is an overestimation of the volume of sand emanating from the Santa Clara River. Brownlie and Taylor (1981) estimated a sand discharge for this river of $\sim 720,000$ yd^3/yr , and Inman earlier (1976) reported a sand volume of $\sim 493,000$ yd^3/yr . These two estimates however, did not include the recent El Niño/Southern Oscillation-induced climate cycle, which extended from 1978 until the present. The wet, El Niño period has been shown by Inman and Jenkins (1999) to result in a mean annual suspended sediment flux five times greater than the dry, La Niña climate cycle in the 20 largest streams entering the Pacific Ocean along the central and southern California coast. Willis (2003) used twenty years of additional river discharge data up to the 2001 water year, which is why his estimate of ~ 1.2 million yd^3 of sand annually is greater than previous estimates.



Fig 5.7: Channel Islands and Port Hueneme harbors



Fig 5.8: Channel Islands Harbor dredging, 1979

Similar to the rivers in the first sub-cell, it is possible that all of the sand delivered from this river is not actually reaching the ocean; it may be stored in the alluvial lowlands and delta. However, the gauging station used by Willis (2003) and Brownlie and Taylor (1981) to calculate sand delivery on the Santa Clara is located just three miles from the mouth of the river; it seems improbable that almost 800,000 yds³/yr of sand is being deposited before reaching the ocean.

In addition, the ~1.2 million yd³ of sand discharged annually reported by Willis and Griggs (2003) includes all sediment coarser than 0.0625mm (4Ø). The littoral cut-off diameter for this cell was determined by Patsch (2004) to be 0.125mm (3Ø). It is possible that a majority of the surplus fluvial sand may be too fine to remain on the beach, and thus, may be lost offshore. It is believed that the inconsistent dredging of Channel Islands Harbor and the use of the sand/silt break instead of the littoral cut-off diameter when assessing the sand contribution of the Santa Clara River may account for much of the apparent surplus of sand in this sub-cell (Figures 5.4 and 5.5). Additional sand has also been stored along the five miles of beach between the Santa Clara River and the Channel Islands Harbor as this area has accreted

over the past 15 years. More research is recommended to determine the extent of beach accretion along this five-mile stretch of coast.

Due to the effective sand-bypass system at Channel Islands Harbor, which pumps most of the sand dredged from the harbor to the beach south of Port Hueneme (Hueneme Beach), very little sand is now lost into Hueneme Submarine Canyon. When dredging Channel Islands Harbor, approximately 5% to 10% of the sand is placed on Silver Strand Beach, between Channel Islands Harbor and Port Hueneme, to maintain the beach. This sand is eventually lost into Hueneme Submarine Canyon.

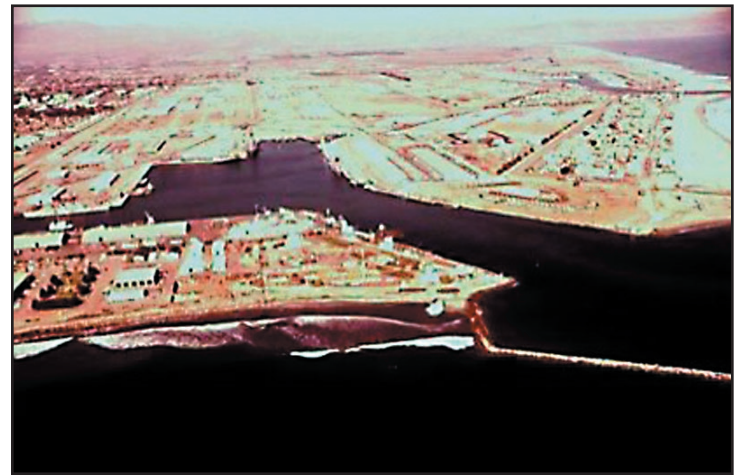


Fig 5.9: Port Hueneme Harbor, 1979

HUENEME SUBMARINE CANYON TO MUGU SUBMARINE CANYON

Between Port Hueneme Harbor and the Mugu submarine canyon, Calleguas Creek is the only source of sand and it supplies this sub-cell with ~65,000 yds³/yr of sand. Added to the ~1,000,000 yds³/yr of sand bypassed from the updrift harbors moving downcoast as littoral drift, this sub-cell has a surplus of sand on the order of ~1,065,000 yds³/yr (Figures 5.4 and 5.5). The beaches between Port Hueneme Harbor and Mugu canyon appear to be in a state of dynamic equilibrium, neither narrowing or accreting in recent years; thus, it is concluded that the ~1,065,000 yds³/yr of sand on average is lost into the Mugu Submarine Canyon, which extends into the surf zone, terminating the Santa Barbara littoral cell. This conclusion is in agreement with Bailard's (1985), Inman's (1976), and Everts and Eldon's (2005) estimates of sand lost into Mugu Submarine Canyon.

SUMMARY OF THE SANTA BARBARA LITTORAL CELL SAND BUDGET

The sand budget for the Santa Barbara Littoral Cell can be depicted as both a simplified box model (Figure 5.4) and also as a shows the cumulative, mile-by-mile, transport of the "river" of sand (Figure 5.5). This cell appears to be in a general state of dynamic equilibrium, with enough sand supplied by the rivers and bypassing operations to feed the beaches of the cell. Sand does appear to be eroding from the beaches, however,

between Santa Barbara and Ventura harbors. Seacliff erosion has been shown to provide a negligible amount of sand (Runyan and Griggs, 2003; Runyan and Griggs, 2002); thus, any sand management plans should focus efforts on sand resources from the rivers and streams in this littoral cell, not seacliff erosion. Overall, sand supply to the Santa Barbara littoral cell has been reduced by 40.4% or $\sim 1,479,000 \text{ yd}^3/\text{yr}$ ($\sim 1,476,000 \text{ yd}^3/\text{yr}$ from the damming of rivers and $\sim 3,000 \text{ yd}^3/\text{yr}$ from the armoring of seacliffs).

There are a few areas of localized beach erosion (Noble Consultants, 1989); however, it is unclear at this point whether this is long-term beach erosion resulting from a reduction in sand supply, or if the observed erosion is the seasonal fluctuation in beach width which has been far more pronounced over the past two decades due to more prevalent and severe El Niño events (Storlazzi and Griggs, 2000; Dave Revell, personal communication).

Three harbors act as constraints or check-points for the littoral drift in this cell. Based on the dredging history over the last 70 years, the longshore drift rates at the Santa Barbara, Ventura, and Channel Islands/Port Hueneme Harbors are: $\sim 300,000$ cubic yards per year, $\sim 600,000$ cubic yards per year, and a minimum of $\sim 1,000,000$ cubic yards per year respectively (Table 5.2). Given the unidirectional southeastward movement of littoral drift in this cell, the entrance channel configurations of the harbors themselves and the lack of significant sand accumulation on the downcoast jetties, the southeastward trending Santa Barbara Channel, and the dominant angle of storm wave approach from the northwest, reverse transport is believed to be negligible, and these rates are believed to represent both the net and gross longshore transport rates.

CHAPTER 6

SANTA MONICA LITTORAL CELL SAND BUDGET

The Santa Monica littoral cell extends 57 miles from Point Mugu near the Mugu Submarine Canyon on the west to Palos Verdes Peninsula on the southeast and includes Santa Monica Bay (Figure 6.1). The beaches of Santa Monica Bay encompass a 36-mile arc from Point Dume (Figure 6.2) on the northwest to Malaga Cove on the southeast, and typically host more than 50 million visitors every year. This stretch of coast, located adjacent to the Los Angeles metropolitan area, also provides innumerable recreational activities including surfing, swimming, hiking, fishing, volleyball, and sunbathing. The beaches in this littoral cell are one of the most important “natural” resources in this region; however, very little sand presently enters this cell to naturally maintain the beaches. The sand budget for the Santa Monica littoral cell is one that has been marked by significant human intervention.

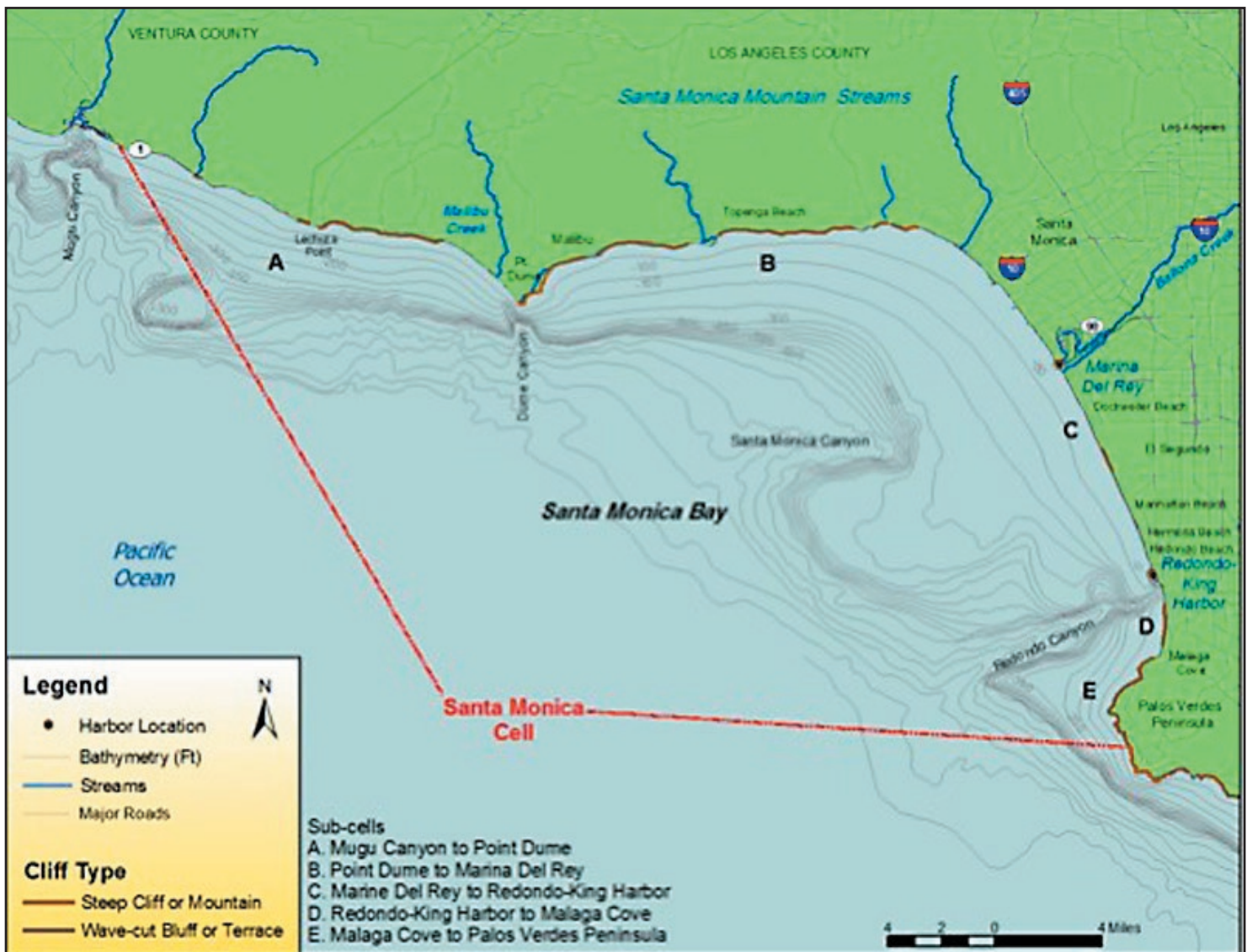


Fig 6.1: Map of the Santa Monica Littoral Cell

For the past 65 years, the beaches in the central and southern portion of Santa Monica Bay have been artificially nourished with sand to provide wide, stable beaches for residents and visitors and also to create a natural buffer from wave attack (Figure 6.3). These beaches are typically 150- to 500-feet wider than the naturally occurring beaches (Leidersdorf et al., 1994). In the northern portion of the cell, from Point Mugu to Malibu, beach nourishment has not been regularly implemented, and, as a result, the natural beaches remain quite narrow (Figure 6.4).

Numerous shoreline engineering structures have been built in this cell in an attempt to retain sand on the beaches, especially where the beaches were artificially nourished. These structures have ultimately compartmentalized the shoreline, reduced alongshore transport,



Fig 6.2: Point Dume. Copyright © 2002 Kenneth & Gabrielle Adelman



Fig 6.3: Beaches in the central and southern portion of the Santa Monica Cell are wide, stable, and artificially nourished (Dockweiler State Beach). Copyright © 2002 Kenneth & Gabrielle Adelman

and minimized the amount of sand lost into the main sink of this cell, Redondo Submarine Canyon. Overall, human intervention, consisting of beach nourishment and the construction of structures, has been successful in cre-

ating wide, stable beaches in the central and southern portion of the Santa Monica littoral (Flick, 1993; Herron, 1980; Leidersdorf et al., 1994).

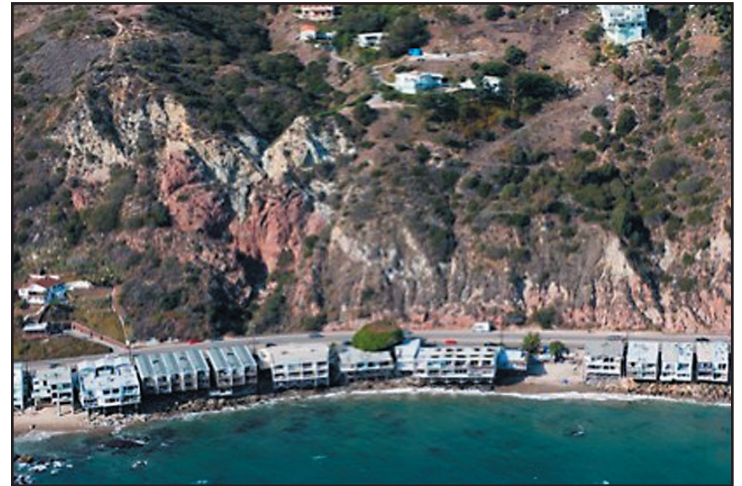


Fig 6.4: Beaches in the northern portion of the Santa Monica cell are not nourished and are naturally narrow (Malibu). Copyright © 2004 Kenneth & Gabrielle Adelman

LONGSHORE TRANSPORT AND THE NATURAL STATE OF THE BEACHES

In their natural condition, the beaches in the Santa Monica cell are quite narrow due to the lack of significant sand sources, high rates of longshore or littoral transport, and the natural loss of sand into Dume and Redondo submarine canyons. Waves enter Santa Monica Bay predominantly from the west resulting in a net transport of sand toward the south and east from Mugu Canyon towards Redondo Submarine Canyon (Leidersdorf et al., 1994). Transport reversals do occur, typically during summer south swell events; however, it has been estimated that the southerly transport rate in the Santa Monica region is seven times greater than the northerly transport (USACOE, 1986). Using the accumulation of sand at coastal structures, Hadin (1951) estimated longshore transport to be $\sim 270,000 \text{ yd}^3/\text{yr}$ at Santa Monica Beach and $\sim 162,000 \text{ yd}^3/\text{yr}$ at El Segundo Beach. More recent estimates of littoral drift vary from $190,000 \text{ yd}^3/\text{yr}$ (Engineers, 1992; USACOE, 1994) to $400,000 \text{ yd}^3/\text{yr}$ (USACOE, 1994). The earlier rates of littoral drift may represent a time when sand supply did not meet the potential longshore transport. As more sand was added to the system through beach nourishment as well as an increase in sand supply and wave energy due to El Niño events (increased sediment discharge from the coastal streams as well as the potential for increased coastal bluff erosion), waves were able to carry the additional sand downcoast thus increasing the estimated longshore transport.

The curvature of Santa Monica Bay south of Redondo Beach and Submarine Canyon produces a net transport of littoral drift to the north (Jones, 1947). Thus, from the northern point in the cell, littoral drift, uninterrupted, will travel south and east until it is eventually lost into

Redondo canyon, and from the southern point in the cell, littoral drift will travel north until it is also lost into Redondo Canyon.

Redondo Submarine Canyon is the confluence of the southern and northern trending alongshore transport of sand established in the Santa Monica littoral cell. With its head located within 200 yards of the shoreline, Redondo Submarine Canyon serves as an effective sink for this cell. Today, due to the extensive compartmentalization of the shoreline in Santa Monica Bay, little sand is lost into the canyon. Before human intervention, it was estimated that 200,000 to 400,000 yd³/yr of sand ended up in Redondo Submarine Canyon (Gorsline, 1958).

STRUCTURES

As of 1990, there were 5 shore-parallel breakwaters, 3 shore-normal jetties, 19 groins, 6 open-pile piers, and 2 harbors in the 21.6-mile stretch of coast between Topanga Beach and Malaga Cove (Corporation, 1992; Leidersdorf et al., 1994; Wiegel, 1994). Locations for these structures are listed in Table 6.1. The groins and jetties extending perpendicular to the coast interrupt the longshore current inhibiting the movement of sand traveling alongshore as littoral drift, thus compartmentalizing the shoreline and creating sub-cells within the larger Santa Monica littoral cell. Due to the unidirectional net transport direction in most of this littoral cell, groins are exceptionally successful at trapping sand and maintaining the beaches (Flick, 1993).

Harbors	Breakwaters (5)	Piers (6)	Jetties (3)	Groins (19)
Marina del Rey	Santa Monica (1)	Santa Monica (1)	Marine del Rey (2)	Sub cell B (12)
Redondo/King	Venice (1)	Venice (1)	Ballona Creek (1)	Sub cell C (5)
Harbor	Marine del Rey (1)	Manhattan		Sub cell D (2)
	Redondo (2)	Hermose		
		Horseshoe (Redondo)		
		Monstad (Redondo)		

Table 6.1: Summary of coastal structures on the beaches of Santa Monica Bay: Topanga Beach to Malaga Cove. Sub-cells: B. Point Dume to Marina del Rey; C. Marina del Rey to King Harbor; D. King Harbor to Malaga Cove. Source: County of Los Angeles, 1990 in Coastal Frontiers Corporation, 1992

SAND SOURCES AND SINKS

Rivers: Rivers typically provide the majority of sand to littoral cells in California (Brownlie and Taylor, 1981; Inman and Frautschy, 1966); however, this is not the case for the Santa Monica cell. The most important historic event impacting the sand budget for the Santa Monica littoral cell was the change in the course of Los Angeles River. Prior to 1825, the Los Angeles River discharged through Ballona Creek providing a substantial amount of sand

to this cell. However, in 1825, unusually heavy flooding caused the river to change its course and discharge into San Pedro Bay, approximately 26 miles southeast of its original outlet (Handin, 1951; Kenyon, 1951; Knur and Kim, 1999; Wiegel, 1994). Thus, for over a century the Santa Monica littoral cell has lacked a major natural source of sand.

Ballona Creek, Malibu Creek, and the Santa Monica Mountains’ streams contribute a minor volume of sand to this cell. Willis and Griggs (2003), using up-to-date stream discharge information, determined that Ballona Creek, a small ephemeral stream, delivers ~3,000 yd³/yr of sand annually, and the Santa Monica Mountains’ streams cumulatively discharge ~43,000 yd³/yr of sand. Today, Malibu Creek contributes ~24,000 yd³/yr of sand annually on average. This is a reduction of 55% from the natural sand discharge due to the damming and control of Malibu Creek (Knur and Kim, 1999; Willis and Griggs, 2003). Thus, streams contribute a total of ~70,000 yd³/yr of sand to the Santa Monica littoral cell on average, which is a total reduction of 30%, or 29,300 yd³/yr, due to the damming of Malibu Creek (Table 6.2). However, this is an over-estimation of the volume of sand that will actually remain on the subaerial beaches of the cell. The volume of sand represented by these numbers is sand that is coarser than 4Ø (0.0625mm), or the sand/silt break on the commonly used Wentworth Scale. The littoral-cut-off-diameter, which is the smallest grain-size of sediment that will remain on the beaches, for this cell was determined to be 3Ø (0.125mm). The grain-size data on sediment discharged by these streams, which is necessary to discern the percentage of sediment sufficiently coarse to remain on the beaches and in the littoral system, is not available.

Bluff Erosion: Seacliffs and bluffs constitute 17 miles of the shoreline in the Santa Monica littoral cell (Figure 6.1). Using factors such as alongshore cliff length, cliff or bluff height, terrace deposit thickness, grain size of cliff or bluff and terrace deposit materials, erosion rate, and littoral-cut-off diameter, bluff erosion was determined to contribute a minimal amount of sand to this littoral cell. Although bluff erosion is not contributing much sand to the littoral budget, it does constitute 60% of the “natural” and 23% of the “actual” sand supplied to this cell (Table 6.2).

With the lack of a large sand contribution from rivers or streams, the role of bluff erosion in contributing sand to the beaches in this cell is increased. Overall, erosion of coastal bluffs contributes an average of ~150,000 yd³/yr of beach-sand-sized material (coarser than 3Ø or .125mm). Nearly 9,000 feet of bluff armoring have reduced the historic, or natural, volume by only 1% (~2,000 yd³/yr; Table 6.2). Most of this sand (~133,000 yd³/yr), however, is emanating from the stretch of coast from Malaga cove to Palos Verdes Peninsula where it travels north and is lost into the Redondo Submarine

Canyon, providing little to no sand to beaches in the northern and central stretches of this cell.

Santa Monica Littoral Cell			
Inputs	Natural Sand (yd ³ /yr)	Actual Sand Yield (yd ³ /yr)	Reduction (yd ³ /yr)
Rivers	100,000 (40%)	70,000 (11%)	30,000 (30%)
Bluff Erosion	150,000 (60%)	148,000 (23%)	2,000 (1%)
Beach Nourishment	0 (0%)	428,000* (66%)	+428,000
Total Littoral Input	250,000 (100%)	646,000 (100%)	-396,000 (+158%)

Table 6.2: Over-all sand contributions and reductions to the Santa Monica littoral cell. Reductions are due to the damming of rivers and the armoring of seacliffs. "Natural" sand yield refers to the estimated original volume of sand discharged by streams and contributed to the littoral budget through seacliff or bluff erosion. "Actual" sand yield refers to the estimated volume of sand reaching the coast under present day conditions taking into account reductions in sand supply from dams and seacliff armoring as well as additions to the budget from beach nourishment. The natural and actual sand yield from bluffs is taken after the construction of the Pacific Coast Highway in 1926.

*Average annual beach nourishment is taken between 1926 and 2004.

Beach Nourishment: Over the last 65 years, beach nourishment has been the main source of sand for the Santa Monica littoral cell, overshadowing the amount of sand supplied by the rivers and bluff erosion. Leidersdorf et al. (1994) estimate that ~33 million yd³ of sand have been placed on the beaches of the Santa Monica littoral cell over a 60 year span, which averages out to be ~550,000 yd³/yr. This is consistent with the estimate made by Flick (1993) of 30 million yd³ of sand over a 50-year span (or ~600,000 yd³/yr) placed on the beaches in this cell. However, since 1970, beach nourishment has significantly decreased. Leidersdorf et al. (1994) determined that only 1.7 million cubic yards (~70,000 yd³/yr) was added to the beaches between 1970 and 1994, in contrast to the 29.8 million yd³ (~1 million yd³/yr) added from 1938 to 1969. Leidersdorf et al (1994) attribute the decrease in nourishment to the following: 1. a decrease in construction projects along the coast; 2. more stringent regulations and standards for the size and quality of acceptable sand used for nourishment; and 3. the relative stability of earlier fill as a result of retention structures.

Some of the largest opportunistic beach nourishment projects came along with the construction and expansion of the Hyperion Sewage Treatment Facility inland of Dockweiler Beach and the construction of the Pacific Coast Highway. From 1938-1989 ~17 million cubic yards of sand were added to the beaches between Santa Monica and El Segundo as a result of the construction and expansion of the Hyperion Sewage Treatment

Facility. From 1946 to 1948 ~14 million cubic yards of sand were excavated from coastal sand dunes during construction of the Hyperion Facility, and disposed of along a 7-mile stretch of beach from the Santa Monica Pier to El Segundo Beach widening the beaches by an average of 600 feet (Leidersdorf et al., 1994; Wiegel, 1994). Prior to this, in 1938, 1.8 million cubic yards of sand were excavated from the sand dunes at the future site of the Hyperion Facility in anticipation of construction and placed on the beach (Wiegel 1994). One of the most recent beach nourishment projects associated with Hyperion occurred in 1989 when 1.1 million yds³ of sand were transported by conveyor belt from Hyperion, across Pacific Coast Highway, and deposited on Dockweiler beach (Flick, 1993).

The construction and maintenance of the Pacific Coast Highway has also provided a large volume of sand to this littoral cell. Large cuts, ranging in height from 20 to 60 feet, were made into the hillside of the Santa Monica Mountains to build the highway. The largest cuts were made between Point Mugu and Little Sycamore Canyon six miles to the southeast (Knur and Kim, 1999). The highway fills were not armored until the 1960's. Knur and Kim (1999) estimate 1.2 million cubic yards of sand were used as beach nourishment from the initial construction of the highway, with another ~150,000 cubic yards of sand from the subsequent maintenance to the highway. Thus, ~1.35 million cubic yards of sand was added to the budget of the Santa Monica littoral cell due to the construction and maintenance of the Pacific Coast Highway since 1926. However, in locations where the highway was built between the mountains or bluffs and the ocean, bluff erosion was eliminated as a long-term source of sand. Because of the location of the highway, only 65% of the bluffs along the Malibu coastline are capable of contributing sand (Knur and Kim, 1999).

Submarine Canyons: Dume Submarine Canyon is located offshore of Point Dume (Figures 6.1 and 6.2). The mouth of Dume canyon reaches to within 800 feet of the shoreline and descends to a depth of over 2,000 feet (Knur and Kim, 1999). Most researchers agree that Point Dume and Dume Submarine Canyon act as partial barriers to littoral drift; however, they do not agree on the volume of sand successfully making its way around the promontory and the volume of sand lost into Dume Submarine Canyon (Inman, 1986; Knur and Kim, 1999; Orme, 1991).

Inman (1986) reports that during moderate wave conditions, 90% of the material traveling as littoral drift southward towards Point Dume is transported around the promontory, bypassing the canyon head. Orme (1991), however, concluded the converse, that only 10% of littoral sediments bypass the point and canyon mouth. Knur and Kim (1999) attempted to resolve this discrepancy by performing their own analysis. They analyzed bathymetric contours from a survey conducted by

the U.S. Army Corps of Engineers (1950), and calculated a "depth of closure" ("depth of closure" is defined as the depth beyond which no significant seasonal transport or movement of littoral sand takes place) by using an equation from the U.S. Army Corps of Engineers' Shore Protection Manual (1984). Assuming that sand transport occurs at an equal rate throughout the zone of transport from the shore to the depth of closure, Knur and Kim found that 70% of littoral drift enters Dume Submarine Canyon, and is effectively removed from the littoral cell budget. Thus, only 30% of the littoral sand bypass Point Dume and Dume Submarine Canyon (Knur and Kim 1999).

Santa Monica Submarine Canyon lies between Dume and Redondo canyons (Figure 6.1) but the canyon head lies about 7 miles offshore near the shelf break so is not a sink for modern littoral sand.

As discussed earlier, Redondo Submarine Canyon is located just offshore of King Harbor in the southern portion of Santa Monica Bay (Figure 6.1). With its head located within 200 yards of the shoreline near the end of the King Harbor breakwater, sand is essentially funneled into Redondo Submarine Canyon, effectively removing it from the sand budget for this cell. Today, due to the extensive compartmentalization of the shoreline in Santa Monica Bay, little sand is actually lost into the canyon. Before human intervention Gorsline (1958) estimated that 200,000 to 400,000 yds³ of littoral sediments per year were lost into the canyon. Retentions structures such as groins have trapped littoral drift, allowing this sand to remain on the beaches.

On- and Off-Shore Transport: Cross-shore transport can potentially be an important sand source or sink for a littoral cell. This component, however, is very difficult to quantify. It has been assumed by many researchers (Best and Griggs, 1991b; Best and Griggs, 1991a; Knur and Kim, 1999; Komar, 1996) that on- and off-shore transport will essentially balance over time, and it is negligible in consideration of the large volumes of sand in a large-scale, long-term littoral cell sand budget. Cross-shore transport of sand has not been quantified by any researchers for the Santa Monica littoral cell, and has not been attempted in this study. High-resolution multibeam bathymetry can delineate seasonal changes in sediment distribution or thickness on the inner shelf or beyond the depth of closure as has been seen off Santa Cruz (Storlazzi, USGS, personal communication).

To date, however, these high resolution bathymetric studies have not been systematic or frequent enough, or combined with bottom current measurements, such that seasonal on- or off-shore net sand transport can be confirmed. Because of the potential importance of this transport and the volumes of sand involved, several such studies are recommended in areas where such cross-shore transport may be significant to balancing the

littoral budget (southern Monterey Bay, for example).

SUMMARY OF THE SAND BUDGET FOR THE SANTA MONICA LITTORAL CELL

A. Point Mugu to Point Dume: Point Mugu (Figure 6.5) and the Mugu Submarine Canyon mark the termination of the Santa Barbara littoral cell and the beginning of the Santa Monica littoral cell. Mugu canyon is an effective littoral trap such that little to no sand is transported from one cell to the other. Just over 5.6 miles of the nine-mile stretch of coast from Point Mugu to Point Dume consist of bluffs interrupted by small pocket beaches. Bluff erosion was found to contribute an average of 8,000 yd³/yr of sand to this sub-cell. The sand contribution has been reduced by approximately 12% (~1,000 yd³/yr) from the natural contribution due to the armoring of ~3,500 feet of bluffs in this stretch of coast. No beach nourishment has taken place in this sub-cell (Wiegel, 1994).



Fig 6.5: Point Mugu. Copyright © 2002 Kenneth & Gabrielle Adelman

B. The Malibu Coastline: Point Dume to Marina del Rey: The 26 mile-long stretch of coast from Point Dume to Santa Monica Canyon in the western Santa Monica Mountains is marked by pocket beaches bounded by rocky headlands and narrow, sand-starved beaches.

The Santa Monica Mountains are an east-west trending range about 50 miles long and 9 miles wide with an elevation range from sea-level to over 3,000 feet. The mountains are generally steep-sided with narrow valleys. Rainfall in the Santa Monica Mountains occurs primarily between November and April, with the largest sediment producing storms occurring between December and February (Knur and Kim, 1999). Bluff erosion was found to contribute an average of ~5,000 yd³/yr of sand to the beaches in this sub-cell, which is a reduction of ~900 yd³/yr (or 18%) due to bluff armoring.

The coastline of the Santa Monica Mountains is characterized by numerous pocket beaches that are bounded by headlands. These headlands result from the high erosional resistance of the bedrock in comparison with the surrounding materials. Resistant headlands include

Sequit Point, Point Dume, and Latigo Point. Headlands are also formed from deltaic deposits, or cobbles and boulders, found at the mouths of streams, which are too large to be moved by the littoral currents, and effectively interrupt littoral drift, much like a shore-perpendicular structure such as a groin. Such headlands occur at Malibu Point, Las Flores Point, and Topanga Point. Most of the pocket beaches are a few hundred yards in length with the exception of Zuma Beach, which is just over four miles long (Knur and Kim, 1999).

Development began in the Santa Monica Mountains in the 1880's. With the construction of dams for irrigation and recreation, and the placement of coastal engineering structures to protect homes and public facilities, the amount of sand reaching the coast in this sub-cell has diminished. Dam construction began in 1881, and by the late 1920's the largest of the dams were constructed. By the 1970's, a total of 22 dams interrupted the flow of water through the streams in the Santa Monica Mountains (Knur and Kim, 1999; Willis and Griggs, 2003; Willis et al., 2002).

Many of these coastal dams, such as the 100-foot-high Rindge Dam on Malibu Creek, are completely filled with sediment, and are no longer providing any value. Rindge Dam, built in 1926, completely filled its 574 acre-foot reservoir in the first 25 years after construction. It is estimated that between 800,000 and 1.6 million cubic yards of sediment is currently stored behind the dam. The U.S. Army Corps of Engineers and California State Parks have undertaken a feasibility study on the removal of Rindge Dam to help restore Malibu Creek's natural sediment supply. Thus far, cost estimates for the removal of Rindge Dam are between \$4 million and \$18 million, depending on the strategy of sediment removal.

Beginning around 1926, development began on the south side of the Santa Monica Mountains, aided by the construction of Pacific Coast Highway through Malibu. In order to build the highway, large sections of the hillside had to be removed. As previously discussed, ~1.35 million cubic yards of sand from these excavations were placed on the beaches as nourishment (Knur and Kim, 1999). From Point Dume to Will Rogers State Beach, along the Malibu shoreline, the sand-starved beaches are narrow and remain close to their natural state. From 1923-1958, 33 groins were built along the Topanga Beach/Will Rogers section of the coast, many of which have now either been destroyed or buried (Shaw, 1980; Wiegel, 1994; Woodell and Hollar, 1991). Will Rogers State Beach currently has an extensive groin field consisting of at least 8 groins to compartmentalize the shoreline; however, the beaches remain narrow at the updrift ends of the structures because no nourishment activity accompanied the construction of the groins.

The Santa Monica Municipal Pier and the adjacent wide, sandy beach is an extremely popular tourist destination

(Figure 6.6). The wide beach is a result of a 2,300-foot-long detached breakwater, built in 1934, just north of the pier and 2,000 ft offshore, to create the Santa Monica Harbor (Wiegel, 1994). Immediately after construction of the breakwater, substantial accretion occurred in lee of the structure that extended southward past the pier. The beach width increased by over 650 feet at a distance of one mile upcoast from the structure (Flick, 1993). Farther downcoast severe beach erosion occurred. Storms associated with the El Niño winter of 1982/1983 damaged the top of the Santa Monica breakwater, lowering it to -6ft (MLLW), and allowing for natural alongshore transport to partially resume (Leidersdorf et al., 1993; Wiegel, 1994).

Venice Breakwater, a detached, shore-parallel, rubble-mound structure built in 1905, is located approximately two miles south of the Santa Monica Pier, and is often connected to the shoreline by a tombolo (Figure 6.7), creating a littoral barrier. This structure is 600-ft long and is located 1,200 ft offshore. Once again, the beaches in this area have historically been maintained by beach nourishment, and have also benefited from the construction of Marina del Rey's northern jetty. Venice Beach was nourished with 150,000 cubic yards of sand in 1945 and some portion of the 13.9 million cubic yards of sand placed on Dockweiler and Venice beaches from the construction and maintenance of the Hyperion Sewage Treatment Facility (Table 6.3) (Leidersdorf et al., 1994).

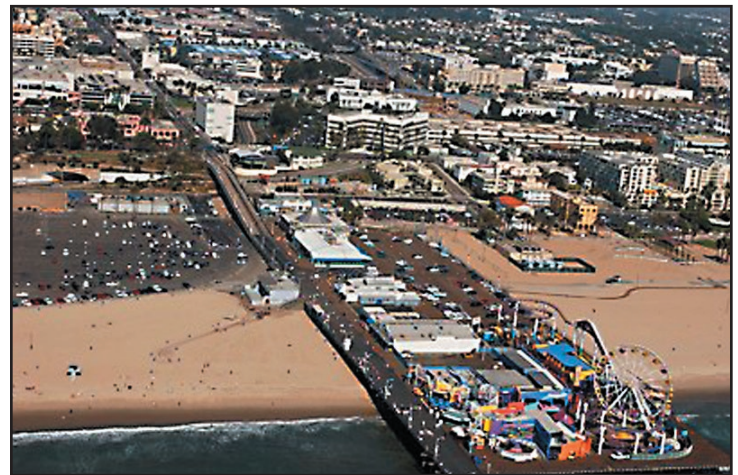


Fig 6.6. Santa Monica Municipal Pier. Copyright © 2002 Kenneth & Gabrielle Adelman

Marina del Rey (Figure 6.8), located 15 miles southwest of Los Angeles, is one of the largest man-made recreational boating and residential marinas in the world with over 6,000 moorings for boats and facilities for thousands more. In the early 1960's, Marina del Rey was constructed by dredging the wetlands of Ballona Lagoon in order to meet the demands of a rapidly growing population in the Los Angeles region. Designed by the U.S. Army Corps of Engineers, the original jetties stabilizing the entrance to the marina were inadequate.

Date	Sub-Cell	Placement Location	Source of Material	Purpose	Quantity (yd ³)	Source
1926+	B	Unknown	PCH construction	Disposal	1,350,000	Knur & Kim (1999)
1938	C	Dockweiler Beach	Hyperion	Disposal	1,800,000	Leidersdorf et al (1994)
1945	B	Venice Beach	Hyperion	Disposal	150,000	Leidersdorf et al (1994)
1947	B/C	Venice/Dockweiler	Hyperion	Disposal	13,900,000	Leidersdorf et al (1994)
1947	D	King Harbor to Malago Cove			220,000	Wiegel (1994)
1947	D	Redondo Beach	Onshore	Nourishment	100,000	Leidersdorf et al (1994)
1956	C	Dockweiler Beach	Scattergood	Disposal	2,400,000	Leidersdorf et al (1994)
1960-62	C	Dockweiler Beach	Marina del Rey	Disposal	3,200,000	Leidersdorf et al (1994)
1962	D	King Harbor to Malago Cove			220,000	Wiegel (1994)
1963	C	Dockweiler Beach	Marina del Rey	Disposal	6,900,000	Leidersdorf et al (1994)
1968-69	D	Topaz St. Groin to Malago Cove	Offshore	Nourishment	1,400,000	Wiegel (1994); Leidersdorf et al (1994)
1984	C	El Segundo	Offshore	Nourishment	620,000	Leidersdorf et al (1994)
1988	C	Dockweiler Beach	Hyperion	Disposal	155,000	Leidersdorf et al (1994)
1988-89	C	El Segundo	Hyperion	Disposal	945,000	Leidersdorf et al (1994)

Table 6.3: Beach Nourishment Projects in the Santa Monica littoral cell

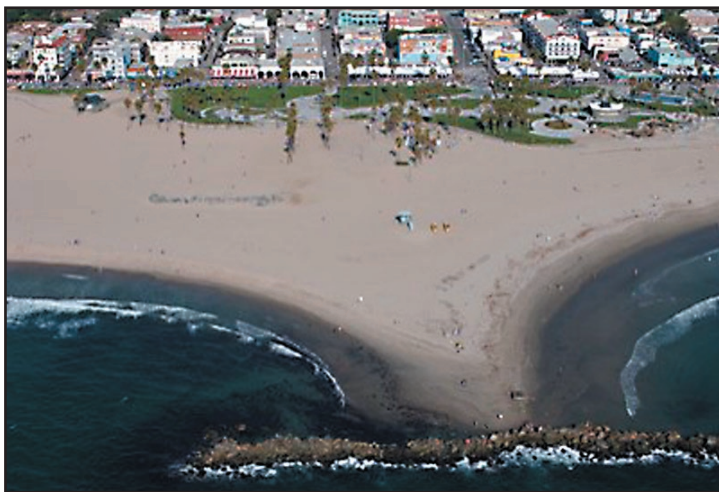


Fig 6.7: Tombolo formation behind the Venice breakwater upcoast from Marina Del Rey Harbor. Copyright © 2004 Kenneth & Gabrielle Adelman

The jetties were intended to dissipate wave energy inside of the marina. However, after their construction and the inhabitation of the marina by boaters, waves as high as six feet began to set up resonance patterns within the entrance channel and traveled into the marina causing extensive damage to boats and facilities. Some boat-owners abandoned Marina del Rey and vendors sued Los Angeles County for lost revenue (Griggs et al., 2005).

The first response to this problem was to install temporary baffles across and within the main channel to prevent waves from entering the harbor. Eventually, after a large-scale modeling effort was completed, a 1,200-foot, detached breakwater was constructed just offshore of and across the ends of the jetties thus creating a safe haven for the boats within the marina.

The construction of the breakwater, although successful in creating a safe harbor, interrupted littoral drift, and

created a navigational hazard in the southern approach to the inlet due to shoaling from the deposition of sand by Ballona Creek adjacent to the south jetty (Griggs et al., 2005).



Fig 6.8: Marina Del Rey and Ballona Creek (1989) Copyright © 2004 Kenneth & Gabrielle Adelman

Dredging of the entrance channel to a minimum depth of 18 feet was initiated in 1969 to maintain a safe navigational channel into the marina (Table 6.4). Although most of this dredged material has been bypassed and used at a source of beach nourishment for the down-coast beaches, often the sand is too contaminated to be placed directly on the downdrift beaches. From 1969 to 2001, 2.2 million yd³ (or 62,500 yd³/yr) of sand was dredged from Marina del Rey and placed on the down drift beaches as opportunistic beach nourishment (Table 6.4).

Two ~650-foot-long, rubble-mound jetties were constructed in 1938 to stabilize the Ballona Creek outlet (Figure 6.8). In 1946, the jetties were extended 590 feet causing significant erosion downdrift. In 1956, 2.4

Year	Quantity (yd ³)	Source	Placement
1939	60,000	Santa Monica Breakwater	Santa Monica Beach
1949	960,000	Santa Monica Breakwater	Santa Monica Beach
1957	780,000	Santa Monica Breakwater	Santa Monica Beach
1969	389,800	Marina del Rey Bypassing	Dockweiler Beach
1973	16,098	Marina del Rey Bypassing	Dockweiler Beach
1975	10,000	Marina del Rey Bypassing	Dockweiler Beach
1980	266,000	Marina del Rey Bypassing	Dockweiler Beach
1981	217,435	Marina del Rey Bypassing	Dockweiler Beach
1987	35,315	Marina del Rey Bypassing	Dockweiler Beach
1992	21,500	Marina del Rey Bypassing	Dockweiler Beach
1994	57,000	Marina del Rey Bypassing	Dockweiler Beach
1996	238,000	Marina del Rey Bypassing	Dockweiler Beach
1998	125,825	Marina del Rey Bypassing	Dockweiler Beach
1999	820,089	Marina del Rey Bypassing	Dockweiler Beach
Total Bypassing	3,997,062	Average annual bypassing for Marina del Rey	62,500

Table 6.4: Sand bypassing for the Santa Monica littoral cell. Sources: USACE Los Angeles District (contact: Mo Chang 2001 and 2005); (Griggs, 1987b); (Leidersdorf et al., 1994)

million yd³ of sand were excavated from the sand dunes between the Hyperion facility and the City of El Segundo and placed along 8,600 ft of Dockweiler beach to mitigate the erosion caused by the Ballona Creek jetties (Wiegel, 1994). The City of Los Angeles constructed two stone groins 4,600-ft and 8,600-ft long in 1956 to help stabilize and maintain the nourished sand on the beach (Pardee, 1960; Wiegel, 1994).

C. Marina del Rey to Redondo/King Harbor: The stretch of shoreline from Marina del Rey to Redondo/King Harbor consists of wide, sandy beaches, stabilized by rock groins, backed by parking lots and park facilities (Figure 6.3). A small stretch of shoreline near El Segundo Beach (Figure 6.1) is backed by bluffs. Erosion of these bluffs under natural conditions was found to contribute ~500 yd³/yr of sand, but these bluffs are now protected leading to a reduction of ~56% (or 1,300 yd³/yr) due to bluff armoring. As previously discussed, Dockweiler State Beach (Figure 6.3) has been nourished over the years with the sand bypassed from Marina del Rey (Table 6.4).

Just downcoast of Dockweiler State beach, El Segundo Beach was nourished with 620,000 cubic yards of sand in 1984, concurrent with construction of El Segundo Marine Terminal Groin, a 915-foot-long rubble-mound structure. Five-hundred and seventy thousand cubic yards of sand were placed updrift of the groin and 50,000 cubic yards of sand were placed downdrift of the groin to prevent future erosion (Leidersdorf et al., 1994). Most of the sand for this nourishment project came from an offshore borrow area in 25 to 45 feet of water depth (Leidersdorf et al., 1994; Moore, 1983). In 1947, 100,000 yds³ of sand, from an onshore source, were placed on Redondo Beach south of the north breakwater for King Harbor (Table 6.3).

King Harbor (Figure 6.9), completed in 1959 and named

after a local congressman, provides anchorage for boats, and its waterfront restaurants and shops are a destination for visitors to Redondo Beach. The harbor is located at the head of Redondo Submarine Canyon, which was discovered to come within 200 feet of the shoreline in 1890. Initially, a pier was built near the canyon to allow ocean-going ships a place to dock, however there was no protection for these ships against large storm waves. Construction of a 1,485-foot long, shore-parallel breakwater was approved in 1938 and built in 1939 at the cost of \$50,000 to provide protection to the ships docked at the pier. This breakwater resulted in severe erosion of the beaches downcoast, however. In 1958, the breakwater was reconstructed and extended 2,800 feet to the south. King Harbor was then constructed by adding a dogleg to the existing breakwater and adding a second breakwater on the south side of the harbor to form the entrance channel between the two structures. Because of its proximity to the head of Redondo Submarine Canyon, this harbor does not require maintenance dredging. Substantial downdrift erosion has resulted from the construction of King Harbor because of sand trapping along the northern margin of the breakwater and the deflection of sand into Redondo Canyon.

D. Redondo Canyon to Malaga Cove: The presence of King Harbor and the mouth of Redondo Submarine Canyon effectively form a 2.8-mile-long sub-cell or beach compartment between the southern breakwater of the harbor and Malaga Cove. This historically narrow beach is backed by 30 to 140-foot-high bluffs that were found to contribute an average of 3,700 yd³/yr of beach-sized sand (coarser than 3Ø) annually. In 1947 and again in 1962, Los Angeles County placed 220,000 cubic yards of sand (source unknown) on the beach (USA/CESPL, 1966a; 1970; Wiegel, 1994) (Table 6.3).

Topaz Street groin, built in 1970, bisects the sub-cell even

further. Along the short stretch of shoreline from Redondo canyon to the Topaz Street groin, littoral drift travels north and sand is eventually lost into Redondo Canyon.



Fig 6.9: Entrance to King Harbor. Copyright © 2002 Kenneth & Gabrielle Adelman

From the groin south to Malaga Cove, the beaches are relatively stable. In 1968-1969 these beaches were nourished with 1.4 million yds³ of sand obtained from ~1,700 feet offshore in water depths of 30-60 feet (Table 6.3)(Anonymous, 1969; Fisher, 1969; USA/CESPL, 1970; Wiegel, 1994). The result of this nourishment activity was to widen the beach by ~300 ft by 1969 (Leidersdorf et al., 1994). The 590-foot-long Topaz Street groin has been successful at stabilizing the beach (Herron, 1986). Much of the original sand from the nourishment project still exists along the stretch of coast from the groin to Malaga Cove (Corporation, 1992; Leidersdorf et al., 1994; Wiegel, 1994).

E. Malaga Cove to Palos Verdes Peninsula: Palos Verdes Peninsula is a large headland, which separates the Santa Monica and San Pedro littoral cells. Extensive seacliffs characterize this stretch of coastline, and are a result of almost 1,500 feet of tectonic uplift. Palos Verdes Peninsula is separated from the Los Angeles Basin by the Palos Verdes Fault. A few, small, pocket beaches formed by cobbles rather than sand exist around this peninsula. Erosion of Palos Verdes Peninsula was found to contribute ~133,000 yd³/yr of sand-sized material annually on average (much of this material is cobble-size). Landslides are common along the peninsula and occur along 53% of the shoreline between Abalone Cove and Point Fermin (Griggs et al., 2005). On the south side of the peninsula, at Portuguese Bend, is the site of the largest, most destructive landslide in this area. Roughly \$65 million dollars of property damage occurred with the total destruction of 150 homes on 300 acres during this slide.

CONCLUSIONS

Dams and seacliff armoring have reduced the total

amount of sand entering the Santa Monica littoral cell by approximately 31,000 yd³/yr (Table 6.2). Beach nourishment, however has provided over 33 million cubic yards of sand (~538,000 yd³/yr) since 1926, effectively widening the beaches in the central and southern portions of Santa Monica Bay by ~150 to 500 feet. Leidersdorf et al. (1994) note that 95% of the sand from beach nourishment projects was placed on the beaches prior to 1970. Since then, the number of nourishment opportunities and projects has significantly decreased. This may be a reason for the perception that the beaches in this cell are currently narrowing. Currently, Professor Tony Orme and two graduate students in the Geography Department at the University of California, Los Angeles, are completing a study of long-term beach width change in southern California that should shed light on the changes that have taken place over the past 50 or 60 years.

The sand budget for the Santa Monica littoral cell is illustrated in Figure 6.10 as a simple box model with sand entering each sub-cell through rivers, seacliff or bluff erosion, and beach nourishment. Sand leaves the cell when it is lost into submarine canyons. Due to the extensive use of groins, this cell is highly compartmentalized resulting in a large storage component; little sand flows from one sub-cell to the other, with the exception of the by-passing operation at Marina del Rey where sand is moved from sub-cell B and placed into sub-cell C. Because of the large storage of sand behind groins and other retention structures, the volume of sand currently entering Redondo Submarine Canyon is unknown.

Rivers historically provided 40% of the littoral sand to this cell (~100,000 yd³/yr) with bluff erosion providing the remaining 60%, or 150,000 yd³/yr (Table 6.2). Thus, the total input of sand into the Santa Monica cell was naturally almost 250,000 yd³/yr. Damming of the rivers reduced the sand input to 70,000 yd³/yr, which is a decrease of 29,000 yd³/yr or 30% of the natural yield (Table 6.2). Bluff armoring reduced the supply of sand from seacliff or bluff erosion by 1% or ~2,000 yd³/yr bringing the actual, or present-day, contribution of sand from cliff erosion to 148,000 yd³/yr (Table 6.2).

By far, the largest contributor of sand to this littoral cell, constituting 66% of the actual total sand budget, is beach nourishment. Since 1926, over 29 million cubic yards of sand (or about 432,000 yd³/yr if averaged from 1926-1988; 428,000 yd³/yr if averaged over the last 78 years from 1926 to 2004) has been placed on the beaches in this cell (Table 6.5). This is nearly twice as much sand as currently enters the cell from rivers (~70,000 yd³/yr) and bluff erosion (~148,000 yd³/yr) combined, a total of 218,000 yd³/yr. Beach nourishment, in conjunction with the emplacement of structures to retain the fill material, has allowed wide, sandy beaches to be built and to remain relatively stable in the central and southern reaches of this cell.

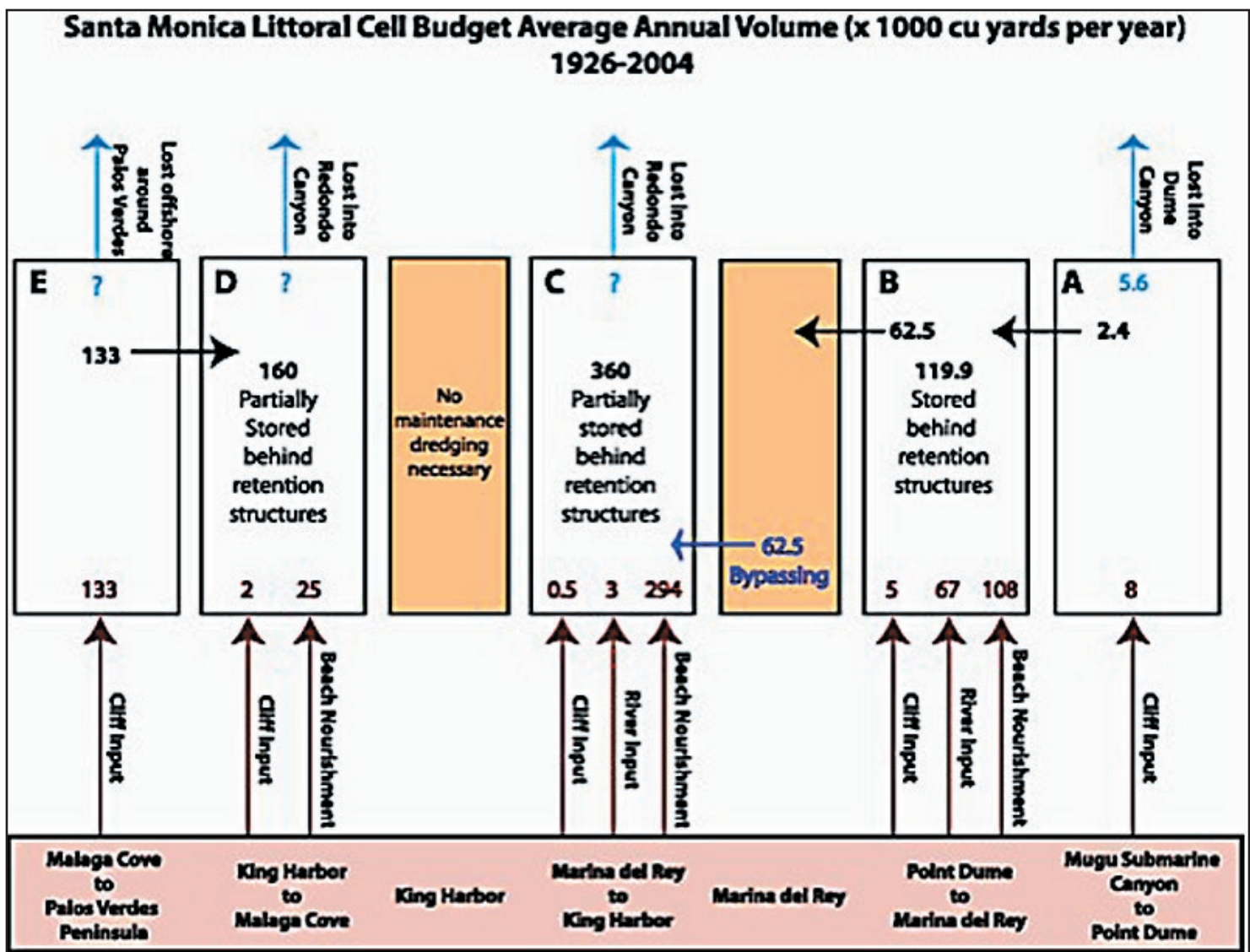


Fig 6.10: Santa Monica littoral cell budget- Box Model. Averages are representative from 1926 to 2004

With an increase in El Niño storm events (which increased wave energy causing increased erosion), and a decreasing trend in the nourishment projects in this cell, it is expected that the beaches will eventually return to their natural, narrow, sand-starved state. As for now, million of people enjoy these artificial, wide, sandy beaches every year.

	Sub-cell	Quantity (yd ³)	Annual Quantity over the last 78 years (yd ³ /yr)
Total 1926-2004	ALL	33,360,000	428,000
Total 1926-2004	B	8,450,000	108,000
Total 1926-2004	C	22,970,000	294,000
Total 1926-2004	D	1,940,000	25,000

Table 6.5: Total Volume of sand added through artificial nourishment to each sub-cell in the Santa Monica littoral cell. Sub-cells: B= Point Dume to Marina del Rey; C= Marina del Rey to Redondo/King Harbor; D= Redondo/King Harbor to Malaga Cove.

Santa Monica Littoral Cell Running Budget

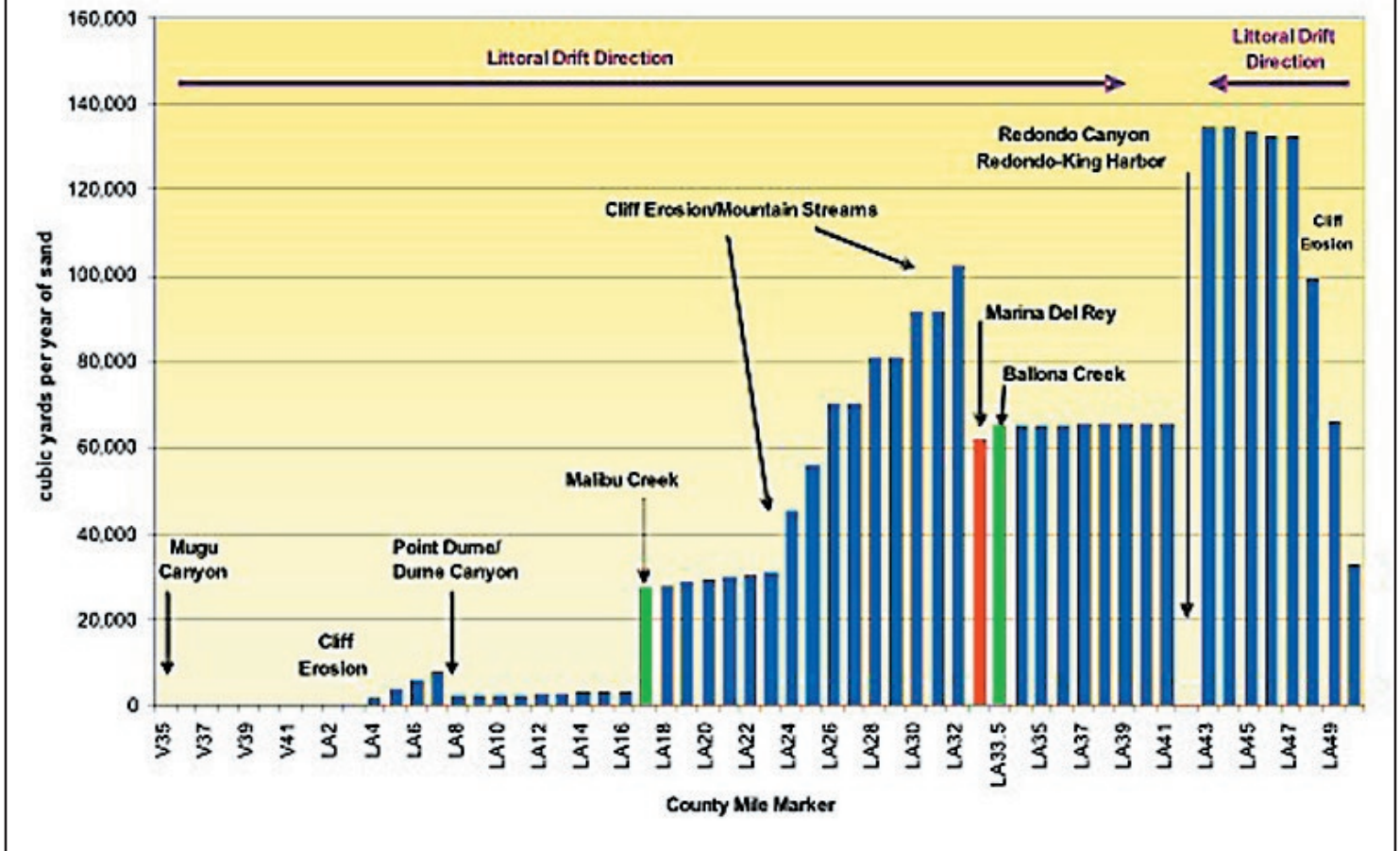


Fig 6.11 portrays the Santa Monica littoral cell budget as a mile-by-mile running total of sand moving as littoral drift through the cell. This illustration shows what the alongshore running budget would look like in its natural state with no groins inhibiting the flow of littoral drift and no additional sand added as beach nourishment. Marina del Rey is used as a constraint and check-point for the budget. Redondo Canyon is the major sink for the cell in its "natural" state.

CHAPTER 7

SAN PEDRO LITTORAL CELL SAND BUDGET

The San Pedro littoral cell extends ~31 miles south-east from Point Fermin, just south of the Palos Verdes Peninsula, and terminates at Corona del Mar, located south of Newport Bay (Figures 7.1 and 7.2). The majority of the shoreline consists of low-lying coastal plains and barrier spits with a small reach of coastal bluffs at Huntington Cliffs. Because of the low-lying nature of this shoreline, coastal hazards associated with beach erosion and storm-induced flooding are extensive.

The shoreline of the San Pedro littoral cell has experienced significant changes as a result of the extensive use of shoreline engineering structures and coastal development. The largest event impacting this stretch of shoreline was the construction of the Los Angeles/Long Beach Harbor complex initiated in 1889.

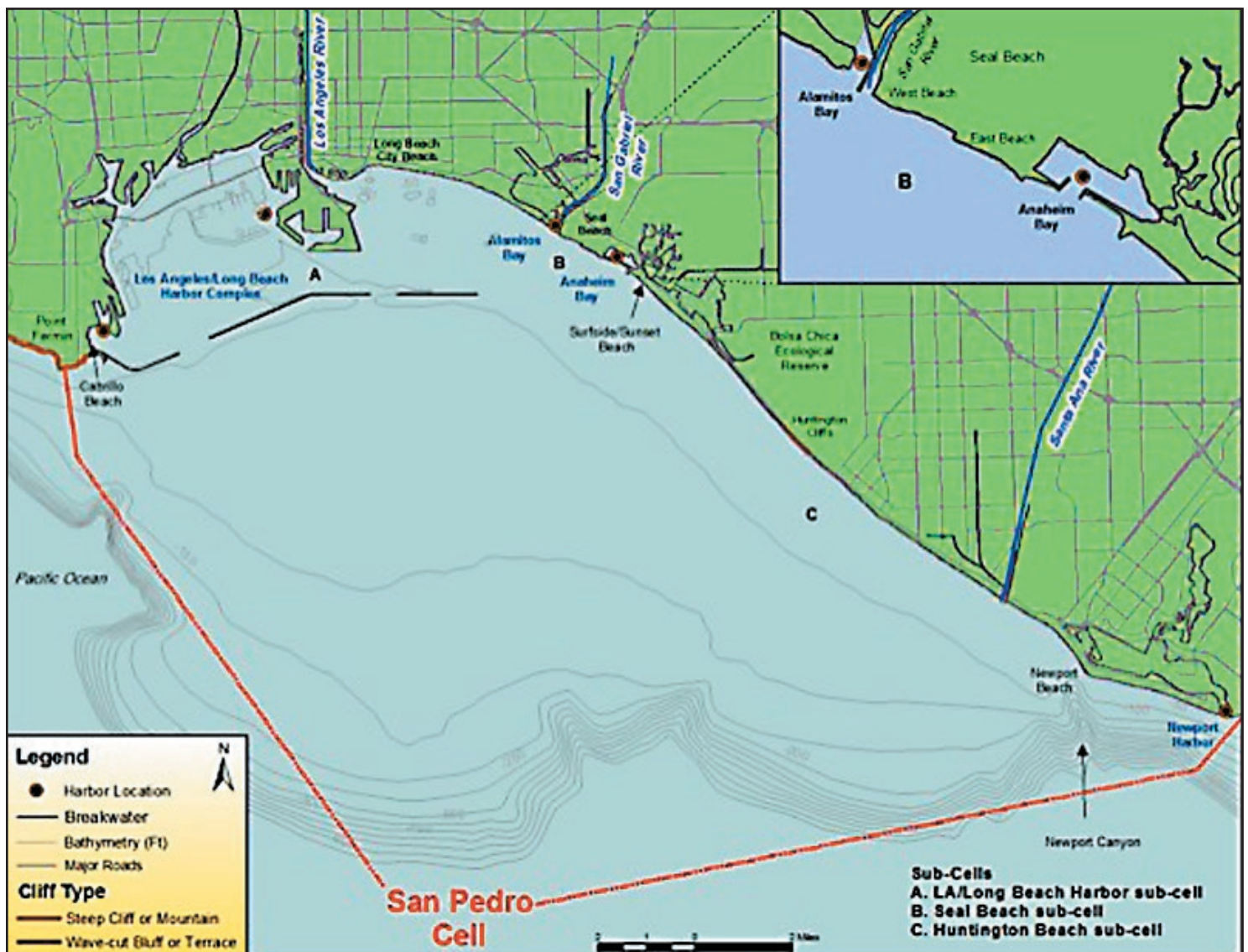


Fig 7.1: Map of the San Pedro littoral cell. Inset shows a close-up of the Seal Beach Sub-cell

The construction of the San Pedro, Middle, and Long Beach breakwaters essentially isolated the 9-mile-long stretch of coast, from Point Fermin to Seal Beach, from the rest of the littoral cell. The coast was further compartmentalized with the construction of jetties at the mouth of the San Gabriel River and the inlet stabilization projects at Anaheim and Newport bays. The construction of dams and debris basins on some of the largest rivers in the cell, which contribute the majority of naturally derived sand, significantly changed the condition of the beaches in the San Pedro littoral cell.

The shoreline of the San Pedro littoral cell has been compartmentalized into three sub-cells due to the extensive use of shore-normal coastal engineering structures, which disrupt the flow of littoral drift and essentially create self-contained sub-cells within the more broadly defined San Pedro littoral cell. The sub-cells are defined



Fig 7.2: Inspiration Point, Corona del Mar, showing beginning of cliffs and the end of the San Pedro littoral cell, 2002. Copyright © 2002 Kenneth & Gabrielle Adelman

as follows: A. Los Angeles/Long Beach Harbor sub-cell, extending from Point Fermin to the west jetty of Alamitos Bay; B. Seal Beach sub-cell, extending from the east jetty of the San Gabriel River to the west jetty of Anaheim Bay; and C. Huntington Beach sub-cell, extending from the east jetty of Anaheim Bay to Corona del Mar (see Figure 7.1).

SAND SOURCES

Rivers: The three largest rivers draining into southern California, the Los Angeles, San Gabriel and Santa Ana rivers, all provide sand to the San Pedro cell; in addition, a small amount of sand is derived from San Diego Creek. Although the sand loads of these rivers, with the exception of San Diego Creek, have been greatly reduced by dams, debris basins, and/or channelization, they are still the main natural source of sand to this cell.

The Los Angeles River is one of the most heavily altered fluvial systems in the United States (Griggs et al., 2005). Dams, debris basins, and channelization have reduced

the transport of sand from this river to almost nothing. The San Gabriel River, located four miles to the east of Seal Beach, still transports sand to the coast during floods; however, like the Los Angeles River, the volume of sand discharged has been reduced due to the effects of dams and debris basins. An average of over 810,000 cubic yards per year of sand (sediment coarser than 0.0625 mm) was originally delivered to the beaches by the Los Angeles, San Gabriel and Santa Ana rivers and San Diego Creek (Willis and Griggs, 2003; Willis et al., 2002). Damming of these rivers has reduced the total sand load by 66% to an average of 278,000 cubic yards annually. Rivers naturally provided 99.8% of the sand to the overall littoral cell sand budget, and today provide only 40.9% of the sand entering this cell (Table 7.1).

Specifically, the sand load of the Los Angeles River has been reduced by about 67%, from an average of ~233,000 yd³/yr to ~77,000 yd³/yr as a result of damming. Dams also reduced the sand yield of the San Gabriel River by approximately 67%, from an annual average of ~182,000 yd³/yr to ~59,000 yd³/yr. The Santa Ana River has also been reduced by 67%, from an annual average of ~379,000 yd³/yr to ~125,000 yd³/yr. San Diego Creek is not dammed and thus the average annual sand yield of ~16,000 yd³/yr has not diminished significantly.

San Pedro Littoral Cell			
Inputs	Natural (cy/yr)	Actual (cy/yr)	Reduction (cy/yr)
Rivers	810,100 (99.8%)	278,000 (40.9%)	532,100 (65.7%)
Bluff Erosion	2,000 (0.2%)	2,000 (0.3%)	0 (0%)
Beach Nourishment		400,000 (58.8%)	+400,000
Total Littoral Input	812,100 (100%)	680,000 (100%)	132,100 (16%)

Table 7.1: Overall sand contributions and reductions to the San Pedro littoral cell. Reductions are due to the damming of rivers and the armoring of seacliffs. "Natural" sand yield refers to the estimated original volume of sand discharged by streams and contributed to the littoral budget through seacliff or bluff erosion. "Actual" sand yield refers to the estimated volume of sand reaching the coast under present day conditions taking into account reductions in sand supply from dams and seacliff armoring as well as additions to the budget from beach nourishment.

Because the Los Angeles River discharges sand behind the breakwaters of the Los Angeles/Long Beach Harbor complex, waves do not have the opportunity to carry this sand down coast as littoral drift. The sand essentially stays within the harbor until it becomes a navigational hazard and must be dredged. Dredged material is typically placed on Cabrillo Beach just upcoast, or Long Beach, immediately downcoast.

Debris Basins: Debris basins are small catchments, typically with capacities between 1,000 and 5,000 cubic yards, designed to allow the passage of water and fine

sediments while trapping or retaining coarse sediment. These basins are created by building small dams across ephemeral stream channels. The purpose of these barriers is to reduce the danger of debris flows by trapping the main source of transported material. To remain functional, the accumulated sediment must be removed routinely from the debris basins (Willis et al., 2002). The Los Angeles Department of Public Works has a protocol for the management and clean-out of debris basins based on fire history and the loss of storage volume.

In California, the majority of debris basins are built around the perimeter of the Los Angeles basin, in the San Bernadino, San Gabriel, Santa Monica, and Santa Susana Mountain watersheds. As of 1978 almost 14 million cubic yards of material had been removed from over 100 debris basins in Ventura, Los Angeles, San Bernardino, Riverside, Orange and San Diego Counties (Willis et al., 2002). For most of these projects, grain-size information on the removed sediment is minimal; thus, the percentage of sand-sized sediment removed is unknown (Kolker, 1982; Willis et al., 2002). Taylor (1981) states that it is reasonable to assume ~50% of the sediments are within the sand-size range. Using this value, ~7 million cubic yards of sand-sized sediment has been removed from the debris basins listed above as of 1978. It is assumed that sediment removed from debris basins represents a permanent sink or loss of sand to a littoral cell sediment budget, as this material is transported to on-land disposal or depositional sites.

As of 2000, Willis et al. (2002) estimated that 163 basins have trapped more than 18 million cubic yards of debris over the cumulative periods of operation, 17,600,000 cubic yards of debris, have been removed to maintain the functionality of the debris basins. Using Taylor's (1981) 50% sand content estimate, Willis et al. estimated that ~9 million cubic yards of sand have been trapped and effectively removed from the littoral budgets in southern California.

While the overall effect of debris basins appears to be the removal of a large volume of sand from the littoral budgets in southern California, the effect of individual structures is minimal. Average sedimentation rates exceeding 1,000 cubic yards annually occur in 82 out of the 182 basins. Only 13 of the 162 basins have average sedimentation rates over 10,000 cubic yards per year (Willis et al., 2002). Applying Taylor's (1981) assumption of a 50% sand content in the trapped material, only three debris basins (Little Dalton, Big Dalton, and Santa Anita) trap an average of more than 10,000 yd³/yr of sand (Willis et al., 2002).

The Los Angeles River watershed has 85 debris basins with a combined capacity of almost 6 million cubic yards, which capture an average of ~3,200 cubic yards of sand annually (~1,600 yd³/yr of sand-sized material). The San Gabriel River watershed has 21 debris basins with a com-

bined capacity of almost 2 million cubic yards that capture an average of 3,400 yd³/yr of sand annually (~1,700 yd³/yr of sand-sized material) (Willis et al., 2002). Overall, debris basins have a minimal effect on the overall sand budget for littoral cells in southern California.

Channelized Streams: A stream is considered to be channelized when "its bed has been straightened, smoothed, or deepened to permit the faster flow of water" (Bates and Jackson, 1984; Willis et al., 2002). Flood control and bank stabilization are the two main reasons to channelize a stream in an urban watershed. According to Mount (1995), urbanization has the following effects on flood hydrographs: 1. the lag-time between peak rainfall intensity and peak run-off decreases; 2. the magnitude of flood peaks increase; and 3. there is an increase in the total run-off volume. Channelization of streams in urban areas attempts to prevent flooding by collecting run-off from impermeable surfaces efficiently.

Hard bottom channels create problems with sediment deposition when the channel can no longer transport the sediment load. The build-up of sediment must be excavated to prevent back-up and flooding. In Los Angeles County, the Department of Water and Power (LADWP) must maintain 460 miles of channels. In 1998 and 1999 LADWP excavated 43,809 tons of sediment from these channels (Willis et al., 2002).

Channelized streams also prevent the lateral and downward incising or erosion of the stream bed that can naturally supply beach-size sediment to the shore, thus reducing the sand budget. Willis et al. (2002) found that due to a lack of data collection and book-keeping concerning channelization and sediment removal from stream channels, it is not possible to assess the significance of this sediment removal to the overall sand budgets in the southern California littoral cells.

Cliff or Bluff Erosion: The San Pedro littoral cell only has one small section of low, Pleistocene-aged coastal bluffs at Huntington Cliffs. These bluffs extend alongshore for ~3,800 feet and have an average height of 100 feet. The littoral cut-off-diameter, or the coarsest sediment grain size that will remain on the beaches in this area, was determined to be 3.25 ϕ (0.105 mm). It was determined that contributions from bluff erosion represent 0.3% of the total sand budget for the San Pedro littoral cell by contributing an average of only ~2,000 yd³/yr of sand annually (Table 7.1).

Beach Nourishment: Harbor and river channel projects over the last 60 years in the San Pedro Cell have contributed 25 million yds³ of sand used as nourishment on 15 miles of public beaches in the San Pedro littoral cell (Coastal Frontiers Corporation, 2000; Herron, 1980; Wiegel, 1994). Federal, state and local governments developed and fund an ongoing beach nourishment project, which uses Surfside/Sunset Beach as a feeder

location and contributes an average of nearly 400,000 yds³ of sand per year (Flick, 1993). Beach nourishment contributes 58.8% of the sand to the budget in the San Pedro littoral cell (Table 7.1).

SAND SINKS

Submarine Canyons: Newport Submarine Canyon is located just upcoast of Newport bay (Figure 7.1). In the past, the canyon served as the main sink for littoral drift traveling through this cell. However, the construction of jetties to stabilize the entrance into Newport Harbor, in addition to a reduction in longshore transport due to the construction of the San Pedro, Middle, and Long Beach breakwaters, and the groin field at West Newport Beach, effectively trapped sand before it was lost into the canyon (Coastal Frontiers Corporation, 2000). During the past few decades, researchers have found that little sand has been lost into Newport Canyon (Everts, 1991; Everts and Eldon, 2005; Felix and Gorsline, 1971; Habel, 1978; Wiegel, 1994). Everts and Eldon (2005) conclude that an average of approximately 1,000 yd³ is lost into the canyon annually.

Subsidence: As a result of the withdrawal of oil and gas from the large Wilmington Oil Field and the Huntington Oil Field dating back to the 1930's, much of the coastline has subsided contributing to beach retreat (Coastal Frontiers Corporation, 2000; Flick, 1993; Griggs et al., 2005). The withdrawal of oil creates a shallow seafloor depression offshore, which ultimately fills with sediment from the nearshore zone, essentially removing this sand from the littoral cell budget. Between 1926 and 1968, Long Beach and Terminal Island subsided substantially, a maximum of 29 feet, (Allen and Mayuga, 1970; Wiegel, 1994), the mouth of the Los Angeles River subsided 9 feet (Allen and Mayuga, 1970; Bush and Steinbrugge, 1961), and Alamitos Bay subsided 15-18 inches (USA/CESPL, 1966b). The subsidence in this littoral cell is equivalent to the loss of over 6.5 million cubic yards of sand (Flick, 1993). Near Huntington Beach, the volume of the subsidence depression is over 20 million cubic yards (Coastal Frontiers Corporation, 1996; 2000). This represents a potentially significant loss of sand to the San Pedro littoral cell. Although about 15 million barrels of oil continue to be extracted from this oil reservoir, the initiation of a subsurface seawater injection program allowed for rebound and a significant reduction of the subsidence, thereby preventing further losses of sediment from the nearshore zone.

Offshore Losses: Sand may be lost offshore and effectively removed from the littoral cell budget by large storm events. This loss is not well understood in the San Pedro littoral cell, and has not been quantified by previous researchers. Estimates of offshore losses of sand are assumed to be in balance with sand entering the cell from offshore such that there is no net gain or loss. Because of the complex nature of the on- and offshore exchange

of sand, estimates were not made in the present study to quantify this component of the sand budget.

Aeolian Deposits Inland: Inland transport of wind-blown sand and the formation and growth of dunes can, in some littoral cells, serve as a significant sink for sand. The potential for sand loss to dunes exists at Seal Beach, Newport Beach, and along Huntington Beach. However, these losses are assumed to be minor and were not quantified for this report.

LONGSHORE SAND TRANSPORT AND LITTORAL CUT-OFF DIAMETER

At different times of the year, waves transport sand in both directions along the shoreline of the San Pedro littoral cell. The net longshore transport of sand, however, is directed to the southeast from Surfside-Sunset Beach, just south of Anaheim Bay, to Newport Bay (Coastal Frontiers Corporation, 2000). Beach sand in the swash zone of this cell was sampled and sieved in this study to determine the average littoral cut-off diameter, which was determined to be 3.25Ø (0.105 mm).

Shore-normal engineering structures such as jetties and groins impound sand to varying degrees and prevent the uninterrupted transport of sand along the entire length of this cell. These structures compartmentalize the shoreline, and, as a result, the San Pedro cell is now divided into sub-cells. There is little to no natural transport of sand between these sub-cells; however, occasionally, sand may be moved from one sub-cell to another for nourishment purposes. In addition, shore-normal structures cause the storage of sand within these sub-cells creating wider beaches than would exist naturally.

SUMMARY OF THE SAND BUDGET FOR THE SAN PEDRO LITTORAL CELL

Los Angeles/Long Beach Harbor Sub-cell: Point Fermin to Alamitos Bay: The Los Angeles/Long Beach Harbor complex sub-cell extends 9 miles from Point Fermin to the west jetty of Alamitos Bay. This shoreline is protected from waves by three breakwaters creating the Los Angeles/Long Beach Harbor complex. Without the wave energy to drive the alongshore movement of sand, littoral drift is nonexistent. Sediment delivered by the Los Angeles River only serves to clog the harbor, and eventually must be dredged from the area to prevent navigational hazards.

Los Angeles/Long Beach Harbor complex was created by the construction of more than eight miles of stone breakwaters within San Pedro Bay. The breakwaters were built in three segments: San Pedro Breakwater, the western most structure, was built in 1912, and extends 11,152 feet in an easterly direction from the shore near Point Fermin; Middle Breakwater is an 18,500-foot-long detached breakwater constructed in the mid 1930's; and the 13,350-foot-long Long Beach Breakwater, is a detached structure built in 1948-49 (Wiegel, 1994). More than 18 square miles of harbor are protected

behind these breakwaters (Figure 7.3; USA/CESPL and CA/DNOD, 1978; Wiegel, 1994). The space between the San Pedro and Middle breakwaters serves as the entrance channel to Los Angeles Harbor, and the channel between the Middle and Long Beach breakwaters serves as the entrance to Long Beach Harbor. Because of the location of these harbors at the northwestern end of the littoral cell, where little to no littoral drift is making its way around Point Fermin, these channels require only minor maintenance dredging on the order of once ever 10 years (Wiegel, 1994). The entrance channel to Los Angeles Harbor has been dredged three times since 1980, with an average dredged volume of about 22,000 yd³/yr (Table 7.2). Long Beach Harbor's entrance channel, between Middle and Long Beach breakwaters, has been dredged only five times since 1970 with an average volume of ~32,000 yd³/yr removed from the channel (Table 7.2). By reducing the wave energy reaching the shoreline in the lee of the breakwaters and ultimately eliminating longshore drift, the original beaches between Long Beach and Seal Beach have been significantly impacted by the harbor construction (Wiegel, 1994).

Within Los Angeles and Long Beach harbors, channels are dredged to a depth of -45 feet MLLW by the Corps of Engineers. Dredging to greater depths is the responsibility of the Port of Los Angeles. Dredge material is either disposed of in the LA-2 disposal site, at an upland disposal area, or used as beach nourishment. LA-2 was designated by the Environmental Protection Agency (EPA) in 1991 as an ocean disposal site for dredge material from the Los Angeles/Long Beach harbor complex located near the edge of the continental shelf, 7.7 miles south of the San Pedro Breakwater. The offshore site area is approximately 2.4 square miles with water depths ranging from 387 to 1,050 feet. Upland disposal of clean material occurs at a location adjacent to the East Basin at the northeastern edge of the Los Angeles Harbor, and is used by the Port of Los Angeles and the Corps of Engineers.

When emergency dredging is required, material is often disposed of in the 600'-by-600' borrow pit located at the mouth of the Los Angeles River. The pit has a maximum depth of -75 feet MLLW, and has a capacity of ~1.7 million cubic yards. The construction of San Pedro Breakwater created the largest artificial beach in southern California, known as Cabrillo Beach (Flick, 1993). The beach is 2,400-feet-long and extends from the ocean side of San Pedro Breakwater northwest where it adjoins the land on the east side of Point Fermin (Figure 7.3). The southern end of the beach is held in place by a 745-foot-long rubblemound groin, built in December of 1962 (Wiegel, 1994). Before the groin was built to stabilize the beach, previous attempts at creating a beach ultimately failed because the sand was lost offshore. In 1927 and again in 1948, 500,000 yd³ and 2.9 million yd³

of sand, respectively, dredged from Los Angeles Harbor, were placed on the beach. Most of this sand was ultimately lost offshore (USA/CESPL, 1989; Wiegel, 1994). After the construction of the groin in 1963, 1.2 million yd³ of sand dredged from the west basin of Los Angeles Harbor was placed onto Cabrillo Beach and proved successful (Dunham, 1965; Herron, 1986; Price, 1966; USA/CESPL, 1989; Wiegel, 1994). However, during the El Niño winters of 1982/83 and 1997/98 Cabrillo Beach experienced significant erosion (USA/CESPL, 1989; Wiegel, 1994). In 1991, Cabrillo Beach was again nourished with 220,000 yd³ of sand from the Hyperion facility (Wiegel, 1994).



Fig 7.3: Cabrillo Beach, the San Pedro Breakwater, and the Los Angeles Harbor. Copyright © 2002 Kenneth & Gabrielle Adelman

Long Beach City Beach is another wide, sandy beach, which receives large amounts of beach nourishment. Between 1943 and 1946, 6 million yd³ of sand dredged from the Los Angeles River delta for flood control purposes was placed on this beach. This nourishment project remained stable and was considered successful because the beach is located in the lee of the breakwater and is protected from wave induced erosion (Wiegel, 1994).

Prior to 1868, the Los Angeles River joined the San Gabriel River upstream from San Pedro Bay. In 1868, extensive flooding caused the San Gabriel to split creating a new channel into Alamitos Bay six miles south of the previous outlet (Kenyon, 1951; Wiegel, 1994). The lower reach of the San Gabriel River became known as the Los Angeles River, and the channel, which spit off into Alamitos Bay, became known as the "new" San Gabriel River. The Los Angeles River currently discharges between Los Angeles and Long Beach harbors directly behind the Queen Mary cruise ship (Figure 7.4).

In 1921, the Los Angeles River was channelized; however, originally no jetties were constructed at its outlet to divert sediment offshore into deeper water. Thus, a delta formed at the mouth of the river; this delta is periodically dredged to provide nourishment to Cabrillo and Long Beach beaches.

Year	LA Harbor	Long Beach Harbor	Alamitos Bay	Anaheim Bay	Newport Harbor
1971				2,260,000	
1972				0	
1973				0	
1974				0	
1975				0	
1976				0	
1977				0	
1978				0	
1979		355,000		0	
1980	356,000	0		0	
1981	0	0		0	81,000*
1982	0	0		0	0
1983	0	0		1,060,000*	0
1984	0	0		1,245,000*	0
1985	0	0		0	0
1986	0	0		0	0
1987	0	0		0	0
1988	0	0		0	0
1989	0	0		0	0
1990	0	0		0	0
1991	0	122,238		0	0
1992	0	0		0	0
1993	0	0		0	0
1994	0	0		0	0
1995	47,022	0		0	0
1996	0	0		0	0
1997		62,426		0	0
1998	122,930	0		0	268,403
1999	0	165,233		331,704	0
2000	0	0		0	0
2001	0	135,171		0	0
2002	0	0		0	0
2003	0	0		0	26,991
2004	0	0		0	0
Average	21,915	32,310	0	144,021	15,683

Table 7.2: Dredging Histories for Harbors in the San Pedro Littoral Cell. Source: Mo Chang (2001; 2005), USACE- LA District, Personal Communication and *Griggs (1987b)

The Los Angeles River under natural conditions transported an average of 233,000 yd³ of sediment annually. This sediment yield has been reduced about 67% by the construction of dams, debris basins, and channelization to an average annual volume of 77,000 yd³. As previously mentioned, this sand does not travel as littoral drift because of the wave protection offered by the Los Angeles/Long Beach Harbor complex breakwaters. This sub-cell ends at Alamitos Bay, which will be discussed in the following section.

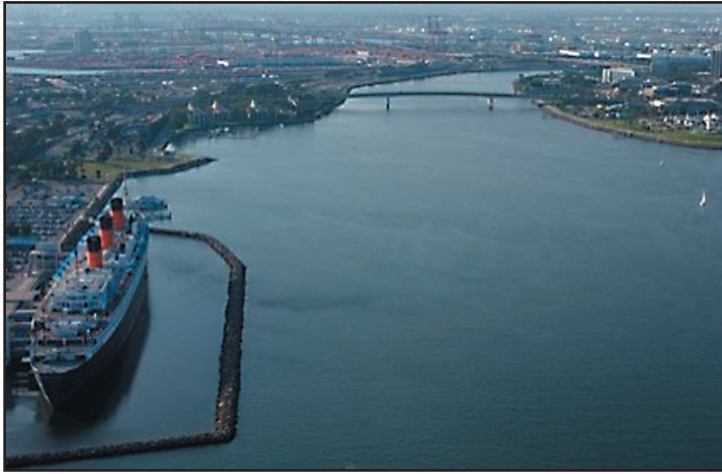


Fig 7.4: The Los Angeles River currently discharges directly behind the Queen Mary cruise ship in between the Los Angeles and Long Beach harbors. 2004. Copyright © 2002 Kenneth & Gabrielle Adelman

SEAL BEACH SUB-CELL: ALAMITOS BAY TO ANAHEIM BAY

Seal Beach sub-cell is a small self-contained stretch of shoreline comprising ~5,300 feet of beach between the San Gabriel River east jetty and the Anaheim Bay west jetty (Figure 7.1). Seal Beach is separated into West Beach and East Beach by a concrete groin built just north of Seal Beach Pier (Figure 7.1 and 7.5). A net northwesterly littoral drift exists in this small stretch of coast which is a result of the sheltering effects of the Long Beach breakwater and wave reflection off the west jetty of Anaheim Bay (Coastal Frontiers Corporation, 2000). Erosion of East Beach, due to the net northwestward littoral drift, has been alleviated by a combination of beach nourishment from outside sources and back passing of material from West Beach (Coastal Frontiers Corporation, 2000; Flick, 1993; Wiegel, 1994)(Tables 7.3 and 7.4).

Wiegel (1994) notes that there has been some discrepancy in the volume of beach nourishment reportedly placed on Seal Beach in 1959 following construction of a sheet pile groin adjacent to the Seal Beach pier. Either 250,000 yd³ of sand dredged from the mouth of the San Gabriel River or 200,000 yd³ of sand dredged from Anaheim Bay's entrance channel was placed on this beach, in addition to an unknown quantity of sand brought in by the city reported by Dunhan (1965). Walker and Brodeur (1993) report that the city of Seal Beach compensates for the transport of sand over and around the seaward

end of the groin by backpassing sand every two years from the west side of the groin to the beaches on the east side of the groin (Tables 7.3 and 7.4). An artificial sand berm has been built on Seal Beach every winter since the 1960's in an attempt to prevent flooding due to storm-wave overwash (Griggs et al., 2005). The berm has prevented a great deal of damage to back-beach development; however, it is occasionally overtopped during El Niño winters (Griggs et al., 2005).



Fig 7.5: Seal Beach, 2002. Copyright © 2002 Kenneth & Gabrielle Adelman

As mentioned previously, the San Gabriel River migrated approximately 2,800 feet to the southeast between 1868 and 1931 eventually discharging into Alamitos Bay. A new outlet to the ocean was constructed for the San Gabriel River in 1933 with the installation of two straight, parallel jetties; the east and west jetties are 725-feet-long and 375-feet-long (extended in 1940 to 725-feet-long) respectively. The new channel, excavated in 1935, provided sand to the surrounding beaches.



Fig 7.6: Entrance to Alamitos Bay and the mouth of the San Gabriel River, 2002. Copyright © 2002 Kenneth & Gabrielle Adelman

Eventually, a new, separate entrance channel for Alamitos Bay was engineered by constructing an additional 800-foot-long jetty parallel to and west of the other two jetties (Figure

Date	Source	Raw Quantity (cy)	Adjustment Factor	Adjusted Quantity (cy)
1967	San Gabriel River	35,000	0.80	28,000
1969	West Beach	130,000	1.00	130,000
1972	West Beach	33,400	1.00	33,400
1974	West Beach	3,000	1.00	3,000
1975	West Beach	5,400	1.00	5,400
1976	West Beach	1,800	1.00	1,800
1983	Anaheim Bay	250,000	0.32	80,000
1988	Anaheim Bay	110,000	0.80	88,000
			Total Quantity	369,000 cy
			Annual Nourishment	12,000 cy/yr

Table 7.3: Beach Nourishment History at East Beach (1963-1994). Adjustment factor refers to the percentage of sand-sized material. Dredged material from rivers is assumed to be 20% fine-grained sediment which will not remain on the beaches unless a more rigorous grain size analysis was done to determine the percentage of beach-quality sediment. Source: Coastal Frontiers Corporation, 2000

Date	Source	Raw Quantity (cy)	Adjustment Factor	Adjusted Quantity (cy)
1967	Nourishment from San Gabriel River	35,000	0.80	28,000
1969	Back passed to East Beach	(-130,000)	1.00	(-130,000)
1972	Back passed to East Beach	(-33,400)	1.00	(-33,400)
1974	Back passed to East Beach	(-3,000)	1.00	(-3,000)
1975	Back passed to East Beach	(-5,400)	1.00	(-5,400)
1976	Back passed to East Beach	(-1,800)	1.00	(-1,800)
			Total Quantity	(-145,000)
			Annual Net Removal Rate	(-5,000) cy/yr

Table 7.4: Beach Nourishment and Back passing History at West Beach (1963-1994). Adjustment factor refers to the percentage of sand-sized material. Dredged material from rivers is assumed to be 20% fine-grained sediment which will not remain on the beaches. Sand back passed from beach sources is assumed to be 100% beach compatible. Source: Coastal Frontiers Corporation, 2000.

7.6). In 1945-46 this new entrance channel was dredged into Alamitos bay providing 800,000 yd³ of sand to the beaches west (or updrift) of the entrance channel (Wiegel, 1994). Alamitos Bay has not needed any maintenance dredging since its construction (Table 7.2).

The San Gabriel River originally provided an average of 182,000 yd³ of sand annually to this sub-cell. Due to the damming of this river and the construction of debris basins, it currently only discharges an average of 59,000 yd³/yr of sand (coarser than 0.0625 mm), which is a reduction of 67% from its natural yield (Willis and Griggs, 2003; Willis et al., 2002).

HUNTINGTON BEACH SUB-CELL: ANAHEIM BAY TO CORONA DEL MAR

Physical Setting: The Huntington Beach sub-cell extends

19 miles from the east jetty of Anaheim Bay to Newport Bay. The majority of this stretch of coast consists of wide, sandy beaches, with the exception of Huntington Cliffs where beaches are narrow to non-existent. The beaches along this stretch of coast are affected by subsidence, the development of Newport Bay and Anaheim Bay, and the historic change in location of the Santa Ana River outlet. Beach nourishment has been an important factor in the widening and stabilization of Surfside-Sunset and West Newport beaches.

During World War II, the U.S. Navy constructed two shore parallel rubble-mound arrowhead jetties forming the entrance to Anaheim Bay (Figure 7.7). This harbor is the site of the 5,256-acre Seal Beach Naval Weapons Station, which was established in 1944. Sand is occasionally forced through the east jetty by wave impact

creating a navigational hazard in the harbor that requires maintenance dredging. Anaheim Bay has been dredged four times since 1971 averaging $\sim 144,000$ yd³/yr (Table 7.2).

The beaches from Surfside (Figure 7.8) to Sunset (Figure 7.9) experienced significant erosion after the construction of the jetties at Alamitos Bay in 1933 (Griggs et al., 2005; Patterson and Young, 1989; Wiegel, 1994). This erosion was further aggravated by subsidence (Habel, 1978; Wiegel, 1994). Beach nourishment is required to maintain and stabilize these beaches to meet the recreational needs of the area. The construction of the Naval Weapons Station between 1944 and 1947 provided 1.4 million yd³ of dredged material, which was placed on the downcoast side of the breakwaters at Anaheim Bay onto Surfside/Sunset beach (Wiegel, 1994)(Table 7.5).



Fig 7.7: Anaheim Bay and the Naval Weapons Station, established in 1944 Copyright © 2002 Kenneth & Gabrielle Adelman

Large-scale nourishment projects are initiated at these beaches because the fill will travel south as littoral drift, and eventually feed Huntington and Newport beaches, where erosion is also threatening back-beach development.

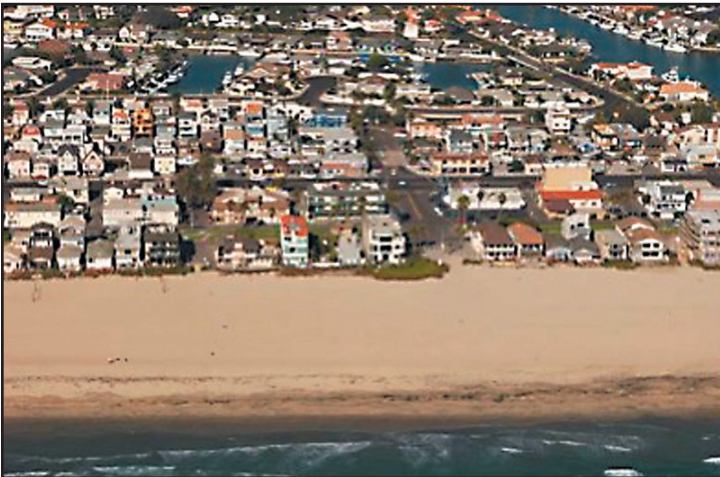


Fig 7.8: Surfside Beach, 2002. Copyright © 2002 Kenneth & Gabrielle Adelman

Huntington Beach (along with Santa Cruz) is known as

Surf City, USA. It is located on a low Pleistocene bluff and is the only cliffed reach in the San Pedro littoral cell (Figure 7.10). As mentioned previously, nourishment of the Surfside/ Sunset beach has provided sand to this stretch of coast as sand moves downdrift in the southerly direction. Despite the nourishment, these beaches are relatively narrow.

Newport Bay/Harbor was created by excavating a lagoon/wetland area (Figure 7.11). The dredged material was used to widen the beach upcoast of the new harbor (Patterson and Williamson, 1960). Although additional dredging has been done in Newport Bay, the projects were not sponsored by the Corps of Engineers, and the material was apparently not placed on the beaches as nourishment (Wiegel, 1994). Since 1981, an average of $\sim 15,700$ yd³/yr of sand has been dredged from the entrance channel of Newport Bay.



Fig 7.9: Sunset Beach, 2002. Copyright © 2002 Kenneth & Gabrielle Adelman

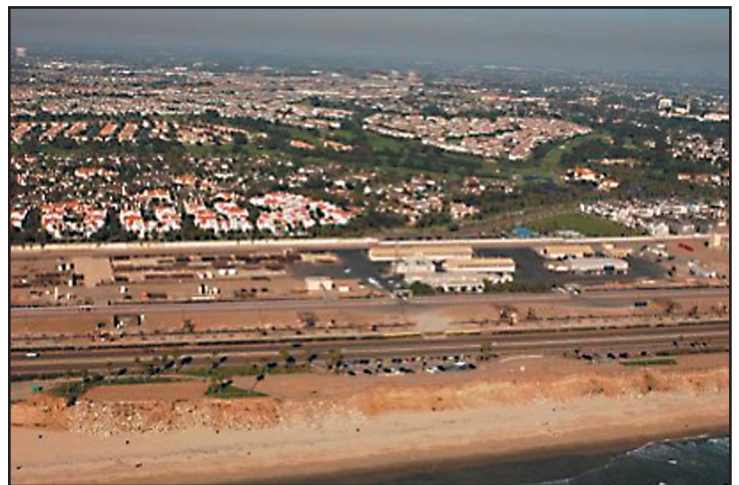


Fig 7.10: Huntington Cliffs, Huntington Beach, California, 2002) Copyright © 2002 Kenneth & Gabrielle Adelman

As a result of severe erosion at West Newport Beach, 8 groins were constructed between 1968 and 1973 (Figure 7.12) in conjunction with a nourishment project which placed a total of 1.8 million cubic yards of sand dredged from the Santa Ana River flood control channel on the

beach in this area (Patterson, 1988) (Table 7.5). This project was successful in stabilizing the beach in this area (Walker and Brodeur, 1993; Wiegel, 1994).



Fig 7.11: Entrance to Newport Bay. Copyright © 2002 Kenneth & Gabrielle Adelman



Fig 7.12: Groins at Newport Beach. Copyright © 2002 Kenneth & Gabrielle Adelman

SAND BUDGET FOR THE HUNTINGTON BEACH SUB-CELL

Beach Nourishment: From 1945 to 2002 more than 15 million cubic yards of sand were placed on Surfside-Sunset Beach as part of a nourishment program (personal communication, Los Angeles District USACE; Coastal Frontiers Corporation, 2000), and nearly 3 million cubic yards of sand were placed on West Newport Beach. This nourishment added approximately 375,000 yds³/yr to the sand budget of this sub-cell (Table 7.5).

River Input: The Santa Ana River (Figure 7.13) is the only significant fluvial source of sand to the Huntington Beach sub-cell. Prior to 1825, the Santa Ana River, originating in the San Bernadino Mountains and flowing across the coastal plain to the ocean, discharged into Anaheim Bay. However, in 1825, extreme flooding caused this river to change its course and shift to the southeast until it eventually discharged near the head



Fig 7.13: Mouth of the Santa Ana River. Copyright © 2002 Kenneth & Gabrielle Adelman

land at Corona del Mar. Charts from 1857 show the river entering the ocean 8,000 feet west of the Corona del Mar headland. In 1861, another major flood caused the mouth of the river to shift again to the base of the headland. Finally in 1920, the river outlet was stabilized with two rock jetties and forced to flow directly into the ocean 5.1 miles updrift of the Corona del Mar headland at the southern end of Huntington State Beach (Patterson and Williamson, 1960; Wiegel, 1994).

The Santa Ana River naturally contributed an average of 379,000 yd³/yr of sand to this sub-cell. This sand yield has been reduced about 67% through damming, and today provides an average of only ~125,000 yd³/yr of sand to this littoral cell (Willis and Griggs, 2003; Willis et al., 2002).

Cliff Erosion: Huntington Cliffs (Figure 7.10), extending ~3,800 feet alongshore, are the only coastal bluffs in the Huntington Beach sub-cell. These bluffs are composed predominantly of fine-grained sediment that will not remain on the beaches when eroded. Through sampling and a grain-size analysis, it was determined that only 14% of the bluff sediment is coarser than 3.25Ø and will remain on the beaches. These bluffs only contribute ~2,000 yd³/yr of sand to the beaches in this sub-cell, on average.

Newport Submarine Canyon: Between West Newport Beach and Balboa Peninsula, Newport Submarine Canyon reaches far enough into the nearshore zone to act as a permanent sink to sand traveling along the shoreline as littoral drift (Coastal Frontiers Corporation, 2000). As previously mentioned, during the past few decades, researchers have concluded that little sand is lost into Newport Canyon (Everts, 1991; Everts and Eldon, 2005; Felix and Gorsline, 1971; Habel, 1978; Wiegel, 1994). Everts and Eldon (2005) estimate that an average of only ~1,000 yd³/yr is lost into the canyon

Subsidence: As discussed previously, subsidence, or the lowering of ground elevation due to oil or water extrac-

Year	Borrow Site	Placement Location	Volume Dredged (cy)	Adjustment Factor	Approximate Sand Volume Placed
1945	Naval Weapons Station	Surfside Sunset Beach	1,400,000	0.80	1,120,000
1964	Naval Weapons Station	Surfside Sunset Beach	4,000,000	0.80	3,200,000
1971	Naval Weapons Station	Surfside Sunset Beach	2,260,000	0.80	1,808,000
1979	Nearshore Borrow Pit	Surfside Sunset Beach	1,644,000	0.80	1,315,200
1983	Naval Weapons Station	Surfside Sunset Beach	500,000	0.80	400,000
1984	Nearshore Borrow Pit	Surfside Sunset Beach	1,500,000	0.80	1,200,000
1984	Naval Weapons Station	Surfside Sunset Beach	783,000		600,000
1988/89	Naval Weapons Station	Surfside Sunset Beach	180,000		72,000
1990	Nearshore Borrow Pit	Surfside Sunset Beach	1,822,000	0.80	1,458,000
1997	Offshore	Surfside Sunset Beach			1,630,000
1999/00	Naval weapons station	Surfside Sunset Beach	330,000		143,000
2002	Offshore	Surfside Sunset Beach			2,223,000
		Annual Nourishment Rate (cy)	= 268,000	Total Quantity (cy)	= 15,278,000
1965	Balboa Peninsula*	West Newport Beach	124,000	1.00	124,000
1966	Balboa Peninsula*	West Newport Beach	60,000	1.00	60,000
1967	Balboa Peninsula*	West Newport Beach	150,000	1.00	150,000
1968	Balboa Peninsula*	West Newport Beach	495,000	1.00	495,000
1968	Santa Ana River	West Newport Beach	246,000	0.80	197,000
1969	Santa Ana River	West Newport Beach	750,000	0.80	600,000
1970	Santa Ana River	West Newport Beach	124,000	0.80	99,000
1973	Santa Ana River	West Newport Beach	358,000	0.80	286,000
1992	Santa Ana River	West Newport Beach	1,300,000	0.80	1,040,000
		Annual Nourishment Rate (cy/yr)	= 223,000	Total Quantity (cy)	= 13,387,200

Table 7.5: Beach Nourishment at Surfside-Sunset Beach and West Newport Beach, 1945-2002. Adjustment factor refers to the percentage of sand-sized material. Dredged material from rivers is assumed to be 20% fine-grained sediment, which will not remain on the beaches.

* Bypassing from Balboa Peninsula is not included in the total nourishment quantity or the annual nourishment rate because it is an intra-cell movement of sand. Data modified from Coastal Frontiers Corporation, 2000, and Los Angeles District, USACE.

tion, has been a significant sink for sand in the San Pedro littoral cell in general, and for the Huntington Beach sub-cell in particular, since the 1920's (Coastal Frontiers Corporation, 1996; 2000; Griggs et al., 2005; Wiegel, 1994). Subsidence had been documented by Orange County and the cities of Long Beach, Huntington Beach, and Newport Beach through long-term monitoring of benchmark elevations (Coastal Frontiers Corporation, 1996; 2000). The estimated sand loss due to subsidence was reported by Coastal Frontiers Corporation (2000) to average $\sim 72,000 \text{ yd}^3/\text{yr}$ in this sub-cell (Table 7.6).

Long-Shore Transport: Estimates of longshore transport for the Huntington Beach sub-cell vary widely depending on the research methods used to calculate the rates. Net longshore transport from Surfside/Sunset beach to Newport Bay is to the southeast, diminishing as you progress towards the Santa Ana River; however season

Sub-Reach	Period	Subsidence (ft/yr)	Sand Loss (cy/yr)
Surfside-Sunset	1976-1986	0.0022	1,000
Bolsa Chica	1976-1986	0.0031	2,000
Huntington Cliffs	1976-1986	0.0525	34,000
Huntington Beach	1976-1986	0.0075	12,000
West Newport	1976-1986	0.0119	7,000
Balboa Peninsula	1963-1992	0.0355	16,000
Total			72,000

Table 7.6: Estimated sand loss due to subsidence in the Huntington Beach sub-cell.

al reversals do occur. Hales (1980) estimated potential littoral drift using detailed wave statistics. His research concluded that there was net transport to the south at an average, annual rate of $276,000 \text{ yd}^3$ at Surfside-Sunset Beach, $112,000 \text{ yd}^3$ at the Santa Ana River Mouth and $127,000 \text{ yd}^3$ at Newport Beach. This is the rate of sand that could "potentially" be transported by the longshore current if that volume of sand were available. It is not a measure of actual littoral drift, however.

SUMMARY

The sand budget for the San Pedro littoral cell is presented in Figure 7.14. The cell has been broken down into three sub-cells: A. Los Angeles/Long Beach Harbor; B. Seal Beach; and C. Huntington Beach. An additional, alongshore, running budget is provided for the area from Anaheim Bay to Newport Bay (the Huntington Beach sub-cell; Figure 7.15). An alongshore running budget was not developed for the Los Angeles/Long Beach and Seal Beach sub-cells as they are almost completely enclosed behind large breakwaters and there is little useful information that would be provided for such a budget.

The Los Angeles/Long Beach Harbor sub-cell extends from Point Fermin to Alamitos Bay; this entire stretch

of coastline is protected from wave action by the breakwaters forming the harbor complex. As a result of these breakwaters, there is little to no alongshore movement of sand in this sub-cell. Sand discharged from the Los Angeles River is the only input of sand, but this sand only serves to clog the harbor. Occasionally, the harbor complex is dredged, averaging $\sim 54,200 \text{ yd}^3/\text{yr}$, and the sand used as nourishment for Cabrillo and Long beaches. The remaining sand, $23,000 \text{ yd}^3/\text{yr}$, is shown as being stored behind the breakwaters of the harbor complex; however this is only an estimate used to balance the budget.

The Seal Beach sub-cell (Figures 7.1 and 7.14) contains a small stretch of coast extending from Alamitos Bay and the San Gabriel River to Anaheim Bay. Unlike the rest of the San Pedro littoral cell, longshore transport or littoral drift, moves to the northwest in this sub-cell. The San Gabriel River discharges an average of $59,000 \text{ yd}^3/\text{yr}$ of sand annually, and beach nourishment from outside sources adds an additional $7,000 \text{ yd}^3/\text{yr}$ of sand to this sub-cell on average. This average does not include sand bypassing operations from West Beach to East Beach because this represents an intra-cell movement of sand, not additional sand to the budget. An average annual sand volume of $66,000 \text{ yd}^3/\text{yr}$ is either stored on the beaches or lost offshore.

Huntington Beach sub-cell is the largest sub-cell in the San Pedro beach compartment, extending from Anaheim Bay to Newport Bay. The sand budget for this sub-cell is shown as a box-model in Figure 7.14 and as a running mile-by-mile alongshore budget in Figure 7.15. Sand sources include an average annual volume of $125,000 \text{ yd}^3$ from the Santa Ana River, $223,000 \text{ yd}^3$ from beach nourishment, and $2,000 \text{ yd}^3$ of sand is provided through cliff or bluff erosion. Sand sinks for this cell include an average annual volume of $\sim 72,000 \text{ yd}^3$ lost through subsidence and $\sim 1,000 \text{ yd}^3$ lost into Newport Submarine Canyon. Anaheim and Newport bays dredge an average of $144,000 \text{ yd}^3/\text{yr}$ and $15,700 \text{ yd}^3/\text{yr}$ respectively. It is assumed that the sand entering these harbors is from the Huntington Beach sub-cell, representing an additional sink. There is a surplus of sand in this cell on the order of $118,000 \text{ yd}^3/\text{yr}$ that is shown to be partially stored behind retention structures resulting in wider than natural beaches, and, to a smaller degree, partially lost offshore.

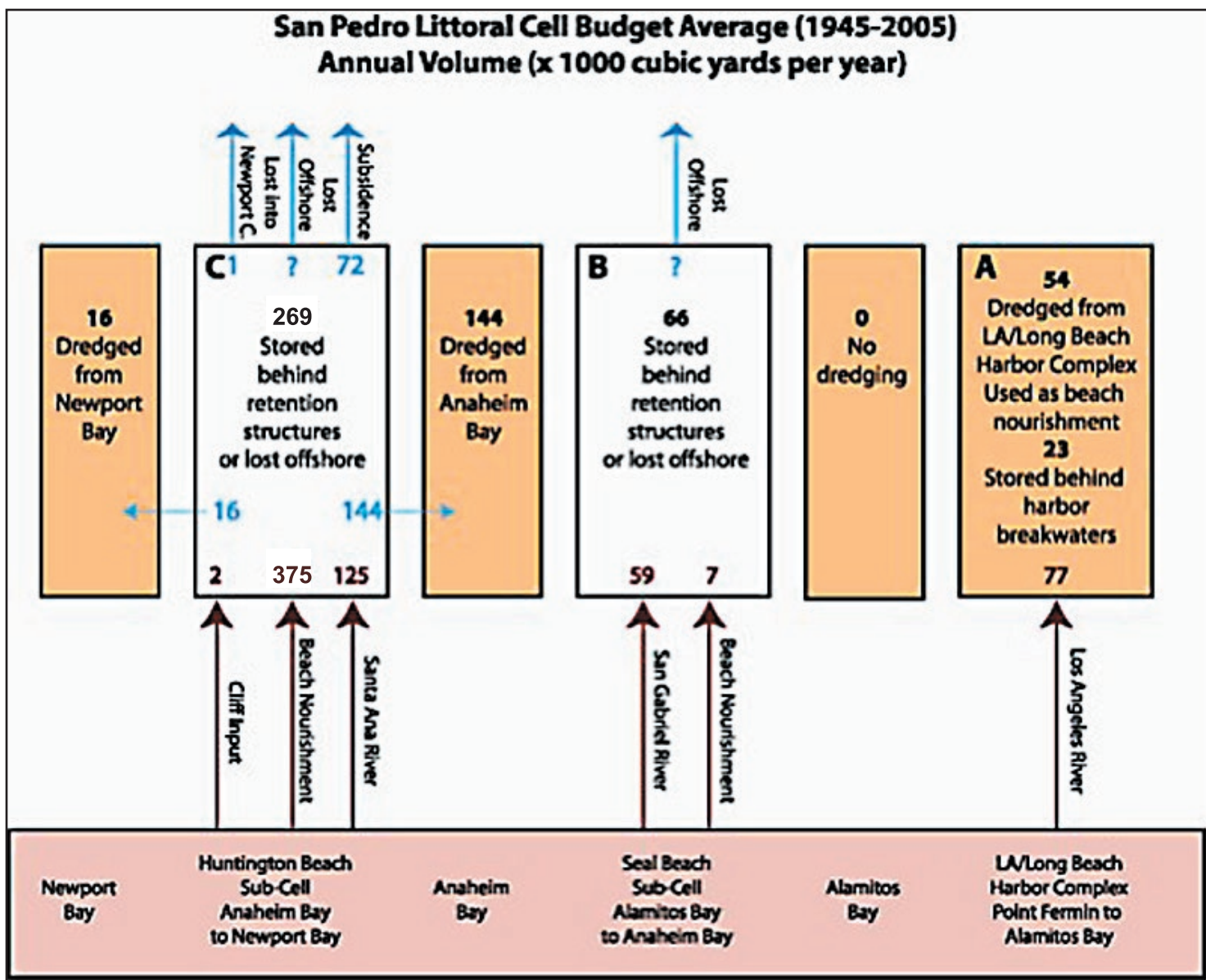


Fig 7.14: Sand Budget developed for the San Pedro littoral Cell from 1945-2005

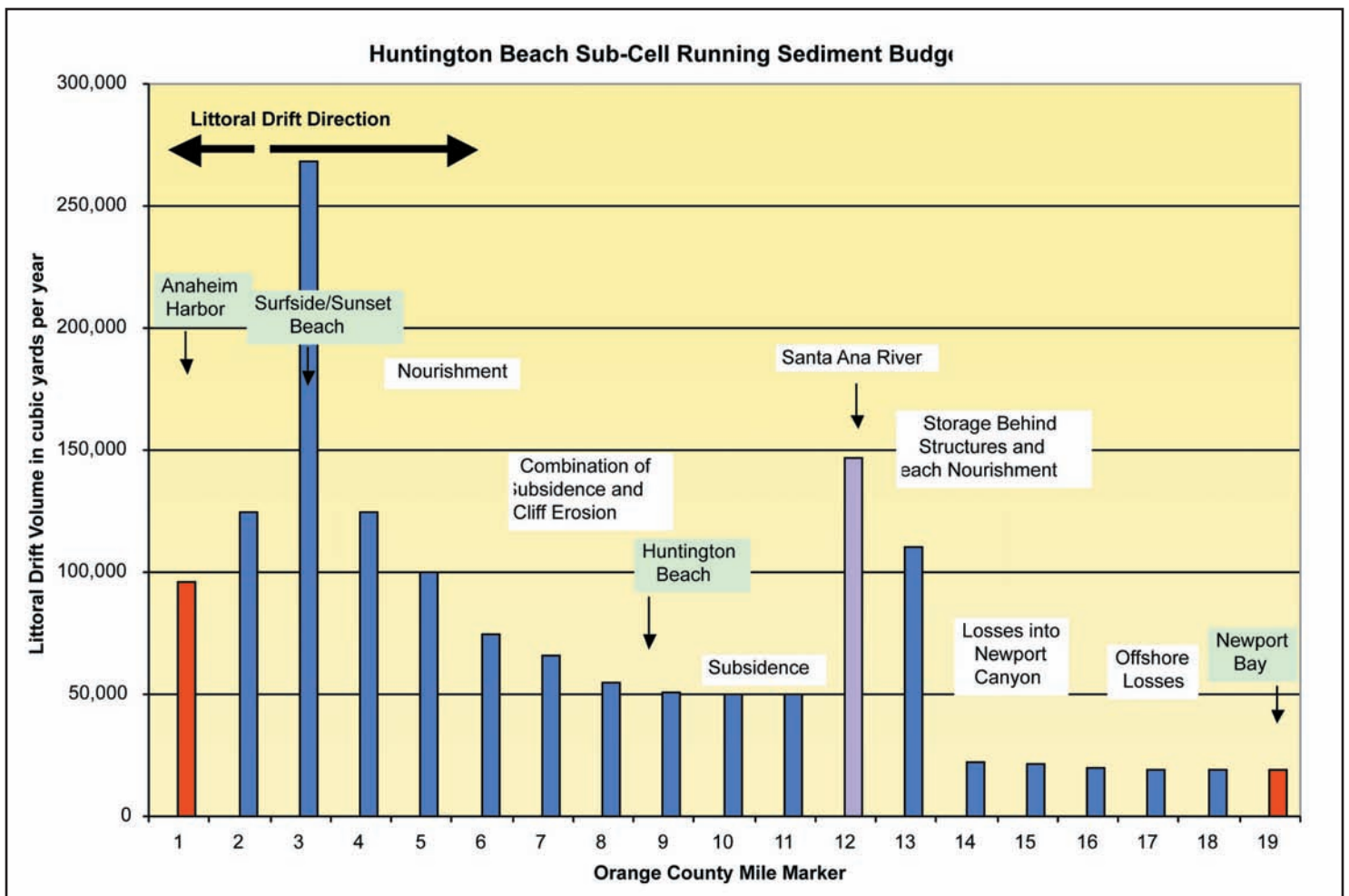


Fig 7.15: Running Budget for the Huntington Beach Sub-cell

CHAPTER 8

LAGUNA LITTORAL CELL SAND BUDGET

The Laguna littoral cell is 13.4 miles long, and is a combination of sub-cells, or mini-cells, confined between Corona del Mar, which ends the San Pedro littoral cell, and Dana Point (Figures 8.1, 8.2, and 8.3). The San Joaquin Hills reach to the Pacific Ocean creating a rocky coastline consisting of resistant headlands and pocket beaches backed by coastal cliffs or bluffs. These sandy pocket beaches are quite wide in some cases; however, access is limited due to bluff-top development and the rugged nature of the coast. Because these beaches are essentially trapped between headlands, they have been relatively stable over the last 50 years (Coastal Frontiers Corporation, 2000). Unlike the other littoral cells in southern California, the Laguna cell has had little human intervention.



Fig 8.1: Map of the Laguna Littoral Cell

The Laguna littoral cell can be divided into 23 "sub-cells"

(Figure 8.3), or mini-cells. Unlike the sub-cells in the San Pedro littoral cell, these sub-cells are not entirely self-contained; in some cases sand makes it around rocky headlands into the adjacent downdrift sub-cell (Coastal Frontiers Corporation, 2000).

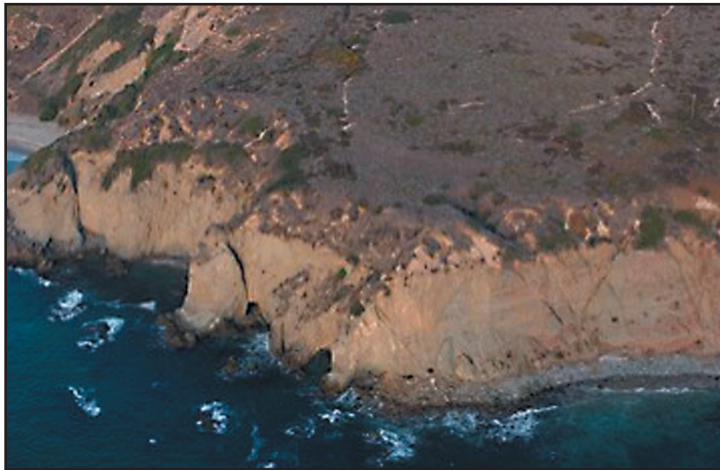


Fig 8.2: Dana Point. Copyright © 2002 Kenneth & Gabrielle Adelman

SAND SOURCES

Rivers: Rivers provide the largest natural source of sand to this region. The three largest streams, Laguna Canyon, Aliso Creek, and Salt Creek (Figure 8.3), provide an average of 1,900 yd³/yr, 12,000 yd³/yr, and 1,200 yd³/yr respectively (Coastal Frontiers Corporation, 2000). Smaller streams and creeks deliver a modest amount of additional sand to each sub-cell. The majority of sand delivered by Aliso Creek (Figure 8.4) is trapped between headlands thus maintaining a stable beach at Aliso Beach (Griggs et al., 2005). Sand discharge from Aliso Creek has decreased from its historic or natural yield due to the infilling of local debris basins and reservoirs; however, this reduction has not been qualified.

The value reported, 12,000 yd³/yr, is under actual, present-day conditions. Coastal Frontiers Corporation (2000) estimate the average annual sand contribution from rivers and creeks to the entire Laguna littoral cell to be ~18,200 yd³/yr, accounting for 66% of the sand to the entire littoral cell budget (Table 8.1).

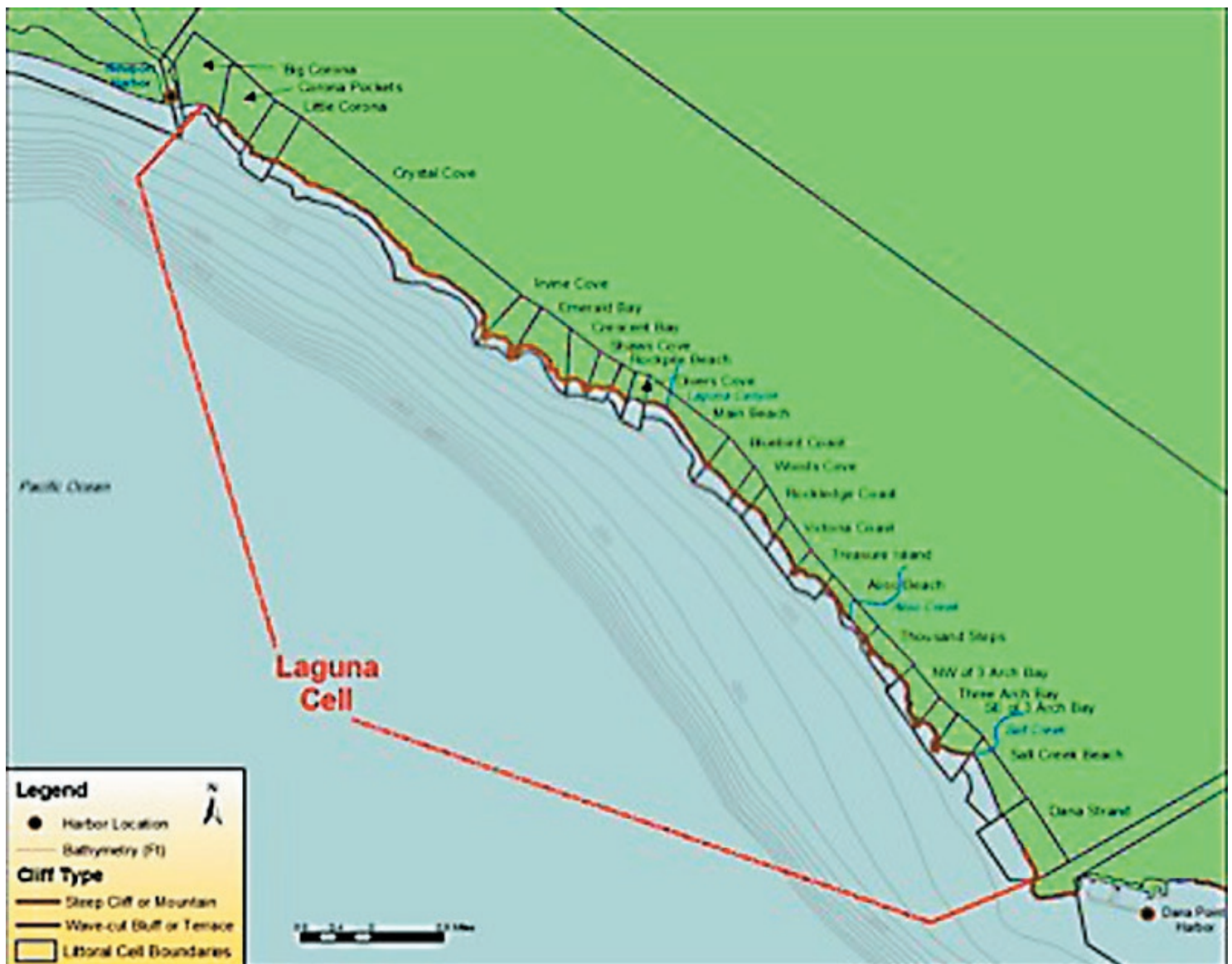


Fig 8.3: Sub-cells and Creeks in the Laguna Littoral Cell

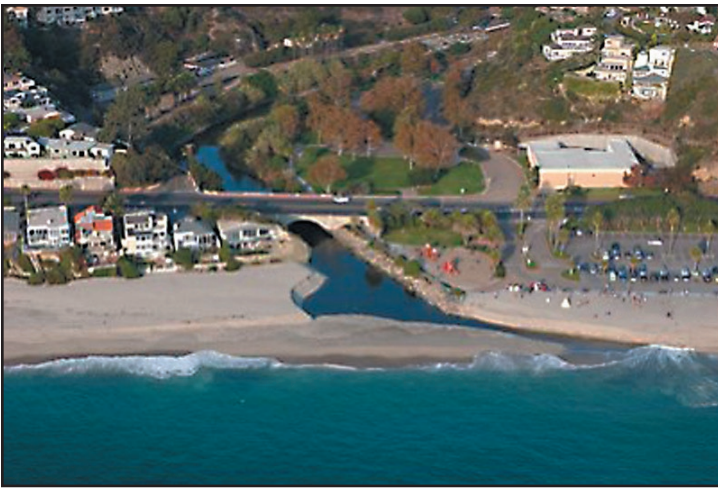


Fig 8.4: Aliso Creek, California. Copyright © 2002 Kenneth & Gabrielle Adelman

Seacliff and Bluff Erosion: Eleven miles of this shoreline are backed by coastal cliffs and bluffs ranging from 15- to 60-feet high with capping terrace deposits up to 15-feet thick; however, cliff erosion rates are minimal due to the resistance of the bedrock forming the cliffs (Griggs et al., 2005). Between Laguna Beach and Dana Point the coastal cliffs and bluffs consist of sandstone with varying degrees of resistance to wave erosion. Retreat rates for the seacliffs along the shoreline of the entire Laguna cell are quite low and range from 0.07 ft/yr to 0.2 ft/yr (Everts, 1995). Cliff erosion was found through this investigation, to contribute an average of $\sim 8,400$ yd³ of sand annually, representing 31% of the overall sand contribution to this cell (Table 8.1). This estimate is in very close agreement with that found by Coastal Frontiers Corporation (2000) of $\sim 7,900$ yd³/yr. Shoreline armoring along a portion of the cliffs has reduced the original, or natural, sand contribution of $\sim 9,700$ yd³/yr by 13%, or 1,200 yd³/yr (Table 8.1).

Laguna Littoral Cell			
Inputs	Natural (cy/yr)	Actual (cy/yr)	Reduction (cy/yr)
Rivers	18,200 (65%)	18,200 (66%)	0 (0%)
Bluff Erosion	9,674 (35%)	8,400 (31%)	1,274 (13%)
Beach Nourishment	0 (0%)	1,000 (4%)	+1,000 (0%)
Total Littoral Input	27,854 (100%)	27,600 (100%)	239 (1%)

Table 8.1: Overall sand contributions and reductions to the Laguna littoral cell. Reductions are due to the damming of rivers and the armoring of seacliffs. "Natural" sand yield refers to the estimated original volume of sand discharged by streams and contributed to the littoral budget through seacliff or bluff erosion. "Actual" sand yield refers to the estimated volume of sand reaching the coast under present day conditions taking into account reductions in sand supply from dams and seacliff armoring as well as additions to the budget from beach nourishment.

Beach Nourishment: Beach nourishment has not been routinely practiced in the Laguna littoral cell. Modest amounts of sand were, however, placed in the Big Corona sub-cell (Figure 8.3) from the construction and maintenance of Newport Harbor (considered in this report to be within the San Pedro littoral cell; Habel and Armstrong, 1978). Coastal Frontiers Corporation (2000) estimated a value of 1,000 yd³/yr of nourishment added to the sand budget in this cell. Their estimate was adopted for this report. Thus, beach nourishment provides $\sim 4\%$ of the sand to the overall littoral budget in the Laguna littoral cell (Table 8.1).

SAND SINKS

Offshore Losses: Because of the crenulated nature of the shoreline and the fact that there are no submarine canyons reaching into the nearshore zone, the largest sink for sand in the Laguna littoral cell is the inner shelf. Coastal Frontiers Corporation (2000) estimated offshore losses by analyzing bathymetric survey data from 1934 and 1975, as well as sand tracers and shoreface slopes. Their findings indicate that the Big Corona sub-cell had a net gain of sand in the inner shelf derived from the offshore region. Rockledge and NW Three Arches Bay had no change in the offshore profiles indicating a zero net transport between the on- and off-shore zones; the rest of the sub-cells lost sand from the inner shelf to offshore. The total flux of sand in all sub-cells is estimated to be an average of $\sim 1,600$ yd³/yr seaward, representing a sink for sand in the littoral budget (Coastal Frontiers Corporation, 2000).

LONGSHORE TRANSPORT

Littoral drift along most of the shoreline in the Laguna littoral cell is interrupted by headlands and trapped in pocket beaches. Alongshore transport rates increase where there is a sand source, such as Aliso Creek, followed by a less crenulated shoreline where the sand has a chance to move downdrift with less interruption by rocky headlands. In these stretches of uninterrupted shoreline, net littoral drift is to the south. Littoral drift had been estimated to be approximately 1,000 yd³/yr to the south from Newport Harbor to Aliso Creek, increasing to approximately 15,000 yd³/yr from Aliso Creek to Dana Point Harbor (Coastal Frontiers Corporation, 2000). These rates are low due to the minimal volume of sand available for transport along this stretch of shoreline. Potential littoral transport rates may be greater; however, with a lack of sand available for transport, the potential is not met, which may result in beach erosion.

SUMMARY

The sand budget for the Laguna littoral cell is shown in Figure 8.5 (on following page). Small sand volumes dominate all sources and sinks for this cell. Due to the crenulated nature of the shoreline, the Laguna littoral

cell is broken into 23 mini-cells or “leaky” sub-cells (Figure 8.3). Sand is supplied to this cell from creeks, sea-cliff or bluff erosion, and beach nourishment. Offshore losses are the main sink for sand. Storage of sand occurs within the sub-cells in pocket beaches, which tend to be stable because the sand is trapped between two headlands. Sand supplied to the beaches through seacliff or bluff erosion has been reduced by ~13% due to coastal armoring; however, this reduction is offset by beach nourishment. Overall, there has been a 1% reduction to the natural sand supply in the Laguna littoral cell when considering beach nourishment as a source of sand in the overall budget. Littoral drift and sand transport between adjacent cells is modest where the beaches are confined between headlands. Sand transport rates alongshore between sub-cells increases south of Aliso Creek (Figure 8.4). Overall, the beaches in the Laguna littoral cell are stable.

Laguna Littoral Cell Budget Average (1927-2005)
Annual Volume (x 1000 cubic yards per year)

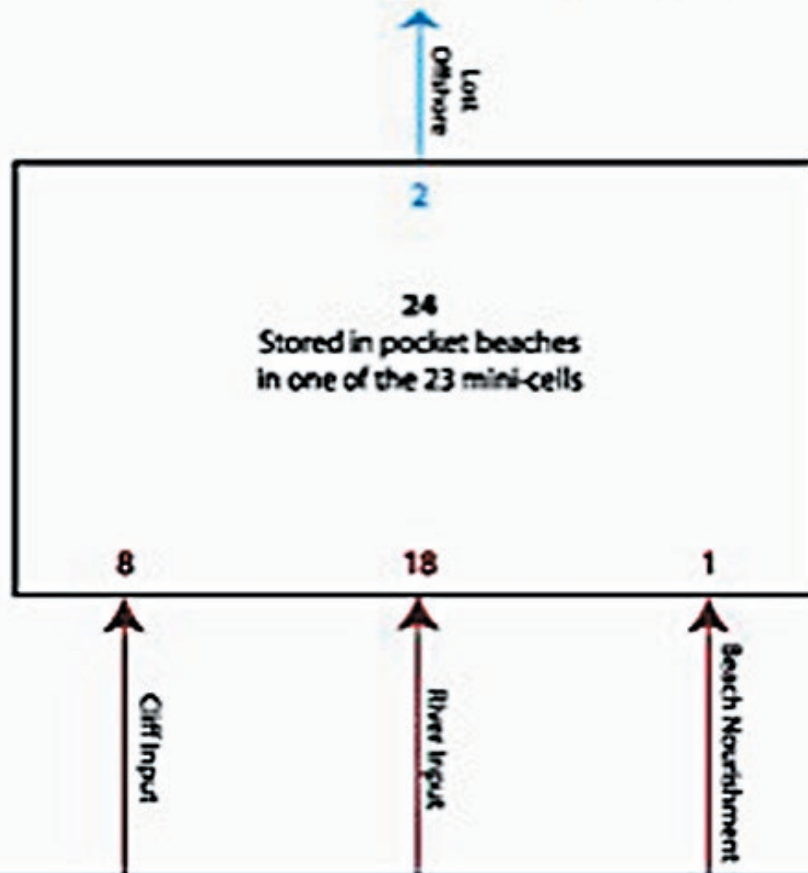


Fig 8.5: Sand Budget for the Laguna Littoral Cell

CHAPTER 9

OCEANSIDE LITTORAL CELL SAND BUDGET

The Oceanside littoral cell (Figure 9.1) extends approximately 50 miles from Dana Point Harbor south to La Jolla and Scripps Submarine Canyons (Habel and Armstrong, 1978; Inman and Frautschy, 1966; Robinson, 1988). The shoreline of this cell consists of a continuous, narrow beach backed by seacliffs or bluffs with the exception of the mouths of coastal rivers and streams. Rocky headlands form the northern and southern boundaries of this cell. The coastal towns of Encinitas and Solana Beach have suffered severe bluff erosion resulting in property damage. Extensive seacliff armoring has been installed over the years in an attempt to halt bluff erosion and protect bluff-top development.

SAND SOURCES

Fluvial Sources: San Juan Creek and the Santa Margarita, San Luis Rey and San Dieguito rivers are the major sources of fluvial sand to the Oceanside littoral cell. San Juan Creek and the Santa Margarita and San Luis Rey rivers each contribute on average $\sim 40,000$ yd³/yr of sand, while the San Dieguito River contributes an average of $\sim 12,500$ yd³/yr of sand to the littoral budget (sediment coarser than 0.0625 mm) (Willis et al., 2002). The Santa Margarita, San Luis Rey and San Dieguito rivers have had their natural sand yields reduced by 31%, 69% and 79%, respectively, (a reduction of $\sim 154,000$ yd³/yr) through damming (Table 9.1)(Willis et al., 2002). Fluvial sources originally provided $\sim 66\%$ of the sand to this littoral cell. Post-damming, the rivers now provide only $\sim 33\%$ of sand to the overall littoral cell budget (Table 9.1).

Sand transport to the coast from these rivers is highly episodic as a function of rainfall duration and intensity. Wiegel (1994) sites a report by Tekmarine (1987), stating that the last time the Santa Margarita and San Luis Rey river mouths were sufficiently breached as to allow a significant volume of sand to be transported into the littoral zone was in 1969 (the time before that was 1941).

Cliff Erosion: Seventy-three percent of the Oceanside littoral cell consists of eroding seacliffs that range in height from 25 to 100 feet with the notable exception of the Torrey Pines area where cliffs reach heights of over 300 feet (Runyan and Griggs, 2002). At most locations in the Oceanside cell, the seacliffs consist of two units: relatively resistant Eocene bedrock, composed of a variety of sedimentary rocks ranging from mudstone to sandstone and conglomerate, and a capping unit of unconsolidated Pleistocene marine terrace material. Once eroded, the bedrock and terrace deposits provide a wide

Legend

- Harbor Location
- Bathymetry (Ft)
- Major Roads

Cliff Type

- Steep Cliff or Mountain
- Wave-cut Bluff or Terrace

Using the littoral cut-off diameter of 0.088 mm, Runyan and Griggs (2002) determined from a grain size analysis of samples collected from the cliff bedrock and terrace deposits that these units contain, on average, about 51% and 57% respectively, of littoral-size material which contributes directly to the coastal beaches.

mately 67,300 cubic yards per year.

Very recent and more detailed work (Young and Ashford, 2006) has re-evaluated the contributions of the seacliff and gully erosion to the beach sand budget in the Oceanside littoral cell using airborne Light Detection And Ranging (LIDAR). Seacliff and gully/terrace beach-sediment contributions were compared to coastal stream beach-sediment contributions from previous studies. This study took place over a relatively dry 6-year period extending from April 1998 to April 2004. The results indicate that during this period seacliffs of the Oceanside Littoral Cell provided about 100,000 yds³ (76,900 m³) of littoral sized sand to the shoreline, almost twice as much as the earlier and less site-specific work of Runyan and Griggs (2002) and earlier values determined by Everts (1990) of 41,600 yds³ (32,000 m³).

Comparison of their results to previous studies suggests that the relative seacliff sediment contributions may be significantly higher than previously thought (25% of the present-day littoral budget; Table 9.1). Again, beach-sediment contributions from gullies and terrace erosion were significantly lower compared with previous studies. This may in part be due to the episodic nature of gullying and the relatively dry study period used by Young and Ashford.

Gully and Terrace Degradation: Additional sand inputs that have been considered in the past to be important to the Oceanside littoral cell include gully and upland terrace erosion or degradation (Kuhn and Shepard, 1984; Robinson, 1988; Runyan and Griggs, 2002). However, as explained above, more recent work by Everts (1990) and Young and Ashford (2006) has been used instead. Based on their shorter-term but more detailed investigation, the contributions of gully erosion and terrace degradation total ~31,500 yds³ of sand annually, or about 7% of the present-day littoral budget for the cell (Table 9.1).

Beach Nourishment: There are two harbors in this littoral cell, Dana Point Harbor, located at the northern end of the cell (Figure 9.2), and Oceanside Harbor (Figure 9.3), located in the middle of the cell. Only Oceanside Harbor requires maintenance dredging and it may be used as an indicator of longshore transport, although there are many complications in the Oceanside cell at this location; the harbor also provides sand for downdrift nourishment. Dana Point Harbor is located at the upcoast, or northernmost point, of the littoral cell, and because of this location at the node between two cells, has not required maintenance dredging since its construction.

Construction began on the Oceanside Harbor in 1942 with the U.S. Marine Corps’ Del Mar Boat Basin. In 1958, its breakwater was extended, and in 1962 the adjacent Oceanside Small Craft Harbor facility was completed, along with another extension of the breakwater. Oceanside Harbor has required routine maintenance dredging since 1963 (Table 9.2). Disposal of dredged material has been used to mitigate the erosion of the downdrift beaches resulting from the construction of the harbor.

In addition to the sand provided by the dredging of Oceanside Harbor, sand was added to the littoral budget in the Oceanside cell from the dredging of Agua Hedionda Lagoon (~4 million cubic yards). Smaller projects such as the construction of the San Onofre Nuclear Generating Station, from 1964-1985, provided an additional ~1.1 million cubic yards of sand to the beaches (Flick, 1989; Wiegel, 1994).

Doheny Beach State Park, located updrift of Oceanside Harbor, was nourished in two increments with sand obtained from San Juan Creek and from local marine terrace deposits (Wiegel, 1994). The downdrift portion of the beach, located 4,500 feet from San Juan Creek, was nourished with 690,000 cubic yards of sand trucked in from old terrace deposits at Camp Pendleton in 1966 (Shaw, 1980; USA/CESPL, 1965; Wiegel, 1994). The second part of the nourishment project took place on the beaches between Dana Point Harbor’s east breakwater and the jetty on the north side of San Juan Creek. In 1964, 94,000 cubic yards of sand, obtained from San Juan Creek, were placed on these beaches (Wiegel, 1994). To maintain the fill, the San Juan north jetty was constructed. This project formed a pocket beach 1,400-

feet-long, which is still heavily used today, and changed the beach from a cobble and rock beach to a sandy beach (Wiegel, 1994).

Oceanside Littoral Cell			
Inputs	Natural (cy/yr)	Actual (cy/yr)	Reduction (cy/yr)
Rivers	286,500 (66%)	132,500 (33%)	154,000 (54%)
Bluff Erosion	118,000 (27%)	100,000 (25%)	18,000 (15%)
Gully/Terrace Erosion	31,500 (7%)	31,500 (7%)	0 (0%)
Beach Nourishment		138,000 (34%)	+138,000 (0%)
Total Littoral Input	435,700 (100%)	401,700 (100%)	34,000 (8%)

Table 9.1: Overall sand contributions and reductions to the Oceanside littoral cell. Reductions are due to the damming of rivers and the armoring of seacliffs. “Natural” sand yield refers to the estimated original volume of sand discharged by streams and contributed to the littoral budget through seacliff or bluff erosion. “Actual” sand yield refers to the estimated volume of sand reaching the coast under present day conditions taking into account reductions in sand supply from dams and seacliff armoring as well as additions to the budget from beach nourishment.

In 1982, 1.3 million cubic yards of sand were trucked in from the San Luis Rey river bed to nourish the severely eroding beaches at Oceanside (Flick, 1994; Wiegel, 1994). In total, beach nourishment (not including bypassing from Oceanside Harbor) has provided ~7.2 million cubic yards of fill on the beaches in this cell, which is ~138,000 yd³/yr over the last 65 years (1940-2005), representing 34% of the sand in the overall littoral budget (Table 9.1).

More recently, approximately two million yds³ of sand were dredged from six offshore sites and placed on the beaches of San Diego County (Patsch and Griggs, 2006). This project was coordinated by local governments working together through SANDAG and was funded by \$16 million in state and federal funds and about \$1.5 million from the region’s coastal cities. It was seen as an initial step in overcoming what has been perceived as a severe sand deficit on the region’s beaches. A total of six miles of beaches were nourished from Oceanside on the north to Imperial Beach on the south. About eighty-five percent of the sand (1,780,000 yds³) went to the beaches of the Oceanside Littoral Cell. This volume was added to the historic 65-year nourishment volumes included in Table 9.1.

Interestingly, although there has been a reduction of about 54% in the littoral sand input to the Oceanside Cell, this was not a source of large amounts of sand under natural conditions (Table 9.1). The average annual nourishment over the past 65 years has nearly made up

for much of the reduction from stream damming such that the total budget for the cell has only been reduced by about 8 percent. While the budget appears nearly balanced on an average annual basis (Table 9.1), with the exception of the 2001 SANDAG nourishment project most of the historic nourishment took place several decades ago so there is still appears to be a significant reduction in sand input to the cell compared to the original natural conditions.

SAND SINKS

Submarine Canyons: Sand entering the Oceanside littoral cell moves southward in the direction of the net along-shore transport and eventually enters the heads of La Jolla and Scripps submarine canyons (Figure 9.1), which are within a few hundred yards of the shoreline, just offshore from Scripps Institution of Oceanography (Inman, 1976). These canyons extend offshore in a southwesterly direction for approximately 33 miles, eventually depositing sediment into San Diego Trough, although it is widely believed that La Jolla Submarine Canyon is not a functioning sink for beach sand at the present time.

Dunes: Sand lost to inland dunes is not a significant factor in the Oceanside cell (Flick, 1994).

Offshore Bar: Dolan et al (1987), by comparing National Ocean Survey Sheets for 1934 and 1971-72, found an offshore bar near the entrance to Oceanside Harbor: "The accretion band extends offshore for about 1.5 miles near Oceanside Harbor and then turns parallel to the existing bottom contours at depths between 40 and 60 ft." This pattern of accretion indicates offshore deflection of littoral sand by the harbor's north breakwater, and subsequent southerly transport induced by a coast-parallel current outside the surf zone. According to Dolan et al. (1987), the total offshore deposition translates into an average annual accretion rate of $\sim 144,000$ yds³/yr, if the deposition dates back to the initial construction of the Del Mar Boat Basin in 1942. Dolan et al. also believe that the gross drift arriving from the south may be partially deflected offshore as well. It had been hypothesized by many researchers (Dolan et al., 1987; Inman and Jenkins, 1985; Wiegel, 1994) that this offshore bar is a major sink for sand in this cell. For the purposes of this study, the offshore bar is used to balance the sand budget for the northern reach of the Oceanside littoral cell. Consistent with the findings of Dolan et al (1987) $\sim 144,000$ cubic yards per year is shown as moving offshore to be stored in the sandbar.

SAND BUDGET SUMMARY FOR THE OCEANSIDE LITTORAL CELL

The Oceanside littoral cell will be divided into two sub-cells for this study—Dana Point to Oceanside Harbor, and Oceanside Harbor to the La Jolla and Scripps submarine canyons.

Dana Point to Oceanside Harbor: Dana Point Harbor, con-

structed in 1970, is situated at the extreme northern end of the Oceanside littoral cell. Since its construction, the harbor has never been dredged for maintenance or navigational purposes. Because it is at the northern tip of a littoral cell with southward-directed littoral drift, and there is little to no sand entering the cell from the rocky stretch of shoreline to the north, this harbor does not act as a sand trap (Griggs, 1987b; Wiegel, 1994). Dana Point Harbor is situated in an ideal location in terms of its position within a littoral cell to avoid the problem of maintenance dredging characteristic of many harbors in California.

Just downcoast of Dana Point Harbor, San Juan Creek (Figure 9.2) enters the ocean, and sandy beaches begin to appear. Littoral drift carries this sand southward until it is joined with the sand from San Mateo Creek and the Santa Margarita River. Combined, these fluvial sources add $\sim 80,000$ yds³/yr of sand to the littoral system (Willis and Griggs, 2003; Willis et al., 2002). Seacliff erosion from this stretch of coast provides an additional $\sim 69,000$ yds³/yr of sand (Young and Ashford, 2006). Gully and upland terrace erosion, provide an additional $\sim 31,500$ yds³/yr. Artificial beach nourishment provides an additional $\sim 110,000$ cubic yards per year of sand to the littoral budget. These sand sources combined supply this stretch of the Oceanside littoral cell with $\sim 290,000$ yds³/yr of sand (Figure 9.4 and 9.5). For the purposes of this study, the offshore bar (seaward of Oceanside Harbor) is used to balance the sand budget for the northern reach of the Oceanside littoral cell. Consistent with the findings of Dolan et al (1987), $\sim 144,000$ cubic yards per year is shown as moving offshore to be stored in the sandbar. The remaining $\sim 146,000$ yds³ of sand being transported as littoral drift ends up in the entrance channel of Oceanside Harbor where it is dredged and bypassed to the downdrift, or southerly, beaches.

Longshore Transport: At least five studies have attempted to calculate alongshore transport rates within the Oceanside littoral cell. Marine Advisors (1960) used available wave data and calculated a net southerly longshore transport rate of 215,000 yds³/yr. Following harbor construction, the accretion rate of sand in the harbor entrance was measured along with the associated loss of sand from Oceanside Beach, downcoast of the harbor. Based on entrance channel dredging and downcoast beach erosion, Inman (1976) concluded that the net longshore transport of sand along the shoreline of the Oceanside littoral cell is about 250,000 yds³/yr to the south.

Hales (1979) and Inman and Jenkins (Inman and Jenkins, 1985) using wave statistics and potential littoral drift theory described in the Shore Protection Manual (USACOE, 1984), determined that an average of 740,000 cubic yards of sand annually are directed to the south and $\sim 550,000$ yds³ of sand are directed to the north per year. This gives an average gross transport

rate of $\sim 1,290,000 \text{ yds}^3$ of sand per year, and an average net southward transport rate of $\sim 194,000 \text{ yds}^3$ of sand annually (Dolan et al., 1987). Seymour and Castel (1985) used continuous directional wave measurements immediately south of the harbor to estimate net sand transport over a one-year period (1980) to be about 6500 yds^3 to the north. All of these are potential littoral drift values and are calculated using the wave energy flux approach. These are maximum possible transport rates, independent of sand supply. These calculations are also extremely sensitive to nearshore bathymetry which will determine the amount of wave refraction and therefore the amount of wave energy directed along-shore. The net transport rate found by the longer-term studies ($194,000 \text{ yds}^3/\text{yr}$ to the south) is somewhat lower than the littoral drift calculated from 38 years of dredging history recorded at Oceanside Harbor (averaging $220,000 \text{ yds}^3/\text{yr}$).



Fig 9.2: Dana Point Harbor and San Juan Creek

Based on the influx of sand to the cell upcoast of the Oceanside harbor ($\sim 290,000 \text{ yds}^3/\text{yr}$), the offshore accumulation of sand in the large bar ($\sim 144,000 \text{ yds}^3/\text{yr}$), the dredging history at the entrance to Oceanside Harbor ($220,000 \text{ yds}^3/\text{yr}$), the net littoral drift near Oceanside Harbor is considered to be $\sim 146,000 \text{ yds}^3/\text{yr}$ in a down-coast or southeasterly direction. The difference between this value and the average annual dredging volume ($220,000 \text{ yds}^3/\text{yr}$) is $\sim 74,000 \text{ yds}^3/\text{yr}$ and is considered to be the average net volume of sand that is transported in a northerly or upcoast into the harbor entrance.



Fig 9.3: Oceanside Harbor

Oceanside Harbor to La Jolla/Scripps Submarine Canyon: South of the Oceanside Harbor the majority of sand, $\sim 50,000$ cubic yards per year, is supplied by fluvial source—

the San Luis Rey and San Dieguito Rivers (Willis et al., 2002). Seacliff erosion, resulting mostly from the erosion of the cliffs in the Torrey Pines area, provides an additional $\sim 44,000 \text{ yds}^3/\text{yr}$ of beach-sand-sized material (0.088 mm or coarser). From the previous discussion regarding balance of transport at the Oceanside harbor, it appears that on average, about $74,000 \text{ yds}^3$ of the $\sim 220,000 \text{ yds}^3$ dredged on average from the Oceanside Harbor annually is transported upcoast into the harbor by littoral drift from the south. Combining these volumes ($\sim 40,000 \text{ yds}^3/\text{yr}$ from streams, $\sim 44,000 \text{ yds}^3/\text{yr}$ from cliff erosion, and $146,000 \text{ yds}^3/\text{yr}$ net downcoast littoral drift at Oceanside Harbor) yields an average of $\sim 226,000 \text{ yds}^3/\text{yr}$ that is added to the beaches between Oceanside Harbor and Scripps Submarine Canyon (Figures 9.4 and 9.5).

There was no significant beach nourishment in this part of the cell until the 2001 SANDAG project added $1,780,000 \text{ yds}^3$ on the beaches south of the harbor. The littoral sand remaining in the system is eventually lost into the Scripps Submarine Canyon (Figure 9.1).

While developing a conceptual model of a littoral cell, such as the Oceanside Cell, with its inputs, outputs, littoral drift and storage is relatively straightforward, attempting to average out the often very large year-to-year fluctuations and produce a quantitative budget is extremely difficult. Those who have studied individual coastal areas or specific littoral cells understand the uncertainties involved. Thus any littoral cell budget is a best estimate based on all accessible information and some judgement calls. Thus while we can calculate a net littoral transport at the Oceanside Harbor of $146,000 \text{ yds}^3/\text{yr}$, there are large year-to-year variations, and changes in patterns over time. Richard Seymour of the Scripps Institution of Oceanography (written communication), has observed, for example, that the Oceanside Harbor is not a perfect sediment trap and:

- preferentially bypasses fine-grained sand and traps coarse sand when transport is from the south.
- is a trap for the bypassed sand when it moves north in the summer
- is shoaled by fine sand, which is then dredged and deposited to the south and is then available to be transported back into the harbor
- sees a very small net transport as the difference between two significant directional transport rates

Thus any littoral cell budget needs to be seen as a work in process complicated and made more difficult by annual variations, uncertainties in measuring and/or quantifying each of the individual components, and human impacts to each of the individual processes and components.

Oceanside Harbor Dredging

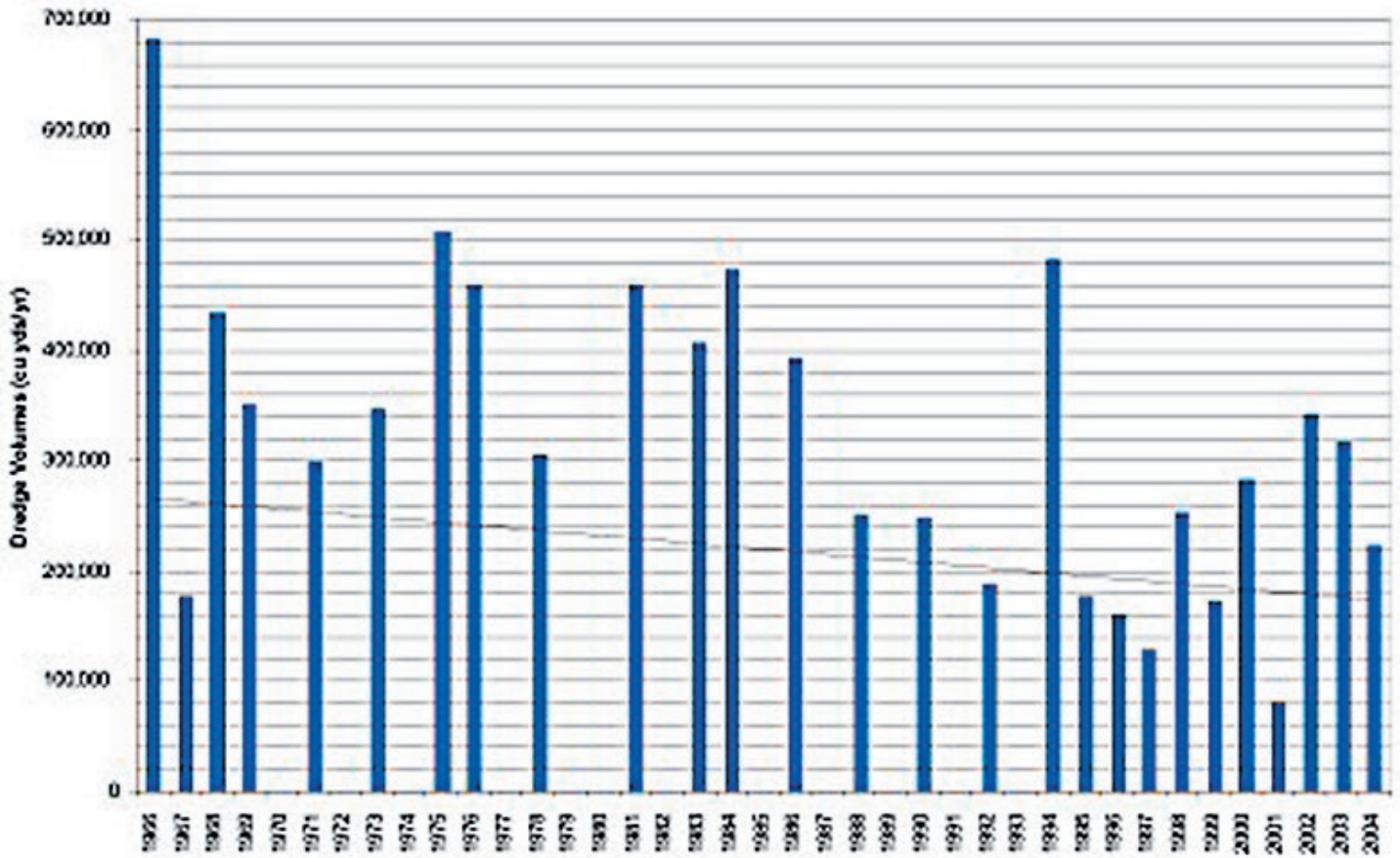


Table 9.4: Annual maintenance dredging volumes for Oceanside Harbor. Average maintenance dredging in the entrance channel from 1966-2004 is ~220,000 yd³/yr. (Chang, 2001; 2005)

Oceanside Littoral Cell Sand Budget (1940-2005)
Average Annual Volume (x 1000 cu yards per year)

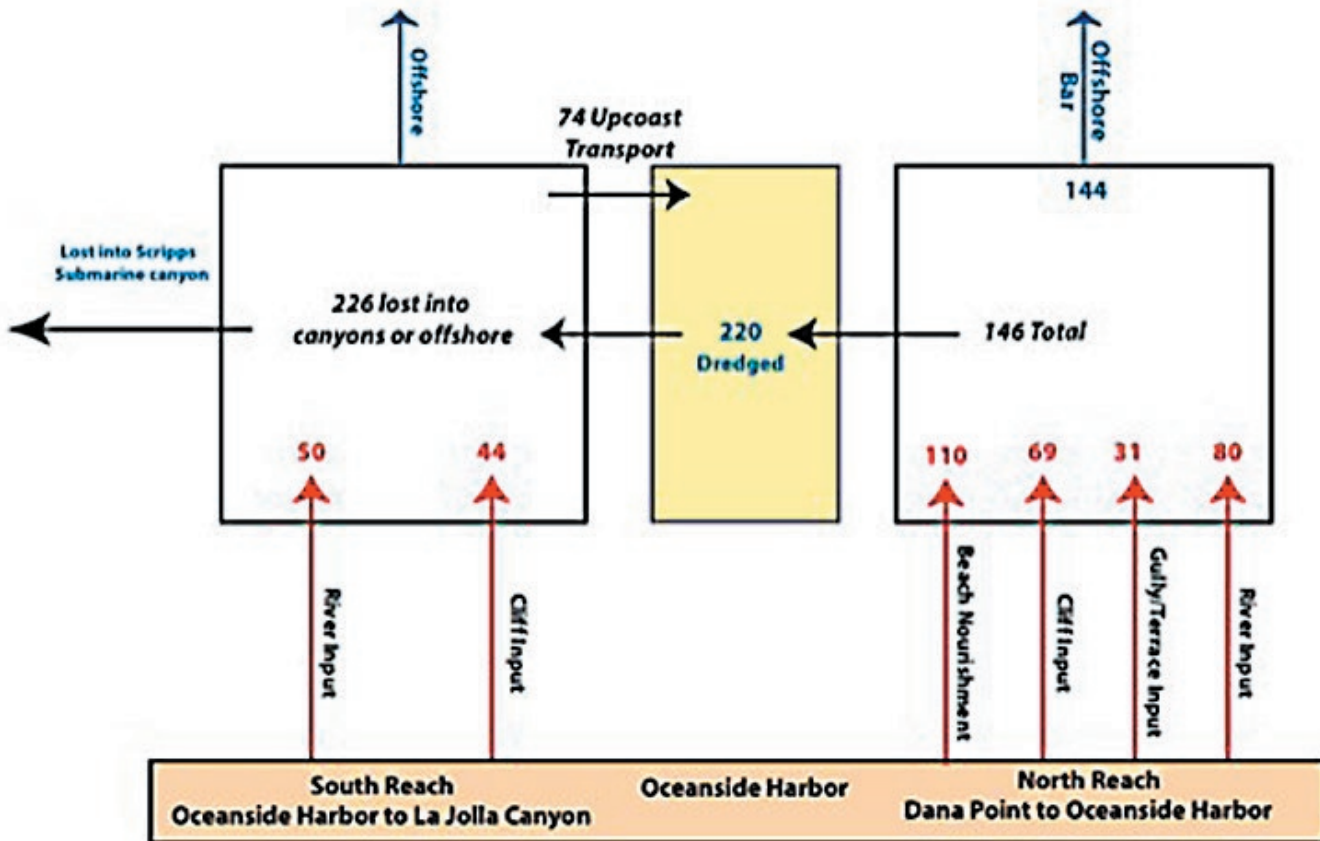


Fig 9.4: Sand Budget for the Oceanside Littoral Cell

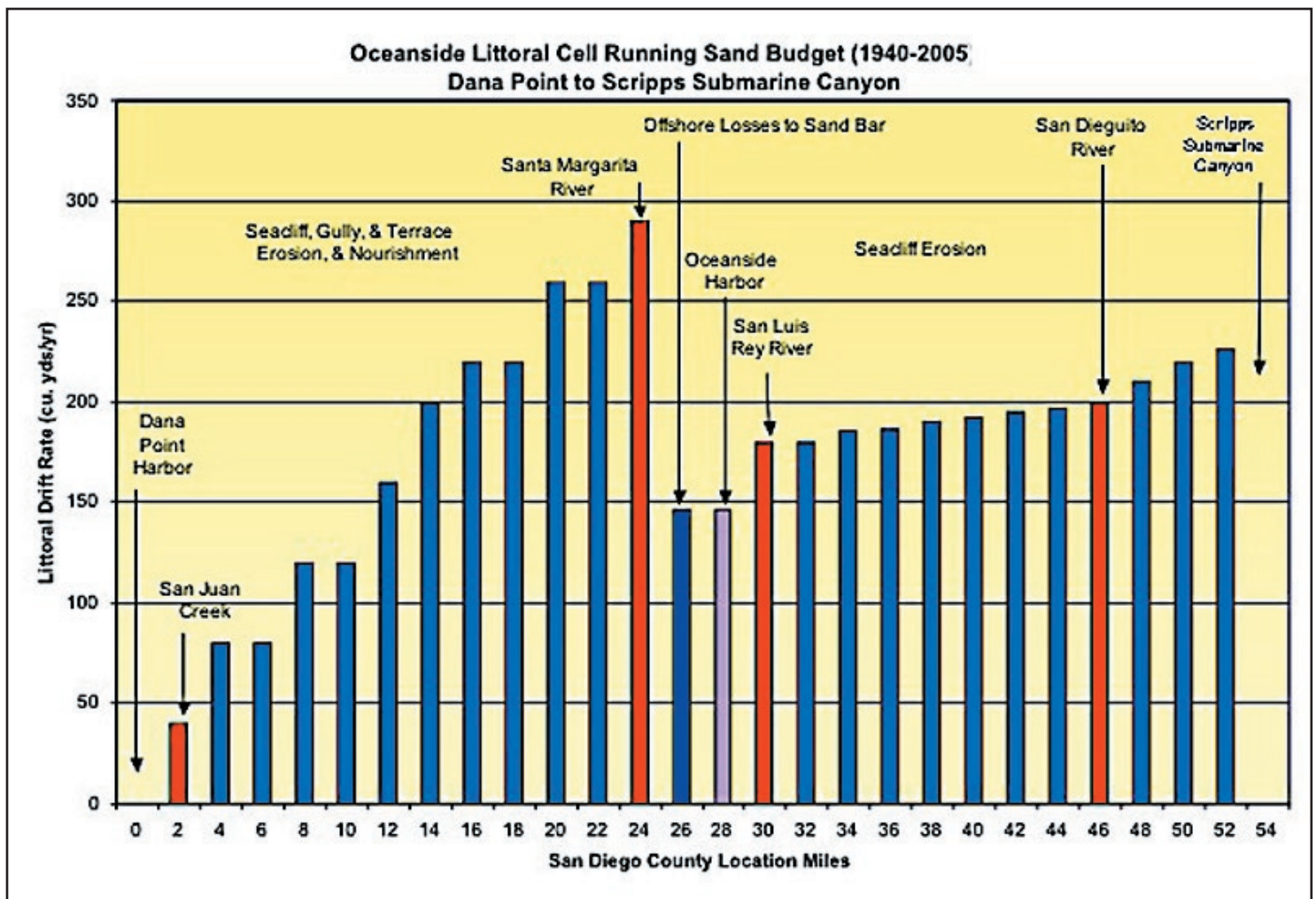


Fig 9.5: Running, mile-by-mile sand budget for the Oceanside littoral cell (no nourishment included)

CHAPTER 10

MISSION BAY LITTORAL CELL SAND BUDGET

Mission Bay littoral cell (Figure 10.1) is a north-south oriented shoreline extending 14 miles from Point La Jolla to Point Loma. The shoreline in this stretch of coast is characterized by coastal cliffs and bluffs with pocket beaches in addition to moderately wide, sandy beaches.



Fig 10.1: Mission Bay littoral cell

PHYSICAL SETTING



Fig 10.2: False Point showing the rocky shoreline of Point La Jolla Copyright © 2002 Kenneth & Gabrielle Adelman

Point La Jolla is a large, Cretaceous-age, rocky promontory distinguished by narrow pocket beaches, caves, and uplifted, wave-cut terraces. Extensive development exists near the cliff edge on this headland; shoreline armoring has been emplaced to protect private, cliff-top development (Figure 10.2).

Located just south of Point La Jolla, Pacific Beach, a moderately wide, sandy beach, extends for 1.5 miles (Figures 10.3 and 10.4). This beach is backed by cliffs or bluffs and dunes ranging in height from ~60 feet at the northern end to beach level at the southern end. The back beach along this reach of coast is extensively developed with residential properties in the northern stretch and commercial development occupying the southern portion. Despite the extensive development fronting Pacific Beach, there are few shoreline protection structures along the northern part of this area; south of Crystal Pier, however, a low concrete seawall is nearly continuous along the back beach (Figure 10.4).

MISSION AND OCEAN BEACHES

Located adjacent to Pacific Beach, Mission Beach is bordered on its west side by the Pacific Ocean and on its east side by Mission Bay (Figures 10.3 and 10.5). Wide, sandy beaches exist on the ocean side; narrow to moderately wide beaches exist on the bay side. These beaches are intensively used recreational areas due to excellent access (access exists at the end of nearly every street) and their proximity to San Diego. Mission Beach has been extensively developed, primarily with residential homes.

Fig 10.3: Mission Bay Littoral Cell (below)

Mission Beach is low-lying and prone to flooding. Beaches on the west, or ocean, side also have coastal hazards associated with wave attack and beach erosion.



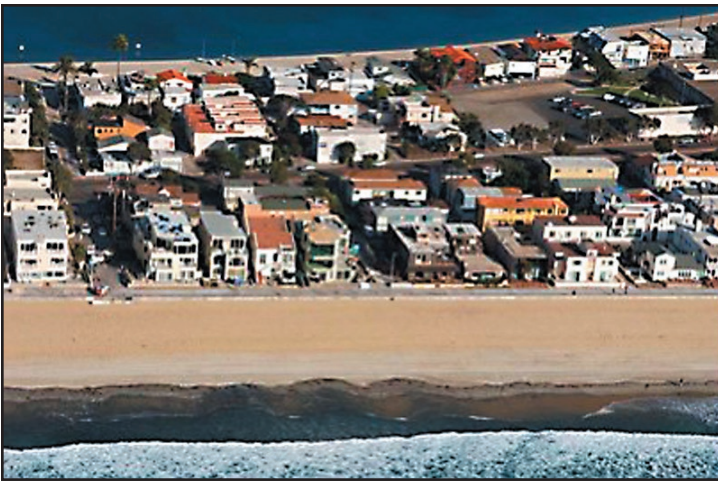


Fig 10.4: Southern End of Pacific Beach, San Diego Copyright © 2002 Kenneth & Gabrielle Adelman associated with wave attack and beach erosion.

The northern jetty stabilizing the entrance to Mission Bay interrupts littoral drift traveling south, trapping sand and creating a wide, sandy beach at the southern end of Mission Beach. Mission Beach is backed by a concrete seawall and promenade, which were overtopped and damaged by large waves during the El Niño winters of 1982-82 and 1997-98 (Griggs et al., 2005). Both Pacific and Mission beaches rest on the former delta of the San Diego River (Griggs et al., 2005).



Fig 10.5: Mission Beach, San Diego Copyright © 2002 Kenneth & Gabrielle Adelman

Mission Bay, formerly called False Bay, is an extensively modified wetland where development began as early as 1921 for boating and tourist activities. Mission Bay is now the largest aquatic park in the world, generating significant revenue for the city of San Diego (Griggs et al., 2005).

In 1949-1950, three straight, parallel, rubble-mound jetties were constructed in a combined flood control project for the San Diego River and Mission Bay Aquatic Park (Figure 10.6). The north jetty, middle jetty, and south jetty are 3,300-feet-long, 3,800-feet-long (extended to 4,270 feet in 1970), and 1,500-feet-long (extended to 2,050 in 1970) respectively (Wiegel, 1994). The middle

and south jetties create the 800-foot-wide San Diego Flood Control Channel (Figures 10.6 and 10.7).



Fig 10.6: Entrance to Mission Bay on the left; San Diego River channel on the right. Copyright © 2002 Kenneth & Gabrielle Adelman

In 1950, a channel was dredged through the north and middle jetties, which are 919 feet apart crest to crest, to create an entrance into Mission Bay; however, the channel was not dredged deep enough, and by 1951 the channel was essentially closed (Hales, 1979). The Korean War interrupted further work on this project until 1955. In 1975, the channel was dredged to a depth of -20ft MLLW meeting standard navigational requirements (Hales, 1979; Herron, 1972; Wiegel, 1994).

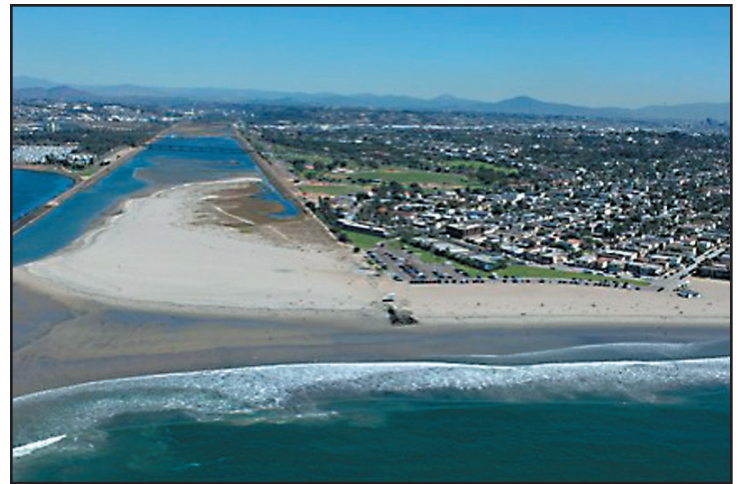


Fig 10.7: Mouth of the San Diego River, 2006. Copyright © 2002 Kenneth & Gabrielle Adelman

Maintenance dredging is required in the entrance channel to Mission Bay because of the small tidal prism relative to the navigational depths required and the width of the entrance channel (O'Brien, 1931; Wiegel, 1994). Since 1948, almost 2 million cubic yards (or 34,000 yd³/yr on average from 1948-2005) have been dredged from the entrance channel and placed on the beaches in the Mission Bay littoral cell, often backpassed upcoast to nourish Mission and Pacific beaches (Chang, 2001;

2005). Overall, including the interior of Mission Bay, 2.5 million cubic yards of sand (or 44,000 yd³/yr from 1948-2005) have been dredged from Mission Bay and placed on the adjacent beaches (Table 10.1).

Date	Quantity (yd ³ /yr)	Disposal Location
1948*	600,000	Pacific Beach
1950	67,000	Ocean Beach
1955*	347,440	Unknown
1957/58	150,000	Mission Beach
1959	342,000	Ocean Beach
1973*	287,150	Pacific Beach
1983*	276,120	Unknown
1984*	448,000	Mission Beach & Ocean Beach
Total 2,517,710		
Annual Average (1948-2005) 44,170 yd ³ /yr		

Table 10.1: Dredging and Disposal History of Mission Bay.*Entrance Channel Dredging or Bypassing (~34,400 yd³/yr: average annual maintenance dredging from entrance channel alone). Sources: (Chang, 2001; 2005; Griggs, 1987b; Wiegel, 1994)

Point Loma, much like Point La Jolla, is uplifted Cre-
taceous-aged bedrock (Figure 10.3). Ocean Beach,
extending 0.6 miles (Figure 10.8), is the only long sandy
beach on Point Loma.



Fig 10.8: Ocean Beach, Mission Bay Littoral Cell. Copyright © 2002 Kenneth & Gabrielle Adelman

The majority of the beaches along this point are pocket
beaches located between rocky headlands with poor
access, with the exception of excellent coastal access at
the southern end through Cabrillo National Monument.
The steep cliffs along much of Point Loma are up to 300-
feet-high and susceptible to wave attack and erosion
(Figure 10.9).

The ocean edge of Point Loma is home to the residential
and commercial communities of Ocean Beach and Sun-
set Cliffs (Figures 10.8 and 10.9), in addition to naval
facilities and the San Diego regional sewage treatment
plant. Ocean Beach and Sunset Cliffs are erosion hot-
spots and problem areas. In the summer of 1955, a rock
groin was constructed to retain ~275,000 yd³ of sand
dredged from Mission Bay and placed on the Ocean

Beach. Bluff retreat at Sunset Cliffs has damaged public
streets and destroyed public and private land.



Fig 10.9: Sunset Cliffs, Point Loma; collapsed cave and
crenulated shoreline Copyright © 2002 Kenneth & Gabrielle
Adelman

Erosion of these cliffs is due to wave-induced erosion
at the base of the cliffs in addition to bluff-top erosion
from surface run-off and human activities. Various types
of shore protection structures have been built over the
years in an attempt to mitigate the erosion and protect
the development. An investigation by the Army Corps
of Engineers found that coastal bluffs at Sunset Cliffs
retreated 40 feet between 1962 and 1976 (a long-term
average erosion rate of almost 3 feet per year) at the
end of Del Mar Ave (Figure 10.10) (Griggs et al., 2005).



Fig 10.10: Shoreline armoring at the end of Del Mar Ave,
Point Loma. Copyright © 2002 Kenneth & Gabrielle Adelman

SAND SOURCES

Rivers: Mission Bay was originally one of two natural
outlets of the San Diego River, the other being San
Diego Bay. In 1855, the U.S. Army Corps of Engineers
constructed a levee to divert the San Diego River to per-
manently discharge into Mission Bay (then called False

Bay)(Herron, 1986; Wiegel, 1994). This levee had to be rebuilt in 1875 and again in 1885 after it was washed out by flooding (Wiegel, 1994). The mouth of the San Diego River is often closed by littoral drift during extreme rainfall and run-off events creating flooding concerns for Mission Valley (sediment accumulation at the mouth of the San Diego River can be seen in Figure 10.7). A lowered weir was constructed into the middle jetty allowing for potential floodwaters to discharge through both the river channel and the entrance to the bay (Griggs et al., 2005).

The San Diego River is a source of sand to the Mission Bay littoral cell. This river drains an area of ~435 square miles, 88% of which is mountainous. For most of the year, the lower reaches of this river are essentially dry due to the construction of two large reservoirs; during the summers, the headwaters are also dry (Hales, 1979). The rock-lined, San Diego Floodway prevents discharge from entering Mission Bay.

Dams built on the San Diego River have reduced the sand supply to the shore by ~91% (Willis et al., 2002). Historically, the San Diego River contributed 71,900 yd³/yr of sand, on average, representing 43% of the sand in the overall littoral budget for this littoral cell. Dams have reduced this yield to 6,600 yd³/yr of sand (Willis et al., 2002), representing only 7% of the littoral budget for the Mission Bay littoral cell (Table 10.2).

Mission Bay Littoral Cell			
Inputs	Natural (cy/yr)	Actual (cy/yr)	Reduction (cy/yr)
Rivers	71,900 (43%)	6,600 (7%)	65,300 (91%)
Bluff Erosion	93,700 (5%)	77,000 (82%)	16,700 (18%)
Beach	0 (0%)	10,500 (11%)	+10,500 (0%)
Nourishment			
Total Littoral Input	165,600 (100%)	94,000 (100%)	71,500 (57%)

Table 10.2: Overall sand contributions and reductions to the Mission Bay littoral cell. Reductions are due to the damming of rivers and the armoring of seacliffs. “Natural” sand yield refers to the estimated original volume of sand discharged by streams and contributed to the littoral budget through seacliff or bluff erosion. “Actual” sand yield refers to the estimated volume of sand reaching the coast under present day conditions taking into account reductions in sand supply from dams and seacliff armoring as well as additions to the budget from beach nourishment. Nourishment includes sand dredged from the interior of Mission Bay but not entrance channel dredging (which is considered bypassing).

Cliffs: Over 9.5 miles of this shoreline are backed by cliffs or bluffs ranging in height from 10- to 300-feet with capping terrace deposits up to 20-feet-thick. Erosion rates for these cliffs range from 1 to 3 feet per year. The bedrock is comprised of 39.5% beach-sand-sized sediment (coarser than 3.25Ø or 0.105 mm, the littoral cut-off diameter in this cell) while the terraces are com-

posed of 88% beach-sand-sized sediment. Armor fronts 2.3 miles of the cliffs and bluffs, essentially removing, for the purposes of this study, the bluffs protected by the armor as a sand source. Seacliff erosion naturally provided an average of ~93,700 yd³/yr of beach-compatible sand to this cell, representing 57% of the overall natural littoral budget. Seacliff armoring has reduced this volume by 18% to ~77,000 yd³ of sand annually (Table 10.2). The majority of this sand (70,000 yd³/yr naturally and 63,000 yd³/yr after armoring) is derived from the 4.5 mile stretch of coast from Sunset Cliffs to the southern end of Point Loma.

Beach Nourishment: As stated earlier, about 2.5 million cubic yards of sand (or 44,170 yd³/yr from 1948-2005) have been dredged from Mission Bay and from the entrance channel and placed on either upcoast or down-coast beaches. However, almost 2 million cubic yards of this total (or 34,400 yd³/yr from 1948-2005) have been dredged from the entrance channel (Chang, 2001) and is, therefore, considered bypassing or backpassing rather than nourishment. The difference between these two, about 500,000 yds³, or 9,000 yd³/yr, 10% of the present-day littoral budget, came from Mission Bay and is included as nourishment in the budget (Table 10.2). As part of the 2001 SANDAG nourishment project, 100,000 yds³ of additional sand was placed on Mission Beach. This has been added to the nourishment component of the budget (Table 10.2)

SAND SINKS

There are no submarine canyons reaching into the near-shore zone in the Mission Bay littoral cell. The largest sand sink is assumed to be offshore as littoral drift travels south along Point Loma and is lost around its tip. Offshore losses have not been quantified for this littoral cell by previous researchers, and therefore, have not been calculated in this study. In order to balance the littoral cell budget, a long-term average of ~83,000 yd³/yr of sand are assumed to be lost offshore or stored behind retention structures in the reach of shoreline from Mission Bay to Point Loma, and an average of 12,000 yd³/yr in the stretch of coast from Point La Jolla to Mission Bay.

Littoral Drift: Net littoral drift in this cell is minimally to the south in the Mission Bay littoral cell. Wave exposure is reduced by the sheltering effects of the offshore islands of San Clemente, Santa Catalina, San Nicholas, Santa Cruz, Santa Rosa, and the Los Coronados Islands of Mexico. In addition, submerged shoals south of San Clemente Island, Tanner Banks and Cortez Banks, also reduce wave exposure providing sheltering to the shoreline. Thus, the shoreline in this cell is exposed to varying wave energies related to the shoreline configuration and the location of offshore islands creating wave exposure windows in some locations and sheltering in others (Hales, 1979). Southward directed transport appears to be only slightly greater than the northward transport,

resulting in minimal net southward movement of sand.

SUMMARY

The sand budget for the Mission Bay littoral cell is shown in Figures 10.11 and 10.12 (found on the following 2 pages) as a box model and a running, cumulative, mile-by-mile budget respectively. From Point Loma to Mission Bay, sand is added to the system through seacliff or bluff erosion ($\sim 9,000 \text{ yd}^3/\text{yr}$), and beach nourishment from dredging in the interior of Mission Bay ($\sim 3,000 \text{ yd}^3/\text{yr}$). The entrance channel to Mission Bay is dredged periodically (averaging $\sim 34,000 \text{ yd}^3/\text{yr}$), which is back-passed upcoast to nourish Pacific Beach and Mission Beach. Adjacent to Mission Bay, on the downdrift or southern side of the entrance channel, the San Diego River discharges an average of $\sim 6,600 \text{ yd}^3$ of sand annually. Ocean Beach is nourished with sand periodically dredged from the interior of Mission Bay ($\sim 7,000 \text{ yd}^3/\text{yr}$). The largest sand source is the erosion of seacliffs along the shoreline of Point Loma, which adds an average of $\sim 69,000 \text{ yd}^3/\text{yr}$ of sand to the littoral budget. The surplus of sand in the southern portion of the cell ($\sim 83,000 \text{ yd}^3/\text{yr}$) is assumed to travel south along Point Loma and is then lost offshore, or stored in pocket beaches between Ocean Beach and the end of Point Loma.

Mission Bay Littoral Cell Budget (1948-2005) **Annual Volume (x 1000 cubic yards per year)**

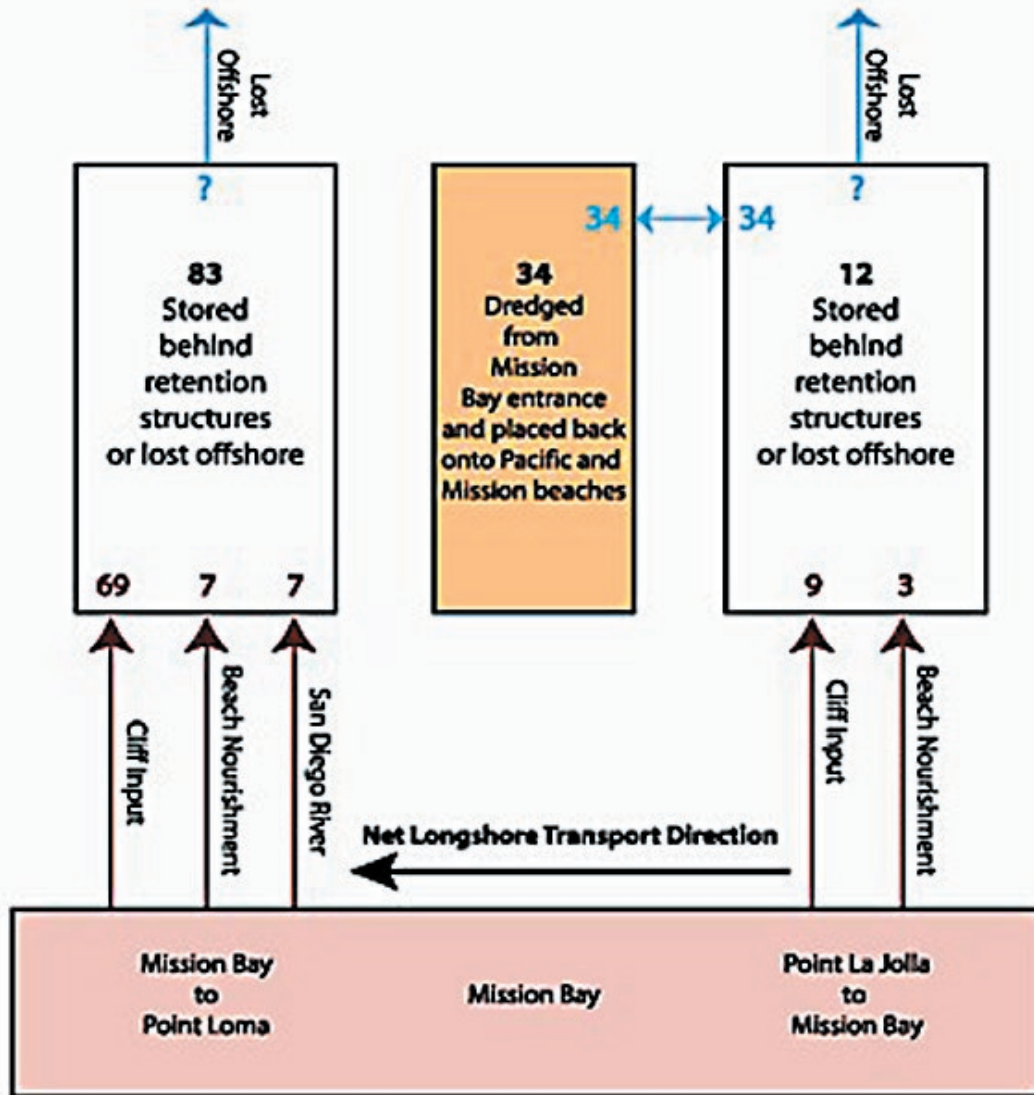


Fig 10.11: Mission Bay Sand Budget (1948-2005)

Mission Bay Littoral Cell: Running Budget 1948-2005

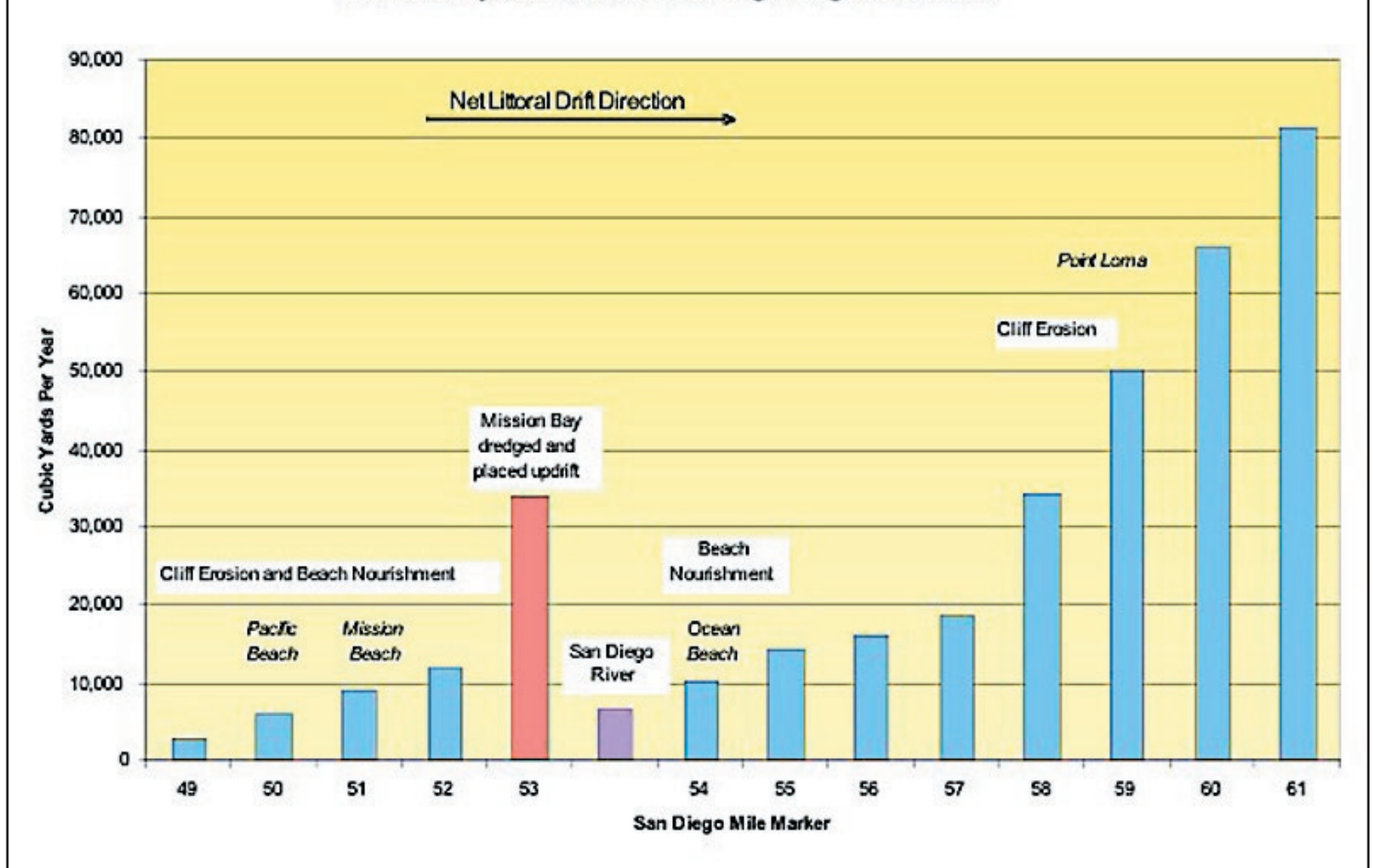


Fig 10.12: Running Budget for the Mission Bay Littoral Cell

CHAPTER 11

SILVER STRAND LITTORAL CELL SAND BUDGET

Silver Strand littoral cell (Figure 11.1) extends from the entrance of San Diego Bay south past the international border (Figure 11.2) and into Mexico, encompassing 16 miles of shoreline in California and another 20 miles into Mexico to Punta El Descanse (Wiegel, 1994). Wide, sandy beaches occupy the shoreline in the California portion of this cell, which will be the focus of this sand budget. South of the Tijuana River delta, the shoreline consists of narrow, sandy beaches backed by bluffs. Beaches in this cell are the most highly altered in southern California.

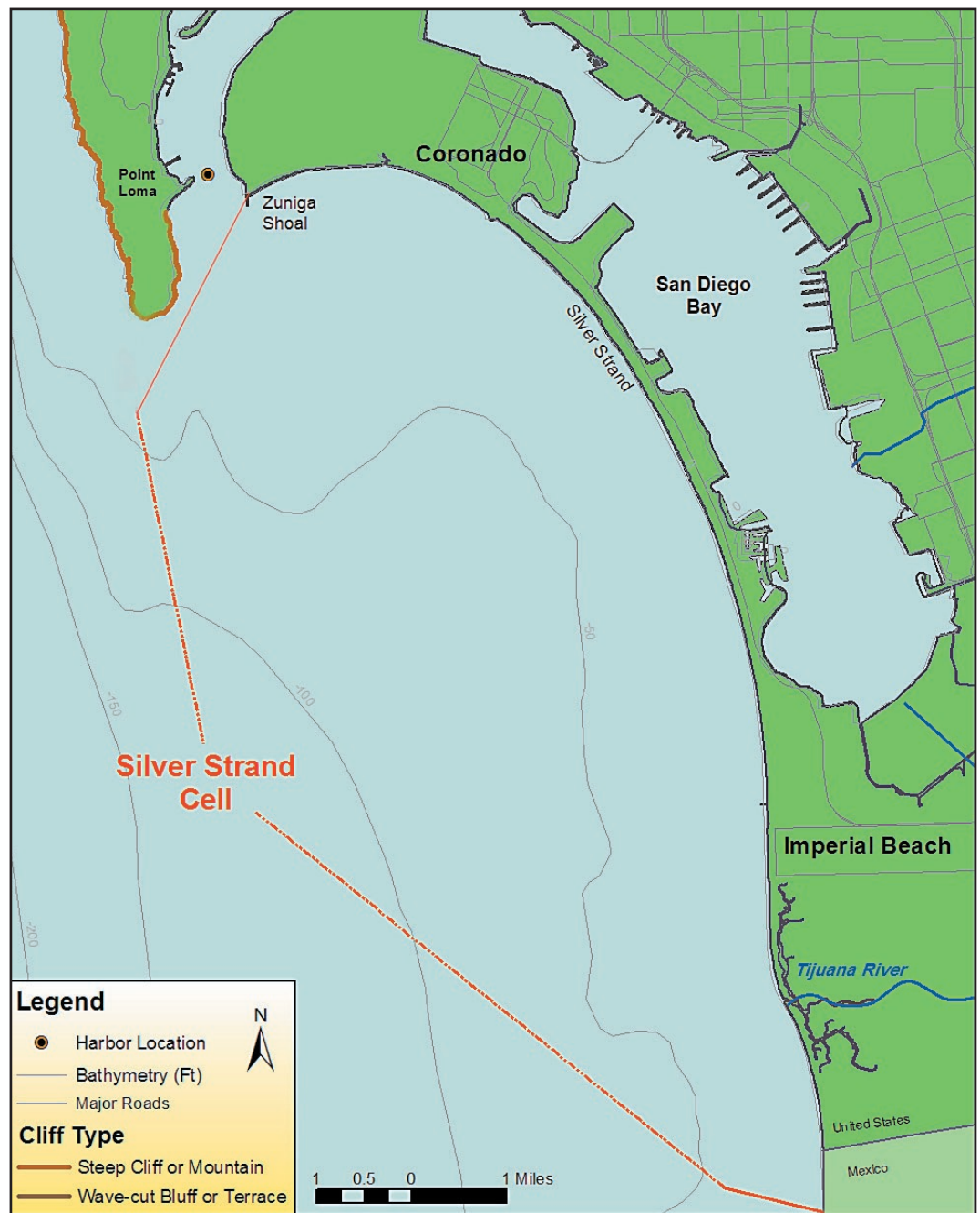


Fig 11.1: Location Map for the Silver Strand littoral cell

From 1940 to 2005, beach nourishment projects added almost 40 million yds³ of sand to this cell in an attempt to mitigate severe beach erosion at Imperial Beach, Silver Strand Park and in the past, Coronado (Flick, 1993; Inman, 1973; Inman, 1974; Inman, 1976; Wiegel, 1994).

San Diego Bay or Harbor is an 18-mile-long, elongated, crescent shaped embayment with a variable width and a high tide area of 16.6 square miles. The Bay is separated from the Pacific Ocean by a narrow sand barrier, Silver Strand, which is connected to Coronado Island and North Island. The entrance to San Diego Bay is self-scouring to a depth of 25 feet; however it is dredged to ~45 ft by the Army Corps of Engineers.

San Diego Bay is a major naval, commercial, and recreational center at the extreme southern limit of California's coast, approximately 110 miles south of Los Angeles. The Navy has facilities at the inner, northern end of the harbor approximately seven miles from the entrance channel. This harbor is a major stopping point for agricultural goods from southern California, Arizona, and New Mexico, and is also the center of the west coast commercial tuna fishing industry. Recreational facilities are near the north end of the harbor and along the shore of Silver Strand.



Fig 11.2: International Border: United States on the left; Mexico on the right. Copyright © 2002 Kenneth & Gabrielle Adelman

Pt. Loma is considered the northern boundary of the Silver Strand Cell (Habel and Armstrong, 1977). The 7,500-foot-long, rubble-mound Zuniga Jetty, completed in 1904, located on the east side of the entrance to San Diego Bay, forms a littoral barrier for littoral transport moving north along the Silver Strand (Figure 11.3). Around 1900, a 1,400-foot-long curved groin was constructed adjacent to the Hotel del Coronado (Figure 11.4) to provide safe anchorage to boats.

The 3-mile-long stretch of coast between Zuniga Jetty and this groin is likely the widest beach in southern California (Flick, 1993). This beach remains relatively stable because it is located at the downdrift end of the littoral

cell; it is protected from all waves except those from due south, and is essentially trapped between two shore-normal structures (Flick, 1993).



Fig 11.3: Zuniga jetty at the eastern side of the entrance to San Diego Bay. Copyright © 2002 Kenneth & Gabrielle Adelman

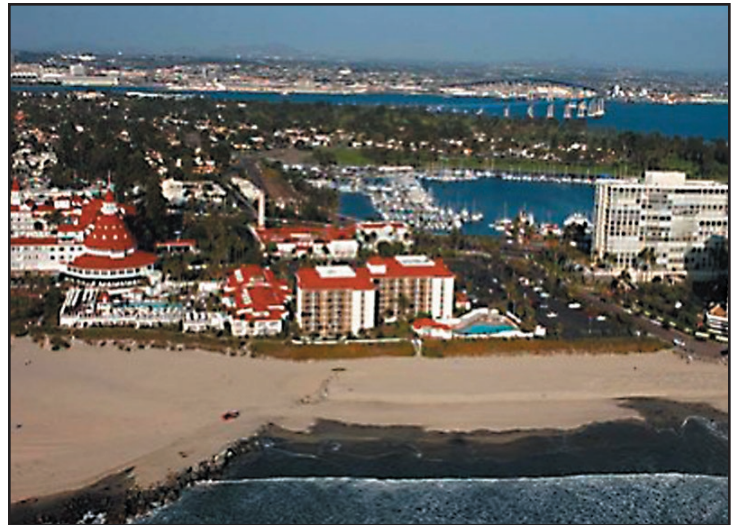


Fig 11.4: Hotel del Coronado, Coronado, California showing groin. Copyright © 2002 Kenneth & Gabrielle Adelman

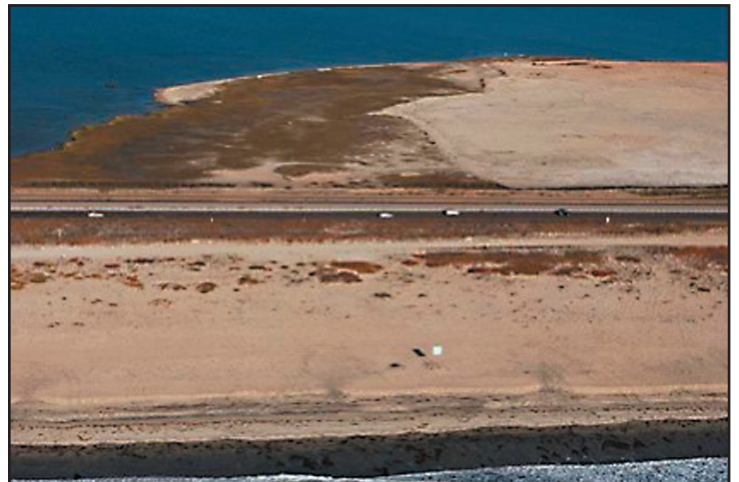


Fig 11.5: Silver Strand State Beach, California: Silver Strand Littoral Cell Copyright © 2002 Kenneth & Gabrielle Adelman

Silver Strand (Figure 11.5) is a relatively narrow stretch

of beach separating San Diego Bay from the Pacific Ocean attached at the northern end to Coronado Island. Coronado (Figure 11.6) is a flat low-lying island, which was originally two distinct landmasses separated by Spanish Bight, a reentrant of San Diego Bay. In 1944, artificial fill was placed in Spanish Bight connecting the northernmost island, North Island, to Coronado.

The continental shelf seaward of Silver Strand extends 15 miles offshore, gently sloping seaward to a depth of 600 feet at the shelf edge. Tijuana Estuary (Figure 11.7) is located at the southern-most part of the California reach of the Silver Strand littoral cell near the mouth of the Tijuana River. The northern side of the lagoon is bounded by a gently sloping marine terrace ranging in height from 50- to 100-feet above sea level, which separates San Diego Bay from the Tijuana River Valley. This elevated marine terrace is occupied by the community of Imperial Beach (Figure 11.8).



Fig 11.6: Coronado, California: Silver Strand Littoral Cell
Copyright © 2002 Kenneth & Gabrielle Adelman



Fig 11.7. Tijuana River Estuary at the mouth of the Tiajuana River. Copyright © 2002 Kenneth & Gabrielle Adelman

Man's alterations to the coastline have significantly changed the beaches in this cell resulting in persistent beach erosion at specific locations. Beach erosion has been documented at the southern end of Imperial Beach

since 1937. In the 1950's, problems resulting from beach erosion extended to the northern end of Imperial Beach. As a result, the Army Corps of Engineers was authorized by the River and Harbors Act of 1958 to construct five rock groins along the City of Imperial Beach shoreline in an attempt to stabilize and maintain the beach for recreational purposes and to prevent over-wash into back-shore areas.

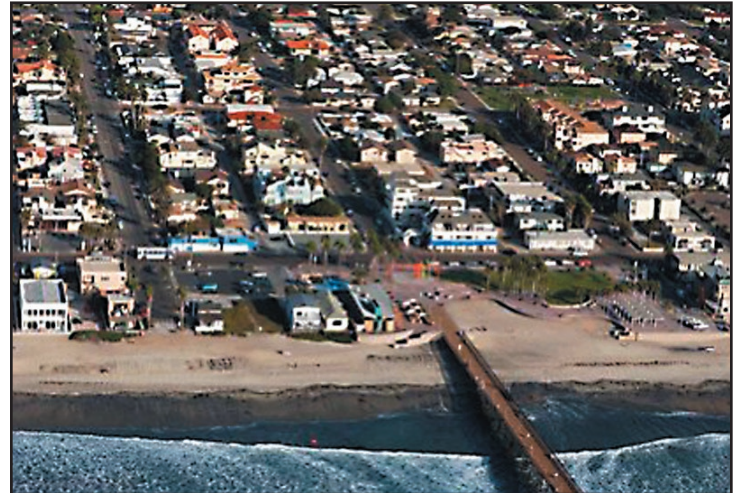


Fig 11.8: Imperial Beach and Imperial Beach Pier. Copyright © 2002 Kenneth & Gabrielle Adelman

The plan called for five groins to be placed along the shoreline at intervals of 1,000 feet. The first groin was constructed in 1959 at the northern end of the city and was lengthened in 1963. This groin proved ineffective at trapping sand, so the second rock groin was built just south of the first one in 1961. Both of these structures were ineffective at controlling beach erosion due to the lack of sand traveling as littoral drift at this location, and the project was subsequently abandoned (Inman, 1976).

In 2002, the Army Corps of Engineers reactivated the City of Imperial Beach project and began investigating alternative means to stabilize and restore the beach. According to estimates made by the Corps of Engineers (2002), $\sim 100,000 \text{ yd}^3/\text{yr}$ of sand is eroding from the shoreline of Imperial Beach, corresponding to a retreat rate of 6.6 feet per year. Occasional beach nourishment projects have slowed the retreat; however, the projects have not been large enough in scale, or placed enough sand, to halt the erosion. At the current retreat rate, the shoreline in the northern portion of Imperial Beach could reach the first line of development by 2007 (USACOE, 2002). As part of the 2001 SANDAG nourishment project, 120,000 yds³ was added to Imperial Beach. The Army Corps of Engineers has plans to nourish the near-shore region with an additional 650,000 cubic yards of sand to mitigate erosion (Ryan, 2005).

LONGSHORE TRANSPORT

There is a pronounced shoal offshore of Imperial Beach and the Tijuana Estuary. Waves converge on this shoal

resulting in an interruption of the longshore current. At this location, the longshore current diverges and flows northward and southward (Inman, 1974; Inman, 1976). Net littoral drift is to the north (north of the Tijuana River) in the Silver Strand littoral cell due to the sheltering effects of Point Loma from waves approaching from the north (Everts, 1987; Flick, 1993; Wiegell, 1994). There is a progressive decrease in mean grain size and better sorting north of the Tijuana River along Silver Strand, also supporting a net northward transport direction (Inman, 1973; Inman, 1974; Inman, 1976).

WAVE CLIMATE

The dominant source of wave energy to the Silver Strand littoral cell is northern hemisphere swell with periods of 6- to 10-seconds arriving from between 295° and 315°. Swell generated in the southern hemisphere is generally lower in height (~3 feet) and occurs predominantly in the summer. The shoreline of the Silver Strand littoral cell is sheltered by Point Loma, and offshore islands, including San Clemente, San Nicolas and Santa Catalina, which diffuse and obscure wave energy approaching from directions greater than 280° (Inman, 1976). The Los Coronados Islands, three islands located ~7 miles offshore just south of the International Border, shelter the shoreline to a lesser degree from southern swells.

SAND SOURCES

Rivers: Since the diversion of San Diego River in 1855 to Mission Bay, Tijuana River (Figure 11.7), discharging near the international border, is the only significant, natural sand source for the Silver Strand littoral cell. Tijuana River is formed by the confluence of Cottonwood Creek, draining the northern third of the drainage basin, and Rio de Las Palmas, draining the southern two thirds of the drainage basin. The watershed, totaling 1,700 square miles, extends through both Mexico and California with elevations ranging from sea-level to 6,000 feet in the upper part of the drainage basin (Inman, 1974; Inman, 1976). Cottonwood Creek is obstructed by Morena Dam (impoundment began in 1911) and Barrett Dam (impoundment began in 1921). The flow of Rio de las Palmas is obstructed by Rodriguez Dam (impoundment began in 1936) just upstream from the city of Tijuana. These three dams impound discharge from over 1,200 square miles, or 70% of the sediment producing drainage basin, from the coast (California, 1969; Inman, 1974; Inman, 1976).

These three dams have reduced the sand supplied to the Silver Strand cell from the Tijuana River by 49%, from an annual average of ~83,000 yd³/yr to ~42,000 yd³/yr (Table 10.1) (Willis and Griggs, 2003; Willis et al., 2002). For this report, based on beach widths, it is assumed that half of this small sand discharge travels north and ultimately ends up offshore near Zuniga Jetty, while the other half is transported south into Mexico.

Sediment entering the ocean from the Tijuana River is mostly fine-grained sand, silt and clay. Much of the coarser material is deposited in the Tijuana Estuary at the mouth of the Tijuana River (Figure 11.7). The estuary is accumulating large residual cobbles and boulders (Inman, 1976). Silt- and clay-sized particles remain in suspension flowing into the ocean where they are distributed over a large area by local currents. This fine-grained sediment is carried offshore before it eventually settles out of suspension.

Other coastal streams north of the Tijuana River, such as Otay and Sweetwater rivers and several small creeks in the city of San Diego, may also contribute minor amounts of sand to this cell. However, the total drainage area of all these creeks and streams is less than 600 square miles, and they all discharge into the east side of San Diego Bay. In addition, most of these small drainages are dammed. Thus, these streams are assumed to provide an insignificant volume of sand to the overall littoral budget for the Silver Strand cell.

Seacliff Erosion: Sand is added to the littoral budget through bluff erosion in the Mexico portion of the cell (Everts, 1987). Access was not available to this stretch of coast, thus an estimation of sand entering the littoral system from these cliffs is unavailable.

Beach Nourishment: The Silver Strand littoral cell is the most highly altered cell in southern California in terms of beach nourishment. San Diego Bay (Figures 11.1 and 11.3) serves as a deep-draft natural harbor formed by Point Loma to the north and Silver Strand sand spit on the west. From 1940 to 1941, 2.3 million yds³ of sediment dredged from San Diego Bay were placed on North Island (Inman, 1976). From 1941 to 1946, the massive expansion of the naval facilities provided approximately 26 million yds³ of additional sand from the bay to Silver Strand (Inman, 1976). Before this nourishment project, Silver Strand was a narrow, marginal, sand spit between San Diego Bay and the Pacific Ocean, which was often over-washed by ocean waves. This nourishment project widened the beach by up to one thousand feet from Silver Strand State Beach to Zuniga Jetty (Flick, 1993; Inman, 1976). Since 1946, the shoreline has retreated as sand eroded from the beaches was transported northward. Just south of the Hotel del Coronado, the Naval Amphibious Base has occasionally imported modest amounts of sand for nourishment creating beaches wide enough for training purposes. Recently, sand dredged from the bay has been transported as far south as Imperial Beach and placed offshore past the surf-zone (Flick, 1993).

However, nourishment projects have significantly decreased in recent years. Since the 1960's, an annual average of only ~256,000 yd³ of sand have been placed on the beaches from the dredging of San Diego Harbor representing 86% of the total littoral budget for the Silver Strand littoral cell (Table 11.1).

Silver Strand Littoral Cell			
Inputs	Natural (cy/yr)	Actual (cy/yr)	Reduction (cy/yr)
Rivers	83,000 (100%)	42,000 (14%)	-41,000 (49%)
Beach Nourishment		256,000 (86%)	+256,000
Total Littoral Input	83,000 (100%)	298,000 (100%)	+215,000 (+259%)

Table 11.1: Overall sand contributions and reductions to the Silver Strand littoral cell. Reductions are due to the damming of the Tijuana River. "Natural" sand yield refers to the estimated original volume of sand discharged by streams. "Actual" sand yield refers to the estimated volume of sand reaching the coast under present day conditions taking into account reductions in sand supply from dams and additional sand added through beach nourishment.

From 1941 to 2005 a total of approximately ~39,800,000 yd³ (613,000 yd³/yr) of sand dredged from San Diego Harbor (Figure 11.3) have been used for beach nourishment in the Silver Strand littoral cell (Table 11.2). Because this sand has come primarily from deepening of the harbor rather than entrance channel dredging, it is considered as beach nourishment in the budget.

In 2001, 120,000 yd³ of sand from the SANDAG project were placed on Imperial Beach, but this is a very small volume relative to the magnitude of historic nourishment.

Year	San Diego Harbor (yd3)
1941-1947	29,868,000
1967-1976	3,485,000
1978	5,880,000
1987	260,313
1988	130,000
1989	97,470
1996	118,563
Total (yd ³)	~39,840,000
Yearly Average (yd ³ /yr)(1941-2005)	~613,000
Yearly Average (yd ³ /yr)(1967-2005)	~256,000

Table 11.2: Dredging History of San Diego Bay

SAND SINKS

Most littoral cells in southern California have a submarine canyon extending into the nearshore zone at the downcoast end of the cell, which acts as the dominant sink for the cell (Inman, 1974; Inman and Chamberlain, 1960; Inman and Frautschy, 1966). However, in the Silver Strand littoral cell, there are no submarine canyons. Instead, sand accumulates at shallow depths on the shelf. Before the construction of Zuniga Jetty, sand accumulated at the end of the cell in Zuniga Shoals (Figure 11.1). A strong ebb tidal current from San Diego Bay transported sediment offshore where it was deposited at relatively shallow depths. This sand would eventually be returned to the shoreline by waves refracted around Point Loma,

thus, creating a system in dynamic equilibrium capable of maintaining the beaches at Coronado and a narrower beach at Silver Strand (Chamberlain et al., 1958).

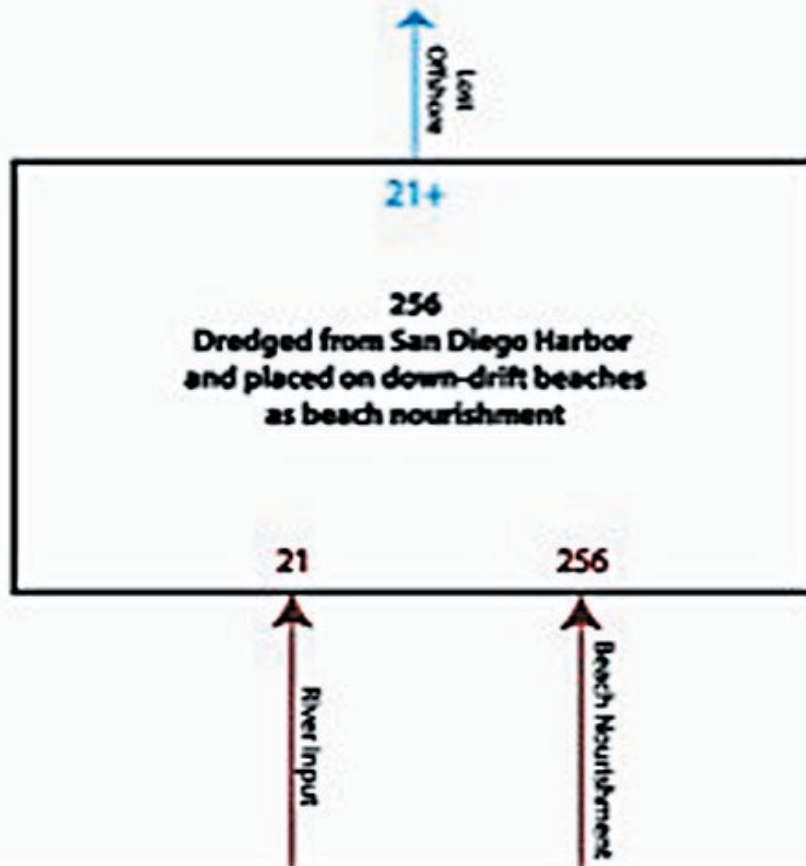
After the construction of Zuniga Jetty, however, the dynamic equilibrium of the Silver Strand cell was disrupted. Sand became impounded in the nearshore area on the east side of the jetty, widening the beach and extending it into the shoal area. Some sand enters San Diego Bay through the permeable jetty and around the tip of the jetty where it is carried seaward by ebb tidal currents (Inman, 1973; Inman, 1974; Inman, 1976). Zuniga Jetty constricts the tidal flow, increasing the velocity and competence of the ebb tidal current in the entrance channel, transporting sand seaward beyond the tip of Point Loma. Sediment flowing in this tidal current is now transported into deeper water where it is permanently lost from the littoral cell. Offshore losses of sand in the region of Zuniga Shoals and seaward of Zuniga Jetty are the main sink for sand in the Silver Strand littoral cell (Everts, 1987; Inman, 1973; Inman, 1974; Wiegel, 1994).

SUMMARY

The sand budget for the California portion of the Silver Strand littoral cell is presented in Figures 11.9 and 11.10 as a simple box model and as a running, mile-by-mile, cumulative budget, respectively. The only natural source of sand to this littoral cell is the Tijuana River, contributing an annual average of ~42,000 yd³ of sand to the littoral system. For the purpose of this budget, it is assumed that sand from the Tijuana River is divided equally between the north and south littoral drift that diverges at this location. Thus, 21,000 yd³/yr of sand is shown to travel south into the Mexico portion of the littoral cell while the remaining 21,000 yd³/yr travels north along Imperial Beach and the Silver Strand where it is eventually deposited into Zuniga Shoals, lost offshore, or accumulated in the entrance channel of San Diego Bay. Very large volumes of artificial fill from the dredging of San Diego Bay were historically added to the beaches of Silver Strand, Coronado and Imperial Beach totaling approximately 256,000 yd³/yr.

With a decrease in beach nourishment projects and a reduction in the volume of sand provided by the Tijuana River, the sand budget for the Silver Strand has had a deficit in recent years. Although 120,000 yds³ were added as part of the SANDAG nourishment project, this was a very small volume of sand relative to historical nourishment from San Diego Bay dredging. The existing beach sand is now feeding the wave induced longshore transport causing beach erosion problems in many areas of the Silver Strand Cell. Net beach erosion, or retreat, has been shown to occur from Playas de Tijuana through Imperial Beach, on Silver Strand State Beach, and from South Coronado to the Hotel del Coronado (Everts, 1987; Flick, 1993).

Silver Strand Littoral Cell Budget Average (1967-2005)
Annual Volume (x 1000 cubic yards per year)



San Diego Bay Entrance to the International Border

Fig 10.9: Sand Budget for the California portion of the Silver Strand Littoral Cell

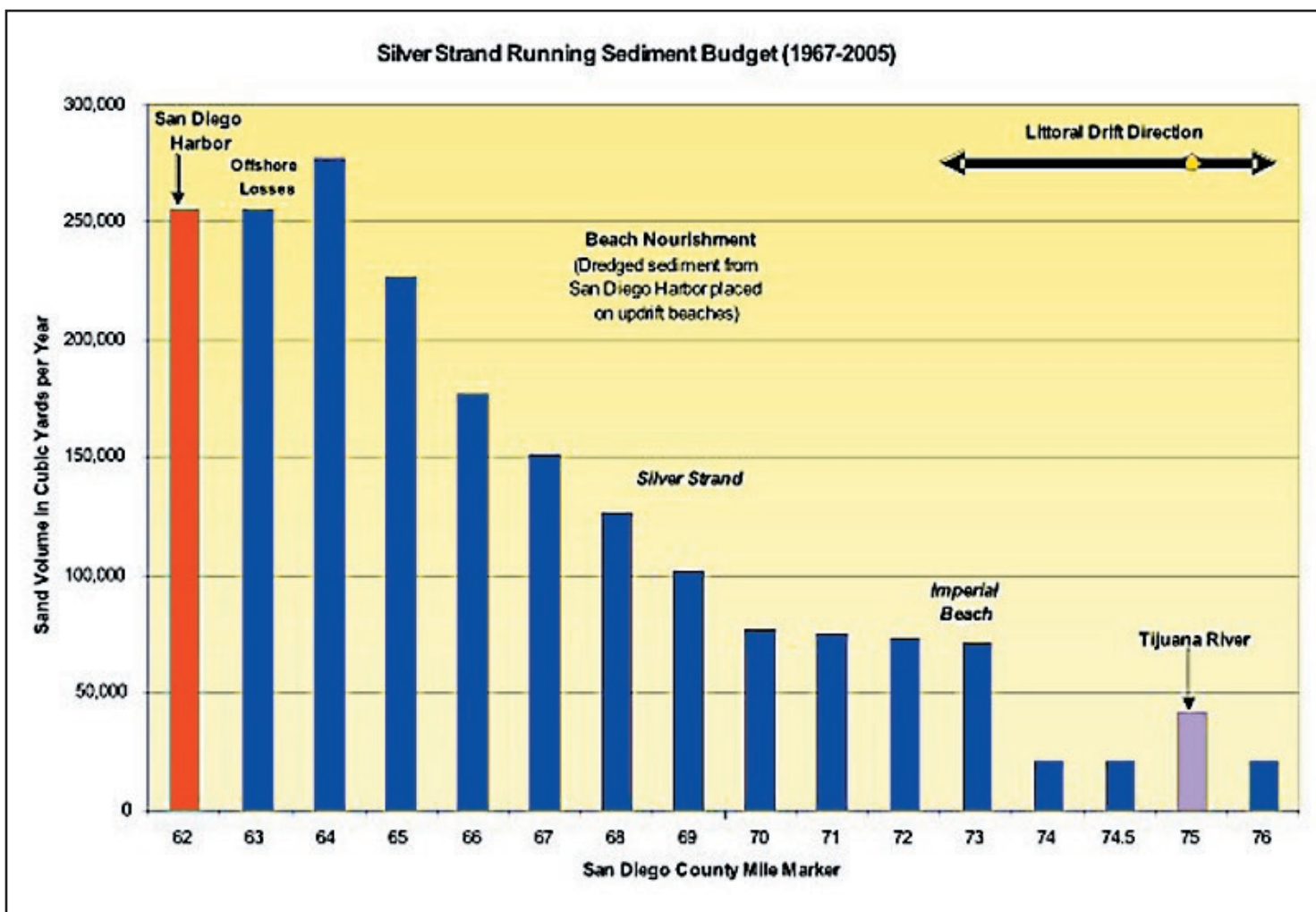


Fig 10.10: Running, mile-by-mile sand budget for the California portion of the Silver Strand Littoral Cell (1967-2005)

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**COASTAL REGIONAL SEDIMENT MANAGEMENT PLAN
FOR
SOUTHERN MONTEREY BAY**

Prepared for

Association of Monterey Bay Area Governments

Prepared by

Philip Williams & Associates, Ltd.

with

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November 3, 2008

PWA REF. 1902.00

Services provided pursuant to this Agreement are intended solely for the use and benefit of the Association of Monterey Bay Area Governments and the California Coastal Sediment Management Workgroup.

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EXECUTIVE SUMMARY

Geographic and Historic Setting

Over the next 50 years, the coastal dunes of southern Monterey Bay between the Salinas River mouth and Wharf II in Monterey are predicted to erode at rates between 1.0 and 6.0 ft/year. Over this planning time frame, eight oceanfront facilities are at high risk due to this erosion, and will require mitigation measures to be implemented to prevent their loss. Six of these facilities; Sand City and Tioga Avenue west of Highway 1, Seaside Pump Station, Monterey Interceptor between Seaside Pump Station and Wharf II, Monterey Beach Resort, Ocean Harbor House condominiums, and Monterey La Playa town homes, are located along the shoreline of the Cities of Sand City, Seaside, and Monterey (the southern bight). The other two facilities are the Sanctuary Beach Resort and Marina Coast Water District buildings, located in Marina one mile south of the only remaining beach-sand mining operation on the west coast of the U.S.

Recognizing that the issue of coastal erosion could not be addressed on a city-by-city basis, the City of Monterey sought to form a regional consortium of local, state and federal agencies to determine what can be done to address this issue. Around the same time, as part of a process to update the Sanctuary's Management Plan, the Monterey Bay National Marine Sanctuary (MBNMS) developed an action plan to address the issues of coastal erosion and armoring along the Sanctuary's 276 miles of shoreline. This MBNMS action plan called for the development of a collaborative regional planning approach to address, along with other issues, coastal erosion in the southern Monterey Bay region. This led to the formation of the Southern Monterey Bay Coastal Erosion Workgroup (SMBCEW). The SMBCEW has developed an extensive list of ways to potentially address the issue of coastal erosion, and will be evaluating the applicability of those potential technologies to southern Monterey Bay erosion problems in the near future.

Regional Sediment Management

The California Coastal Sediment Management Workgroup (CSMW) is working with regional stakeholder groups such as the AMBAG and SMBCEW to develop Coastal Regional Sediment Management (RSM) Plans within specific regions of coastal California to help city, county, and coastal managers, and local and state-wide regulatory personnel identify and resolve issues of concern within that region. This Coastal RSM Plan examines a subset of the options to be explored by the SMBCEW, specifically those options that restore coastal habitat by removing or lessening disturbances to natural sedimentary processes that exacerbate coastal erosion. Within this subset, this Coastal RSM Plan recommends implementing the following four regional sediment management strategies for the southern Monterey Bay shoreline:

1. ***Investigate beach nourishment and other beach restoration strategies to ameliorate erosion in the stretch of shoreline within the Cities of Sand City, Seaside, and Monterey.*** Here, the majority of high risk facilities are located, and healthy beaches are particularly important for recreation and tourism. Beach nourishment is feasible in the southern bight for a number of reasons. Low wave energy, low sand transport, and the location within a defined sub-cell (the southern bight is nearly self-contained in terms of sand transport) means that any placed sand would remain at the site for a longer period of time. This Coastal RSM Plan shows that there is clear economic justification for beach nourishment of the southern bight and it has the potential to deliver substantial benefits for the recreational value of the shoreline and for protection of its infrastructure assets. Beach nourishment may also reduce the need for ‘hard’ shore protection, and provide ecologic benefits associated with wider beaches.
2. ***Reduce or eliminate removal of sand from the beach at Marina.*** The large extraction of beach sand permanently removes sediment that would otherwise feed beaches elsewhere along southern Monterey Bay. If this sand is released and subsequently transported alongshore, it could provide a significant additional buffer to dune erosion by waves. The effect would be more immediate at the Sanctuary Beach Resort and Marina Coast Water District buildings critical erosion sites, but would eventually benefit the shoreline further away as the sand migrates. The U.S. Army Corps of Engineers has reportedly issued a ‘determination of non-jurisdiction’ which allows the mining of beach sand at Marina to proceed without a permit from the Corps. The operation started prior to the passage of the California Coastal Act (1972) and therefore may be ‘grandfathered’ into legal non-conforming use. This Coastal RSM Plan recommends several potential routes that could be taken to reduce or eliminate removal of beach sand at Marina including:
 - Communication of the economic impacts of erosion associated with beach-sand mining on down coast communities
 - Revisit the U.S. Army Corps of Engineers determination of non-jurisdiction
 - Determine whether a change in operations post-1976 (i.e. the increased extraction with introduction of a new dredge sometime after 1979) requires a new permit from the City of Marina.
 - Communication of impacts that the beach-sand mining is having on endangered species
 - Examine the possibility of alternative mining operations.
3. ***Allow dune erosion to continue without human intervention north of Sand City to the Salinas River.*** This erosion will continue to provide large quantities of sand to the beaches, maintaining their healthy condition and provide benefits for sensitive species and habitats, and recreation and tourism. Apart from the Sanctuary Beach Resort and Marina Coast Water District buildings, this area does not contain any facilities at high risk of erosion.

4. ***Use this Coastal RSM Plan as a baseline to build a regionally comprehensive erosion abatement approach through the ongoing efforts of the Southern Monterey Bay Coastal Erosion Workgroup (SMBCEW).*** The SMBCEW is preparing to evaluate additional erosion control methods, including retention structures such as offshore reefs, beach dewatering and pressure equalizing modules, and other technologies that could help reduce coastal erosion along the southern Monterey Bay shoreline. The information gathered for the RSM framework presented within this Coastal RSM Plan will provide the basis for evaluating the feasibility of potential erosion control technologies that will work locally and address regional sediment imbalances that are aggravating coastal erosion. Taken together, these two interconnected efforts should collectively provide valuable guidance and reference to city coastal managers, local and state-wide regulatory personnel, the AMBAGs Board of Directors, and state and federal funding entities, thereby setting the stage for specific projects to reduce coastal erosion.

RECOMMENDED MANAGEMENT AND POLICY CHANGES

Regional and local policies and management decisions affect the natural delivery of sand to and along the California coast. Historically, these policies and management decisions have not focused on protecting or preserving natural processes delivering sand to the coast, but rather, have been developed piece-meal and for the explicit purpose of protecting and/or managing terrestrial natural resources. Consequently, the application of these decisions has often hampered coastal restoration efforts. This Coastal RSM Plan recommends adopting the following seven management and policy changes for the southern Monterey Bay shoreline:

1. Formalize the governance structure for coastal RSM projects with staff from the AMBAG member agencies, including a dedicated staff member to assist the AMBAG Executive Director. In the recommended structure, the AMBAG as a Joint Powers Authority would be responsible for adopting and updating this Coastal RSM Plan, and implementing regional sediment management in southern Monterey Bay. Advice and guidance on RSM issues would come from the Southern Monterey Bay Coastal Erosion Workgroup (SMBCEW), a group of local stakeholders already set-up to address coastal erosion issues. A regular post-Plan program of outreach should be started by the AMBAG (meetings, workshops) to disseminate information and educate the public on coastal erosion issues and how this Coastal RSM Plan can help implement potential RSM activities within the southern Monterey Bay region.
2. Coordination with local cities, Monterey County, California Department of Parks and Recreation, California Coastal Commission and other relevant agencies will be essential to secure effective implementation of projects. The AMBAG should work with the County of Monterey and coastal cities to identify how this Coastal RSM Plan can be

recognized (referenced) in the county general plan and Local Coastal Programs (LCPs). In addition, steps should be explored on how to add the Coastal RSM Plan and its alternatives to address coastal erosion as items requiring answers on the CEQA checklist. Furthermore, the AMBAG should investigate whether RSM activities benefiting the entire region can be streamlined through a regional general permit from the California Coastal Commission.

3. Formalize coordination with the Monterey Bay National Marine Sanctuary (MBNMS) for joint shoreline management and coastal zone planning. The collaboration should work towards development of RSM strategies that would allow for the extraction and placement of beach-compatible sediment within the Sanctuary boundaries as a means to restore sands previously eroded from the beaches. This effort would require interpretation and discussion of the potential to modify the Sanctuary's Harbors and Dredge Disposal Action Plan in order to employ further beach nourishment sites in addition to those already approved by the Sanctuary (e.g. adjacent to Wharf II).
4. Adopt a consistent approach to planning for sea-level rise in RSM using the most recent predicted estimates. Currently, the recommended predictions of sea-level rise (by the California Resources Agency) for California are 16 inches (1.3 feet) by 2050 and 55 inches (4.6 feet) by 2100, and this Coastal RSM Plan uses these estimates as a basis for assessment of future shoreline erosion and the vulnerability of oceanfront properties. Management and policy regarding future set back distances also requires consideration of the erosion impacts of sea-level rise. It is recommended that Land Use Plans (LUPs) develop a strong set back ordinance for oceanfront development that puts high use facilities at an appropriate distance from the ocean. The set back distance should include the historical erosion rate plus a natural buffer (primary set back) plus erosion due to future sea-level rise (secondary set back). As part of this ordinance, consideration should be given to an extended planning horizon of 100 years for large cost or long-term projects.
5. The AMBAG should work with the Chambers of Commerce in Monterey, Sand City, Seaside, and Marina to develop a dedicated source of local funding in order to provide statutorily-required local matches to state and federal funding that would be required for any beach nourishment projects. For example, the Sanctuary Beach Resort charges a \$15 per night fee to occupants to fund habitat restoration on its property. Other potential local sources of funding such as real estate transfer taxes, general sales taxes attributable to sporting goods, and parking and beach-user fees should all be explored. A dedicated source of local funding should enhance the southern Monterey Bay region's ability to compete for limited state and federal funding for erosion control projects that involve sediment management. Both the California Department of Boating and Waterways (CDBW) and the U.S. Army Corps of Engineers (major funding sources) are committed to RSM and may likely base future allocations of limited funding on whether a proposed project aligns with an approved Coastal RSM Plan.
6. Use the Sand Compatibility and Opportunistic Use Program Plan (SCOUP) process to obtain an opportunistic use program permit to facilitate beneficial reuse when local sand

sources become available. This SCoup permit process will streamline the regulatory compliance process through establishment of a regional program providing for placement of opportunistic and compatible sand at pre-defined beach receiver sites with limited review from regulatory agencies. Having a program in place where appropriate sediment can be transported to the beach (or stockpile area) without lengthy and costly delays increases the chances that the opportunistic sands will be beneficially reused. Assessment of whether this process can facilitate a regional permit from the Coastal Commission should be investigated.

7. Secure and develop a sediment stockpiling and sorting facility at Fort Ord to aid in implementing the SCoup opportunistic use program. Such a facility would help to facilitate the use of appropriately sized sand should any become available from future flood control, development, and other projects. Providing a location in advance where appropriate sediments can be transported relatively quickly eliminates lengthy and costly delays encountered if a permit is applied for at the time of the project, and would encourage beneficial reuse of sediment.

RECOMMENDED PROJECTS FOR FEASIBILITY ANALYSIS

Studies should be initiated to investigate the feasibility of large-scale beach nourishment using sand from offshore deposits. Sediment analyses should follow the protocols in the Sand Compatibility and Opportunistic Use Program Plan (SCoup Tier II) to assess compatibility and include assessments of the technical feasibility of both subaerial-beach and nearshore placement in southern Monterey Bay. The projects are prioritized as follows.

1. ***Investigate other 'soft' erosion control technologies in southern Monterey Bay.*** This study should assess erosion control approaches such as sand retention devices, beach dewatering techniques, and pressure equalizing modules, including an evaluation of regulatory requirements and potential constraints. These approaches are to be examined by an MBNMS-funded project, complementary to this Coastal RSM Plan, under the SMBCEW umbrella.
2. ***Technical and environmental feasibility of sand placement in the southern bight.*** This study should investigate the feasibility of placing sand (both on the beach and nearshore) between Monterey Beach Resort and Ocean Harbor House condominiums as a beach nourishment solution. Important considerations in the study should include the specific placement location, volume of placed sand, cross-shore and longshore sediment transport processes, sand dispersal rates and distribution, and the impacts of placement on sensitive species and habitats.
3. ***Use of offshore shelf sand deposits.*** This study should assess the feasibility of using sand from relict offshore deposits and the identification and feasibility of using active offshore

sand bodies. The sand offshore from a convergence of alongshore sediment transport at Sand City should be investigated as a potential nearby (and therefore economical) source for beach nourishment.

4. ***Use of sand deposits intercepted before they are lost to Monterey Submarine Canyon.*** This study should include the feasibility of intercepting and extracting sand before it is lost to the Canyon. This effort would examine the results of the recent study supported by CSMW. The study should also address regulatory feasibility given that the proposed source area is part of the MBNMS.
5. ***Use of dune sand at Fort Ord.*** This study should assess the feasibility of using dune sand at Fort Ord to nourish the southern bight beaches. Particular consideration should be given the particle size relationships of the source and receiver sites, and the regulatory requirements of removing sand from an inland dune source.
6. ***Reuse of sand from Monterey Harbor maintenance dredging.*** This study requires investigation of the quantities of compatible sand (particle size and contamination) that could be made available for beach nourishment from dredging of Monterey Harbor.
7. ***Reuse of sand from Moss Landing Harbor entrance channel maintenance dredging.*** This study should focus on the feasibility of using compatible sand from Moss Landing Harbor entrance channel. Attention should be given to the potential competition for the sand from sites that are currently being nourished using the sediment and the potential need for sediment for restoration of Elkhorn Slough.

SUMMARY OF SCIENTIFIC FINDINGS

The following scientific findings were compiled from existing sources and represent the latest research and information available on sediment, coastal erosion, economics, regulations, and species and habitat along the southern Monterey Bay shoreline. No new research was conducted in preparing this Coastal RSM Plan.

Sediment (Sand) Budget

1. Over 96% by length of the southern Monterey Bay littoral cell is undeveloped, comprising sand beaches backed by actively eroding dunes, which supply sediment to the littoral system. Less than 4% of the shoreline is armored with concrete seawalls and rock revetments.
2. Shoreline armoring and the impacts of placement loss and passive erosion are evident at Monterey Beach Resort and Ocean Harbor House condominiums. The removal of the riprap at Stilwell Hall in 2004 and the subsequent erosion of previously armored dunes to an equilibrium position parallel with adjacent shoreline segments shows the restoration

potential of the beach and shoreline, as well as the difficulties associated with armoring strategies.

3. Historically, the beaches and dunes of southern Monterey Bay were supplied with abundant sand from the Salinas River. This supply has been significantly reduced because of the shallowing of the river gradient due to sea-level rise, and the relatively low flow at which the river overflows its banks and deposits sediments in the flood plain.
4. The current average discharge rate of beach-size sand by the Salinas River to the littoral cell is estimated at approximately 65,000 yd³/year. Only 10,000 yd³/year is estimated to move south and 55,000 yd³/year to move north.
5. The dominant supply of sand to the littoral cell is from erosion of low resistance unconsolidated coastal dunes south of the Salinas River. Rates of erosion are greatest at Fort Ord decreasing to the north and south, consistent with the general distribution of wave energy approaching the coast.
6. The constant supply of sand from dune erosion has meant that the beaches within the littoral cell have been sustainable over the long term. In areas with no shoreline armoring, the dune face has translated landward whilst the beaches have retained their width.
7. Average dune erosion rates during the years of drag line sand mining from the surf zone between 1940 and 1984 ranged from 1.0 to 6.5 ft/year, equating to a sand volume of approximately 350,000 yd³/year from the dunes to the littoral system.
8. Up to 1990, large quantities of sand were mined from the surf/swash zone using drag lines at Sand City. Three operations mined a total average of approximately 111,000 yd³/year. Up to 1986, two similar operations at Marina removed an average of approximately 33,000 yd³/year. This sand mining was a predominant cause of coastal erosion in southern Monterey Bay prior to 1990.
9. Between 1985 and 2005, after closure of drag line sand mining operations, but continuation of hydraulic mining at Marina, the dune erosion rates ranged from 0.5 to 4.5 ft/year, equating to a sand volume of approximately 200,000 yd³/year from the dunes to the littoral system.
10. In 1965, hydraulic mining of sand from a dredge pond was introduced at Marina. Between 1965 and 1990, this operation removed a further 105,000 yd³/year of sand from the littoral system.
11. As other mines closed, the ongoing operation at Marina increased its extraction to 200,000 yd³/year today. This is similar to the annual sand volume eroded from the dunes. Erosion rates at Marina increased after 1985, and are believed to be related to an increase in sand extraction at the Marina sand mine in the mid 1980s, 1990s, and 21st century.
12. Erosion rates at Sand City decreased after 1985, and are believed to be related to closure of drag-line mining at three sites at Sand City between 1970 and 1990.
13. Future dune erosion rates along the southern Monterey Bay shoreline will likely increase because of predicted sea-level rise.

Sediment (Sand) Transport

14. Net alongshore sediment transport rates are relatively low in southern Monterey Bay because the dominant wave crests approach near-parallel to the shoreline.
15. The net direction of alongshore sediment transport varies along the shoreline. North of the Salinas River the net transport is to the north into the head of Monterey Submarine Canyon and lost from the littoral system. South of the Salinas River to Sand City there is seasonal variability in transport direction with a net transport to the south. Sediment transport from Wharf II to Sand City is to the north resulting in a convergence of sediment transport near Sand City, and possible deposition of sand offshore from the convergence.
16. The total sand transport in all directions (also called gross transport to distinguish from net transport) is high owing to the exposure to north Pacific swells and storms. The gross transport is greatest in the center of southern Monterey Bay due to the refraction effects of Monterey Submarine Canyon on incident waves. The high gross transport results in rapid redistribution of perturbations such as beach-sand mining and local bluff erosion. Hence, mining of sand from the beach affects the entire area from the Salinas River mouth to Monterey Harbor.
17. Winter offshore transport of sediment may result in temporary loss from the beaches, which recover during the dominant onshore transport in summer. However, during large wave and storm events, sand may be transported offshore to water depths where summer waves cannot transport it back onshore. This means that there is potentially a net transport of sediment from the beaches to the offshore over the long-term, resulting in a loss from the beaches.

Beach Sediment Characteristics

18. There is a general trend of decreasing beach particle size (not including the shoreface) from north to south in southern Monterey Bay. Mean particle sizes are greater between the Salinas River and Fort Ord, where the wave energy is highest and smaller near Monterey Harbor where wave energy is lowest.
19. The composite particle size envelope of the beaches for two miles north of Wharf II is 0.2-0.4 mm; between this two-mile marker and Sand City the envelope is 0.4-0.8 mm, and north of Sand City the envelope increases to between 0.5 and 0.9 mm.
20. Approximately 50% of the sediment stored in the eroding dunes has particle sizes that are large enough to be retained on the beaches and shoreface. The smaller sand sizes are winnowed to the nearshore.

Critical Areas of Erosion

21. Critical areas of erosion were assessed using the following criteria:
 - a. What is at risk?
 - b. What is the probability that it will be impacted by coastal erosion over a management planning horizon of 50 years?
 - c. What are the consequences of loss of the facility (economic, ecologic, recreational and public safety)?
22. The application of the above criteria identified eight segments of shoreline as high to moderate-risk, high-consequence critical areas of erosion. These are (from north to south) the Sanctuary Beach Resort and Marina Coast Water District buildings near Reservation Road, beach access and hazardous rubble in the vicinity of the seaward end of Tioga Avenue, Seaside Pump Station at Bay Avenue, Monterey Interceptor wastewater pipeline between Seaside Pump Station and Wharf II, Monterey Beach Resort, Ocean Harbor House condominiums, and Monterey La Playa town homes.
23. Six of the eight critical erosion areas (apart from the Sanctuary Beach Resort and Marina Coast Water District buildings) are located in the Cities of Sand City, Seaside, and Monterey (southern bight).
24. Extension to a longer planning horizon (100 years) would increase the number of critical erosion areas of concern to include portions of Highway 1 and other regional wastewater facilities as well as private development.

Critical Species and Habitat

25. The beaches and dunes of southern Monterey Bay provide habitat for numerous native animals including the threatened western snowy plover and numerous rare plants, including Yaden's wallflower. Sensitive subtidal habitat is located adjacent to Monterey Harbor and comprises rocky reef, kelp forest, and eelgrass meadow.
26. Beach nourishment has the potential to adversely impact sensitive species and habitat through disturbance or damage as a direct impact of placement or as an indirect impact through sediment transport away from the placement site. Of particular concern is the potential impact of sedimentation and turbidity on eelgrass and kelp/rocky reef in the southern bight. Beach nourishment also has potential to improve habitat for shorebirds, pinnepeds and other beach users and is generally considered preferable to coastal armoring.
27. Mitigation measures for construction should include buffer zones around kelp forest and eelgrass meadow, avoiding placement during nesting seasons for western snowy plovers and during grunion runs, and possibly implementing smaller-scale placements at several sites to maintain connectivity of the food chain.

Potential Receiver Site and Sediment (Sand) Sources

28. In order to mitigate for potential construction and post-construction impacts to sensitive species and habitat in the southern bight, a receiver site for both subaerial-beach and nearshore sand nourishment is recommended between the Monterey Beach Resort and the Ocean Harbor House condominiums. This location would allow dispersal of sand through gross alongshore sediment transport to feed critical areas of erosion to the north and south.
29. Four potential sand sources recommended for further investigation are in coastal and offshore locations. These are Moss Landing Harbor entrance channel, Monterey Harbor, north and south of the Monterey Submarine Canyon, and the offshore shelf (particularly near Sand City). The two harbors would provide limited volumes of sand for nourishment and it would be necessary to supplement with sand from other sources. In contrast, both Monterey Submarine Canyon and the offshore shelf could potentially provide large (millions of yd³) repositories of sand.
30. These potential sources appear to be physically compatible with the potential receiver sites and relatively clean and free from pollutants, because they contain sediment that has been transported and reworked along and across the beaches, shoreface and offshore in southern Monterey Bay.
31. The coastal dune field of Fort Ord represents a fifth recommended source of sand for beach nourishment. The sand in these dunes was originally derived from the beach, and could provide large quantities of sand compatible with the beaches of the southern bight. The location of any dune sand extraction at Fort Ord would have to be carefully considered so as not to remove sediment that would otherwise supply the beaches through dune erosion over the next 50 years.
32. Although no upland sources of beach quality sand were identified, this Coastal RSM Plan recommends continued evaluation of any potential sources for smaller maintenance-style nourishment projects such as development projects at Fort Ord, river dredging, and CalTrans maintenance projects. If sand does become available from these potential sources, it could be stockpiled at a regional stockpile area (recommended at Fort Ord) until volumes become sufficient for a nourishment project. Sediment trapped behind dams is not considered a priority source at this time owing to the distance and trucking impacts, which do not compare favorably with offshore sand sources.

Economics of Beach Nourishment

33. Beach nourishment of the southern bight has a positive benefit-cost ratio and has the potential to deliver substantial benefits to its recreational value, through increase in beach width, and protection of the many valuable assets located along this shoreline.
34. Sand offshore from Sand City is the most cost-effective source due to its proximity to the southern bight receiver site.

Regulatory Processes

35. Potential beach nourishment projects in southern Monterey Bay would need regulatory compliance at federal, state, and local levels.
36. The issuing of federal permits for beach nourishment is the responsibility of the U.S. Army Corps of Engineers and National Oceanic and Atmospheric Administration (because of the Monterey Bay National Marine Sanctuary), with input from resource agencies such as the U.S. Fish and Wildlife Service (endangered terrestrial species), National Marine Fisheries Service (endangered aquatic species), and the U.S. Minerals Management Service (public mineral resources).
37. State permits would need to be obtained from the California Coastal Commission, California State Lands Commission, and State Water Resources Control Board/Regional Water Quality Control Board, with input from resource agencies such as the California Department of Fish and Game and California Department of Parks and Recreation.
38. At a local level, the Cities of Marina and San City, and the County of Monterey have Local Coastal Programs (LCPs) certified by the Coastal Commission. The Cities of Seaside and Monterey have certified Land Use Plans (LUPs) but do not have approved LCPs. Beach nourishment projects along the shorelines with certified LCPs would require a Coastal Development Permit (CDP) issued by that jurisdiction. Projects in Seaside and Monterey would require a CDP from the Coastal Commission.

Recommended Projects to Fill Sediment Budget and Critical Species and Habitat Data Gaps

1. Undertake a regional particle size assessment to:
 - a. determine the littoral cell cut-off diameter and envelope of particle sizes for each sub-cell to better judge beach nourishment needs and compatibility of source sediments
 - b. investigate sediment particle sizes of potential source areas necessary for SCOP Tier II protocols and permitting
 - c. examine the relationship between the particle size distributions of the dunes, beaches and shoreface to provide a better appreciation of the sediment retention in the littoral zone.
2. Use divers to survey the present-day distribution of nearshore kelp forest and eelgrass meadow in the southern bight to assess potential impacts of beach nourishment. Investigation of beach and upland flora and fauna may also be needed although it appears there is sufficient data to evaluate these for environmental review, until more details are needed for the permit process for a particular beach nourishment activity (project).
3. Establish the extent of species and habitats in the potential offshore borrow areas to assess the impacts on these communities of sediment extraction. The investigations would include locating the limits of reef, eel grass, and kelp.

FUNDING CREDIT AND DISCLAIMERS

Funding for this project was provided to the AMBAG by a California Department of Boating and Waterways grant as part of CSMW's efforts related to implementation of their Coastal Sediment Master Plan. The AMBAG has utilized the funding to develop findings and recommendations that are in accord with local issues and needs, and CSMW has participated in an advisory role in order to help maintain consistency with similar projects elsewhere in coastal California.

Recommendations are presented in this report solely for consideration by government agencies, organizations, and committees involved in the management and protection of coastal resources in southern Monterey Bay. This document was prepared with significant input from CSMW members but does not necessarily represent the official position of any CSMW member agency.

This Coastal RSM Plan does not preclude the study and implementation of other erosion control alternatives such as perched beaches, groins, dynamic revetments, breakwaters, submerged breakwater, headland enhancement, etc. nor does the proposed Joint Powers Agreement Authority in Section 10 have any jurisdiction over these intervention measures.

1. INTRODUCTION

1.1 REGIONAL SEDIMENT MANAGEMENT

For social, recreational, economic, and environmental reasons, the coast of southern Monterey Bay is among the region's most prized natural resources. The sandy beaches and coastal dunes offer recreational activities and economic opportunities to Monterey Bay residents and visitors; they afford a natural barrier that protects the shoreline during storm events; they provide habitat



for numerous shorebirds, including critical habitats for threatened or endangered species; and they are desirable places to live near, increasing property values and revenue for the community. Due to a persistent rise in sea level, changes in sand availability, and previous unsustainable public and private development practices, the southern Monterey Bay beaches and coastal dunes south of the Salinas River are eroding, on average, at the fastest rate in California (Hapke et al., 2006). Erosion compromises the

ability of the beaches and dunes to buffer oceanfront development and infrastructure from storms and flooding, to provide vital natural habitat, and to successfully accommodate recreation and tourism.

Along the California coast, state, federal, and local agencies are now attempting to address sediment supply and coastal erosion problems caused by human modification through Regional Sediment Management (RSM). RSM focuses on restoring coastal habitat by eliminating or reducing disruptions to natural processes, which produce sediment imbalances and exacerbate coastal erosion. Hence, RSM solves sediment-related problems by designing solutions that recognize the regional nature of natural processes. RSM also recognizes that sediment is a resource integral to the economic and environmental vitality of coastal beaches, and that sustainability can be achieved through beneficial reuse of littoral, estuarine, and river sediments. RSM in California is being facilitated through the California Coastal Sediment Master Plan (Sediment Master Plan) developed by the California Coastal Sediment Management Workgroup (CSMW, 2006). Coastal RSM Plans are being prepared for specific regions of coastal California as a means to identify and target issues of concern within that region.

Regional Sediment Management is a collaborative effort between state, federal, and local agencies, and non-governmental organizations to evaluate California's coastal sediment management needs on a regional basis. More information is available on the CSMW web-site (<http://www.dbw.ca.gov/CSMW>)

1.2 SOUTHERN MONTEREY BAY COASTAL RSM PLAN

1.2.1 Development

The Association of Monterey Bay Area Governments (AMBAG) retained a team led by Philip Williams & Associates (PWA) to develop this Coastal RSM Plan for southern Monterey Bay. The objective of this Coastal RSM Plan is to provide consensus-driven management and policy recommendations on ways to reduce shoreline erosion and restore and maintain coastal beaches through implementation of regional sediment management and beneficial reuse of sediment.

The technical basis for this Coastal RSM Plan is an understanding of the local sedimentary and coastal processes, erosion rates, and sand budget. Using these data in combination with economic, environmental, and societal considerations, critical areas of erosion are identified, critical species and habitat are delineated, and recommendations are proposed for RSM. These recommendations are meant to inform the local decision-making process to help maintain the beaches and dunes of southern Monterey Bay and other critical areas of sediment deficit, in order to restore coastal sandy habitats, sustain recreation and tourism, enhance public safety and access, and reduce proliferation of protective shoreline structures. Other parts of this Coastal RSM Plan explore:

- economic benefits and costs of RSM in southern Monterey Bay
- permits required for planning and implementing RSM, and how to proceed through environmental review and regulatory compliance
- potential sources of funding for costs associated with managing sediment
- a recommended governance structure for implementation of this Coastal RSM Plan in southern Monterey Bay.

This Coastal RSM Plan has been produced within the framework of the Sediment Master Plan (CSMW, 2006). Funding was provided by the California Department of Boating and Waterways (CDBW) on behalf of CSMW. This Coastal RSM Plan was also developed in close collaboration with the Southern Monterey Bay Coastal Erosion Workgroup (SMBCEW). The SMBCEW was initiated in 2005 by the Monterey Bay National Marine Sanctuary (MBNMS), with the City of Monterey, state and other local partners, as part of a process to update the Sanctuary's Management Plan. The SMBCEW was established to address the issues of shoreline erosion and armoring in southern Monterey Bay and to develop a regional planning approach. The goals of the SMBCEW are:

- compile and analyze existing information on coastal erosion rates and threats to private and public facilities within southern Monterey Bay
- identify and assess the range of options available for responding to coastal erosion
- develop a regional shoreline preservation, restoration, and management plan for responding to coastal erosion that minimizes environmental and socioeconomic impacts.

Since its inception the SMBCEW has completed several projects that feed into the RSM process and are integrated into this Coastal RSM Plan. The projects include information on critical areas of erosion (SMBCEW, 2006c), regulatory and policy considerations (MBNMS, 2007b), and funding opportunities (MBNMS, 2007a). It is anticipated that the SMBCEW would serve as a technical advisory committee to the AMBAG in the proposed governance structure for implementation of this Plan (Section 10).

The SMBCEW is also evaluating potential solutions to coastal erosion in southern Monterey Bay that don't involve beneficial reuse of sediment (see below). The SMBCEW and Coastal RSM Plan efforts are intended to be individual, yet complementary, components of a larger integrated approach for addressing sediment management and coastal erosion in southern Monterey Bay. The MBNMS is in the process of funding, on behalf of SMBCEW, a technical evaluation of additional erosion control methods, including retention structures such as offshore reefs, beach dewatering, pressure equalizing modules, and other technologies that could help reduce erosion along the southern Monterey Bay shoreline. This project will also be carried out under the direction of the AMBAG and SMBCEW.

1.2.2 Purpose

The erosion of the southern Monterey Bay shoreline creates complex management problems; property owners want to protect their homes and businesses, municipalities want to protect their tax base and infrastructure, sand mine operators want to continue to remove sand from the beach and generate income, environmental groups want to preserve habitat and minimize damage to the beaches and dunes, and resource managers want to balance public access and habitat protection. This Coastal RSM Plan, which focuses primarily on sand management and mitigation of shoreline erosion, forms part of the solution to these broader shoreline management and coastal zone management challenges. Hence, the Plan could be considered a component of Land Use Plans, Local Coastal Programs, and the MBNMS Draft Management Plan, particularly the harbors and dredge disposal components (Sections 8 and 10).

In addition to the Plan's focus on how RSM can help address coastal erosion problems within the region, it should also enhance the southern Monterey Bay region's ability to compete for limited state and federal funding for erosion control projects that involve sediment management. The CDBW and U.S. Army Corps of Engineers (both members of CSMW) are major funding sources (Section 9) committed to RSM as a means to reduce coastal erosion. Both agencies have many requests for project funding, but only limited funds to disburse, and therefore look for benefits when making funding decisions. Hence, they may be likely to base future allocations of funding on whether a proposed project aligns with an approved Coastal RSM Plan.

This Coastal RSM Plan provides baseline information and a subset of regional recommendations for sediment management that address sediment imbalances aggravating coastal erosion. The information presented in this Coastal RSM Plan is important for evaluating the feasibility of

potential erosion control technologies being undertaken by the SMBCEW (Section 1.2.1). Taken together, these two linked efforts will provide valuable guidance and reference to city and coastal managers, local and state-wide regulatory personnel, the AMBAGs Board of Directors, and state and federal funding entities, thereby setting the stage for specific projects to reduce coastal erosion.

This written Coastal RSM Plan is one of three main deliverables. The other two are a searchable database of references relevant to southern Monterey Bay, and a set of GIS data files to complement the information provided here. The database and GIS data files are accessible on the CSMW web-site (<http://www.dbw.ca.gov/CSMW>).

1.2.3 Implementation

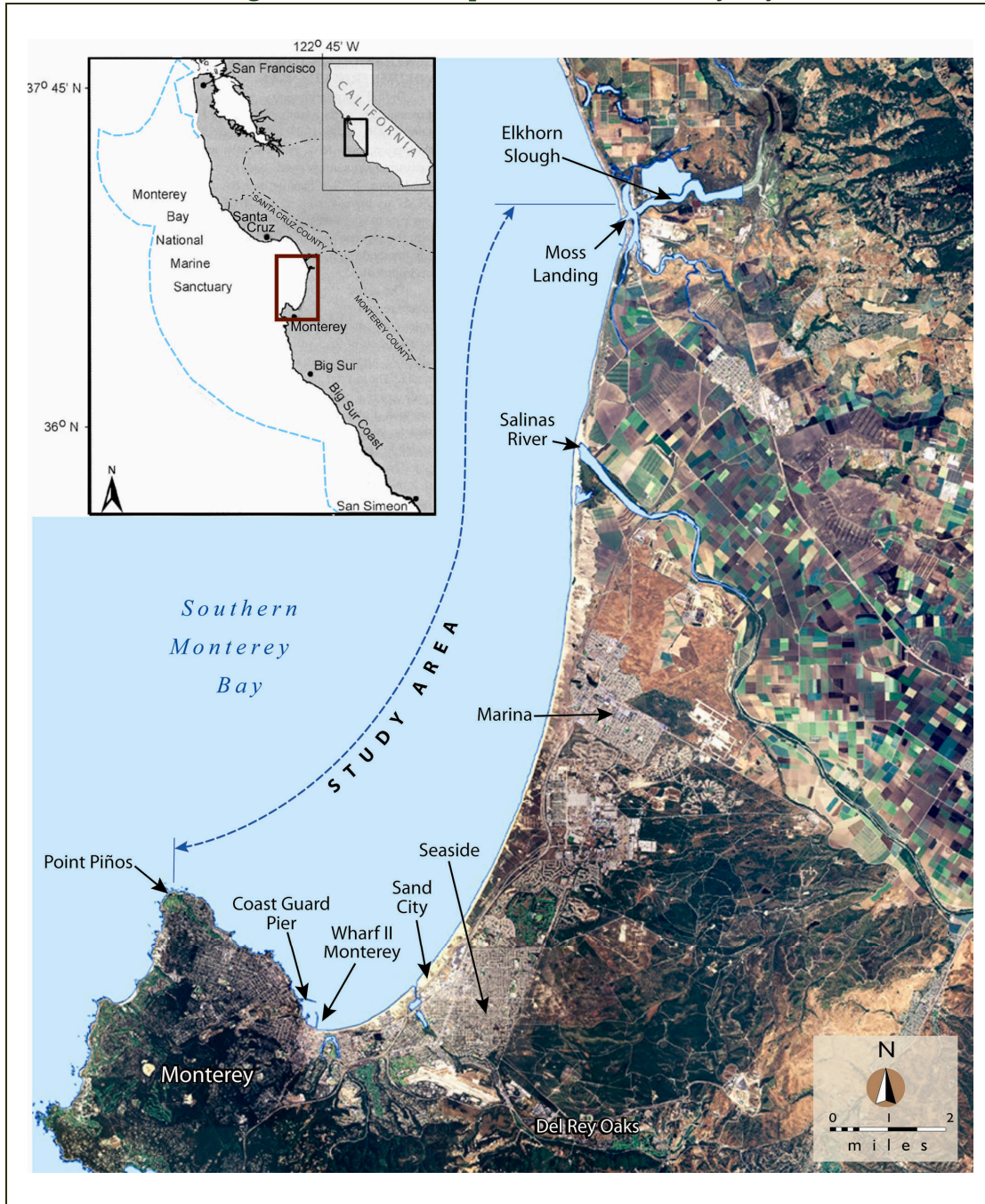
Implementation of this Coastal RSM Plan will require significant coordination with local cities, Monterey County, California Department of Parks and Recreation (CDPR), California Coastal Commission, and other relevant agencies. The AMBAG, as a Joint Powers Authority with a regional perspective, is best positioned for implementing RSM in southern Monterey Bay (Section 10). The AMBAG should work with the County of Monterey and coastal cities to identify how this Coastal RSM Plan can be recognized (referenced) in the county general plan and Local Coastal Programs (LCPs). Advice and guidance on RSM issues would be provided by the SMBCEW.

1.2.4 Jurisdictional Boundaries

Consistent with the California Coastal Act and the Coastal Zone Management Act, the coastal strip between Moss Landing and Wharf II (Figure 1) is divided into six coastal zone management planning areas. From Moss Landing to the northern boundary of the City of Marina (approximately one mile north of Marina sand mine), the shoreline falls within the jurisdiction of the Monterey County Local Coastal Program (LCP), more specifically the North County Land Use Plan (LUP). The City of Marina planning area is between the northern city limit and the northern boundary of Fort Ord. This approximately three-mile stretch of shoreline falls under the jurisdiction of the City of Marina LCP and is designated as habitat reserve and other open space in the City's LUP. Fort Ord is currently an uncertified coastal area and is within the jurisdiction of the Fort Ord Reuse Authority and is subject to the provisions of the Fort Ord Reuse Plan. However, the City of Marina LUP designates the northern half of Fort Ord as within its proposed 'sphere of influence' and hence also subject to the provisions of the LUP. South of Fort Ord is the City of Sand City planning area which extends to approximately 500 feet northeast of Monterey Beach Resort. The coastline for the remaining 500 feet to the northern boundary of Monterey Beach Resort is part of the City of Seaside LUP. The remaining stretch of coast southwest to

Wharf II is part of the City of Monterey planning area, which currently is an uncertified LCP. Any proposed amendments to permitted projects or additional coastal development project proposals in the City of Monterey planning area must go through the California Coastal Commission for approval. Details on the regulatory processes within each of these jurisdictions for implementation of beach nourishment projects are described in Section 8.

Figure 1. Location Map of Southern Monterey Bay



1.3 GEOMORPHOLOGY

Monterey Bay is a lowland coastal embayment, bounded by resistant rock headlands at its north (Santa Cruz) and south (Monterey) ends (Figures 1 and 2). The shoreline between the Salinas River mouth and Wharf II breakwater in Monterey is mostly composed of wide sandy beaches backed by relict (approximately 5,000 to 3,000 years old) sand dunes up to five miles wide and 150 feet high (Griggs and Patsch, 2005; Smith et al., 2005; Thornton et al., 2006). The sand dunes, referred to as the Flandrian and pre-Flandrian dunes, were deposited during the Quaternary.

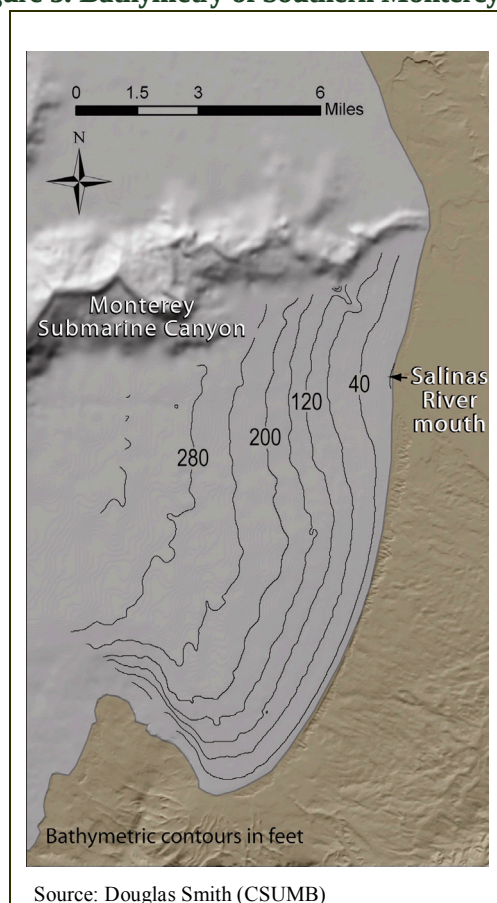
Figure 2. Location Map of the Southern End of Southern Monterey Bay



Approximately 18,000 years ago, at a lower stand of sea level, the dunes extended seven miles seaward of the present day shoreline (Chin et al., 1988). Historically, the beaches of southern Monterey Bay were supplied by large volumes of sand from the watershed of the Salinas River, when the river had a much steeper gradient and a larger transport capacity for sediments. The abundant sand in combination with dominant onshore winds created an extensive dune field in southern Monterey Bay. During the Flandrian (last 10,000 years) the shoreline eroded in response to sea-level rise, migrating landward to its present position at an average erosion rate of approximately 2.3 ft/year. This value is a rough measure of the historic average erosion rate due to natural causes such as sea-level rise and offshore losses. Since the present rate of sea-level rise is lower than the Flandrian rate, but erosion rates in general are higher than the historical mean value (Section 2.3.3), other processes have changed, such as a decrease in the amount of sand contributed by the Salinas River (Sections 2.3.1 and 2.3.2) and sand losses due to mining of the beach (Sections 1.4.4, 2.5.4, and 2.5.5).

The shoreline from Moss Landing to two miles south of the Salinas River mouth is occupied by low relief active (recent) dunes (i.e. dunes that are currently being supplied with wind-blown sand) backing wide sandy beaches. The beach-dune interface is less obvious north of the Salinas River and here the dunes are stable or accreting (Section 2.5.1) (Cooper, 1967; Hapke et al., 2006). Pockets of recent dunes are also present between Marina and Monterey (Section 2.5.2). Areas landward of the dunes are dominated by lowlands, and seaward the beaches are bounded by a continental shelf which descends into the Monterey Submarine Canyon (Figure 3) (Section 2.5.3). A second prominent offshore bathymetric feature is the ancient sediment lobe off the mouth of the Salinas River, which forms a bulge in the nearshore and offshore (Figure 3).

Historically, the Salinas River flowed north parallel to the shoreline behind the dune field and entered Monterey Bay north of present day Moss Landing Harbor. It may also have discharged near its present location, which is aligned with the ancient sediment lobe (Figure 3). In 1910, the river breached the dunes and was diked at its current location (Figure 1) to prevent northward flow into its old channel. In 1946, the U.S. Army Corps of Engineers (Corps) constructed two jetties and dredged an entrance channel at the present opening to Moss Landing Harbor. The historic opening of the Salinas River to the north eventually silted in as a result of the reduction in flow.

Figure 3. Bathymetry of Southern Monterey Bay

1.4 INFRASTRUCTURE AND THE EROSION PROBLEM

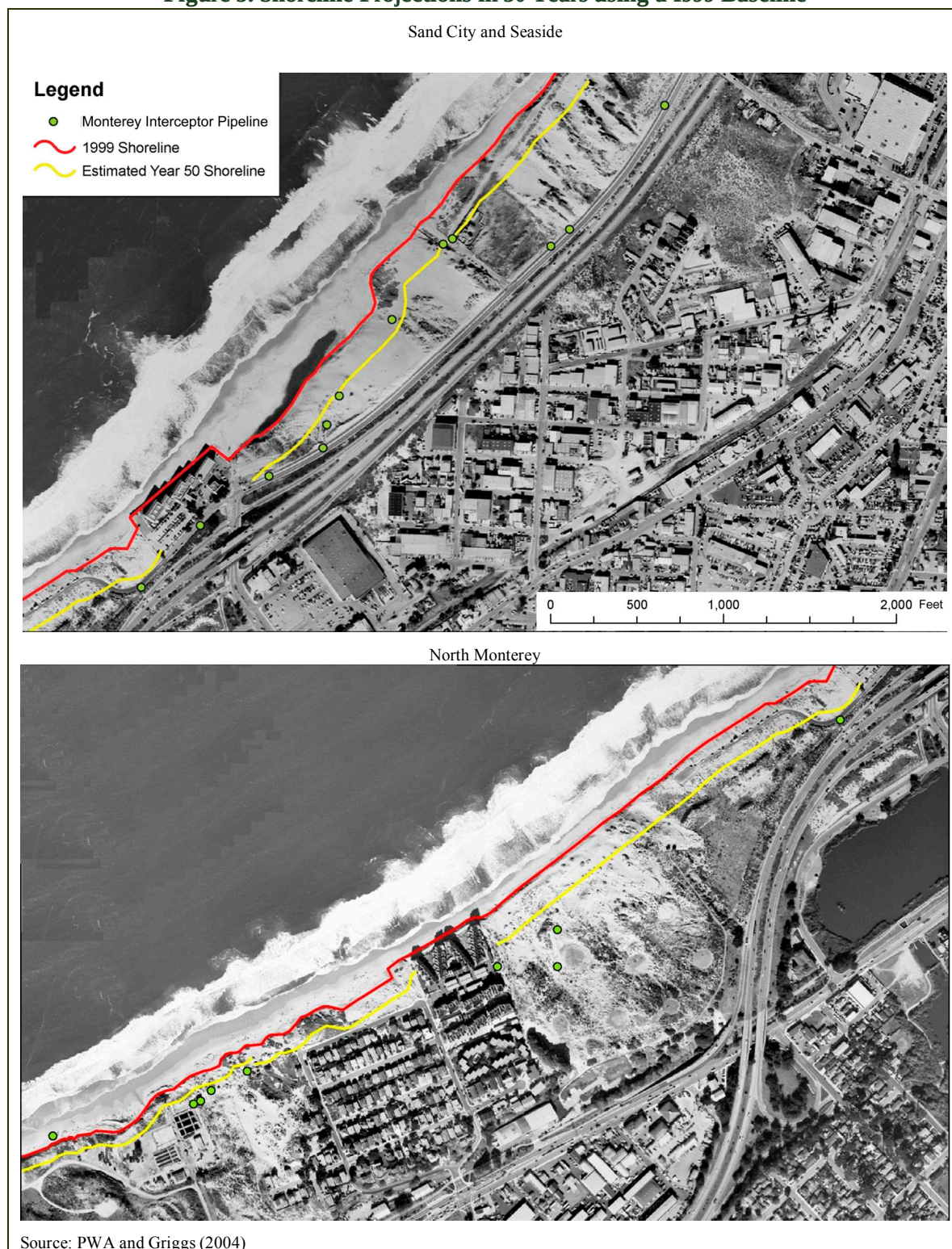
The southern Monterey Bay shoreline is highly susceptible to erosion given the unconsolidated nature of the sand beaches and dunes, and high degree of wave exposure (Section 1.5.2). The seaward face of the relict dunes that line the majority of the shoreline is an eroding bluff (Figure 4). PWA and Griggs (2004) predicted the position of the shoreline between Sand City and Monterey in 50 years time using a 1999 baseline and historic erosion rate data from Conforto Sesto (2004). They showed that over a 50-year timeframe, critical infrastructure including the Monterey Interceptor wastewater pipeline, which transports raw sewage from the Monterey Peninsula to the regional treatment plant in Marina, and other coastal developments would be undermined by erosion (Figure 5). This critical infrastructure is described in Sections 1.4.1 to 1.4.3.

Figure 4. Eroding Dune Bluffs at Fort Ord



Photo taken: September 19, 2007 (Justin Vandever, PWA)

Figure 5. Shoreline Projections in 50 Years using a 1999 Baseline



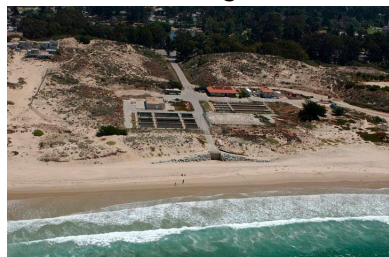
1.4.1 Coastal Armoring and Development

Apart from short lengths of riprap and seawall at Sand City, Monterey, and Moss Landing the majority of the southern Monterey Bay shoreline is unarmored (Stamski et al., 2005a, b). Approximately 0.6 miles at the southern end and 0.1 miles at the northern end of the 16-mile shoreline are currently armored (approximately 4%). Shoreline armoring in the south is focused at the privately-owned oceanfront Monterey Beach Resort and Ocean Harbor House condominiums (Figure 2). At these facilities the shoreline is fixed, and adjacent beaches and dunes continue to erode, causing armored areas to protrude seaward into the beach runup zones, and even the surf zone. The result is loss of beach width, and an adverse effect of blocking lateral beach access and recreation, posing a public safety hazard (Figure 6, left panel). The armoring consists of 600 feet of seawall to protect Monterey Beach Resort and 700 feet of emergency riprap to protect the Ocean Harbor House condominiums. The riprap in front of the Ocean Harbor House condominiums (Figure 6, right panel) is due to be replaced with a permanent seawall within the footprint of the condominiums. The seawall fronting the Monterey Beach Resort is due to be replaced with a new seawall abutting the front of the present structure.

Figure 6. Armoring at Monterey Beach Resort and Ocean Harbor House Condominiums

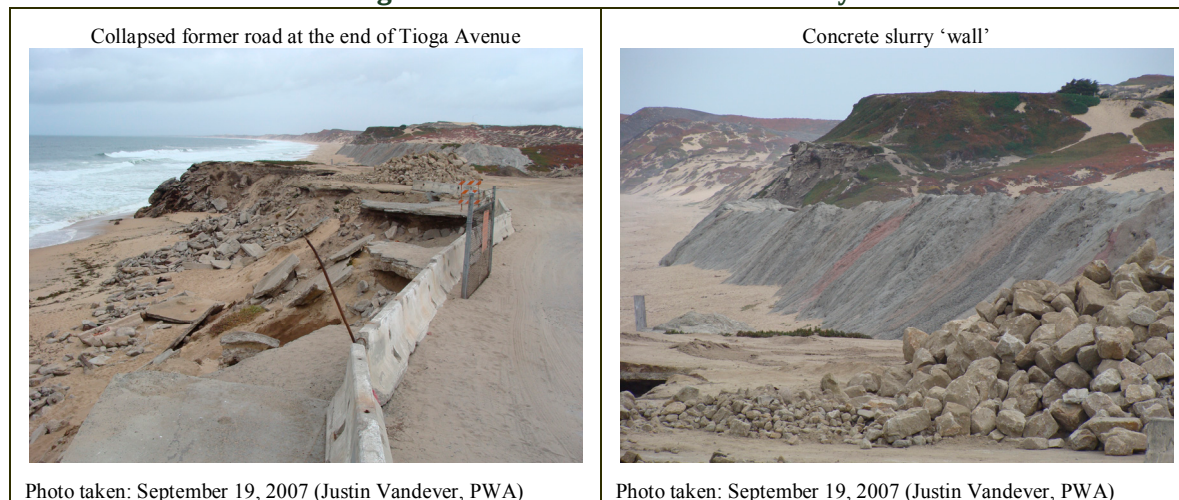


Shoreline armoring in the form of concrete and other debris is also present fronting the former sand mining complex at Sand City (Figure 2). Here, remnants of a cement mixing facility are located immediately north of Tioga Avenue. The facility is now used for temporary storage of construction equipment. Until at least 1990, concrete slurry was dumped here parallel to the shoreline to form an 800 foot-long concrete ridge that effectively acts as a seawall (Figure 7, right panel). In addition, at the seaward end of Tioga Avenue



there is a 750 foot-long collection of debris and riprap, composed predominantly of un-engineered cement and asphalt blocks, and the remains of a former road (Vista del Mar Street) where much of the asphalt has fallen over the bluff (Figure 7, left panel). A further 130 feet of riprap fronts the Del Monte Lake outfall (Figure 2) (inset). There is also a 470 foot-long concrete seawall in front of the main Monterey Bay Aquarium Research Institute (MBARI) building at Moss Landing (Figure 1).

Figure 7. Coastal Structures at Sand City



1.4.2 Utilities

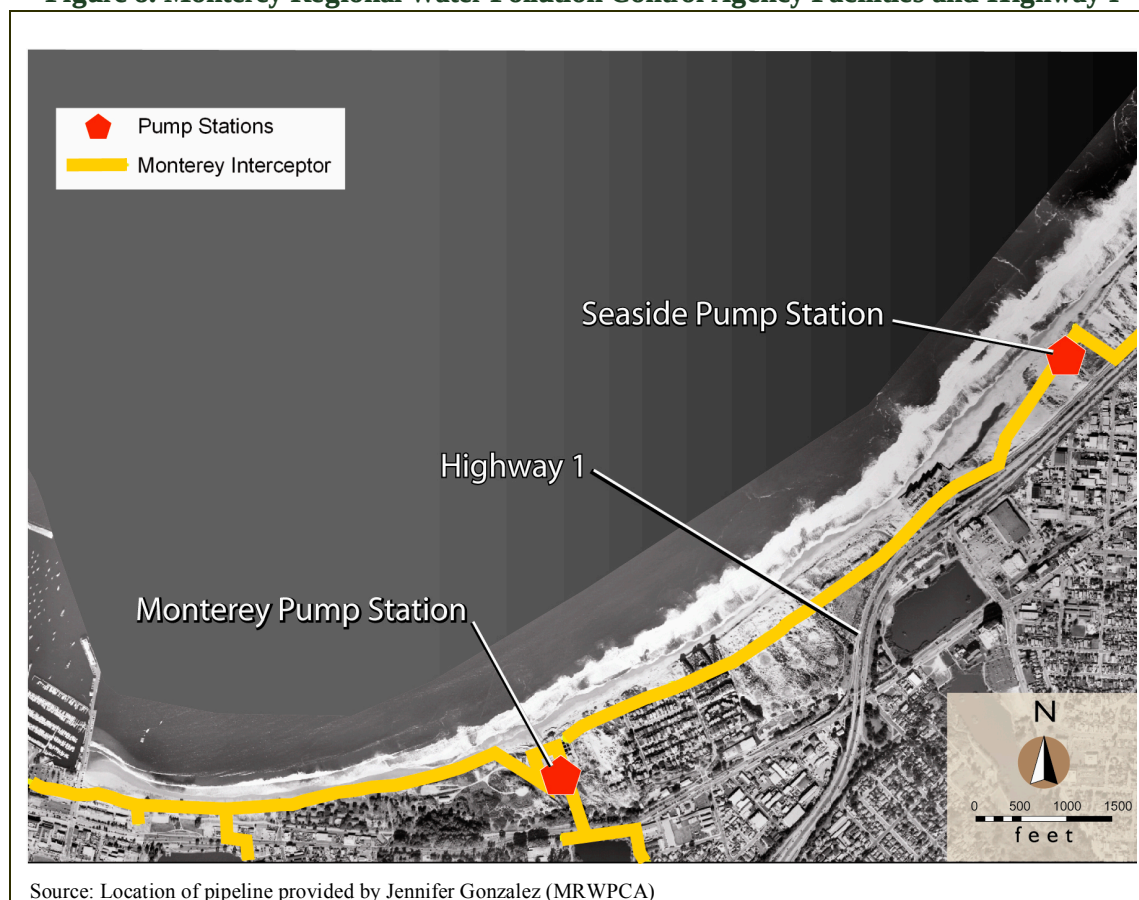
Monterey Regional Water Pollution Control Agency (MRWPCA) pump stations, pipelines, and outfalls extend along the southern Monterey Bay shoreline from Marina to Wharf II (PWA and Griggs, 2004). Pump stations are surface or sub-surface structures housing wastewater pumps and pipeline connections. At the shoreline, wastewater transport pipelines are typically buried in the dunes or beneath the beach. The MRWPCA oceanfront facilities include (Figure 8):

- Monterey Interceptor pipeline extending from Seaside Pump Station to Wharf II. This pipeline is buried in the dunes between Seaside and Monterey Pump Stations and beneath the beach between Monterey Pump Station and Wharf II
- Seaside Pump Station which is set back approximately 100 feet from the present dune edge
- Monterey Pump Station which is set back approximately 350 feet from the present dune edge.

The Monterey Interceptor pipeline was constructed between 1977 and 1981 to collect the raw wastewater from Pacific Grove, Monterey, Seaside, Sand City, and Fort Ord for regional secondary treatment at the Marina sewage treatment plant before discharge into Monterey Bay.

The pipe ranges in diameter from 3.0 to 3.5 feet, and there are manholes approximately 500 feet apart along the pipe and at each point of connection. The manholes, in accordance with California Coastal Commission permit requirements, were set so that their tops were approximately four feet below the lowest ‘normal’ sand level on the beach. Several of the manholes are now sometimes exposed, and are at risk of damage due to erosion (PWA and Griggs, 2004).

Figure 8. Monterey Regional Water Pollution Control Agency Facilities and Highway 1



1.4.3 Highway 1

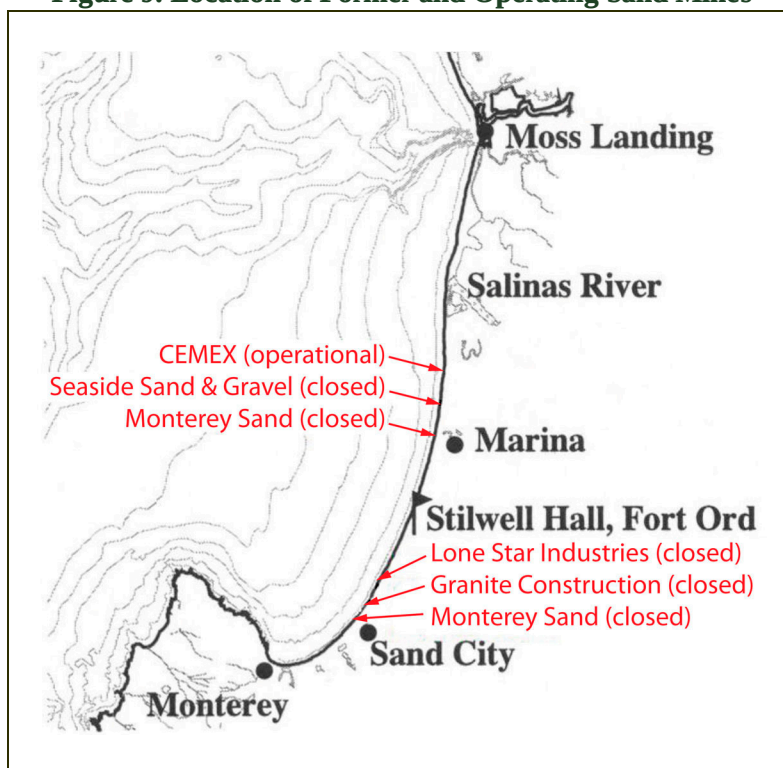
Portions of Highway 1 curve seaward at Sand City and in the vicinity of Monterey Beach Resort (Figures 2 and 8). These sections of the highway may be threatened by coastal erosion in the future.

1.4.4 Sand Mining

Southern Monterey Bay has been the most intensively mined shoreline in the U.S. Sand mining near the mouth of the Salinas River started in 1906, and expanded to six commercial sites; three at Marina and three at Sand City (Figure 9). Five of these operations used drag lines to mine coarse sand from the surf/swash zone (inset). In the summer months, when swell waves transported relatively fine sand back onshore, the operations were sometimes suspended. The sixth mine is located at Marina approximately two miles south of the Salinas River mouth, where the sand is hydraulically extracted just landward of the beach berm by a dredge floating on a self-made pond. Although all drag line sand mines were closed by 1990, the Marina operation (Pacific Lapis Plant) owned by CEMEX is ongoing (Section 2.5.4) (Figure 9).



Figure 9. Location of Former and Operating Sand Mines



The sand of southern Monterey Bay is economically valuable owing to high silica content, hardness, roundness, amber color, and is used for a variety of purposes including packing for water well casings, filtration, sandblasting, foundry and surface finishing (Combellick and Osborne, 1977). The time line of sand mining in southern Monterey Bay is:

- **1906** - Sand mining started near the Salinas River mouth
- **1940** – Start of intensive drag line sand mining directly from the surf/swash zone
- **1965** – Start of hydraulic sand mining of the pond at Marina
- **1980s** - Larger hydraulic dredge introduced to mine pond at Marina, continuing today
- **1986** - Sand mining by drag lines stopped at Marina
- **1990** - Sand mining by drag lines stopped at Sand City

1.5 PHYSICAL PROCESSES

1.5.1 Tidal Regime

The southern Monterey Bay coast experiences mixed semidiurnal tides, with two high and two low tides of unequal height each day. The mean tidal range (defined as mean low water minus mean high water) at Monterey Harbor (Station ID: 9413450) is 3.5 feet and the diurnal range (defined as mean higher high water minus mean lower low water) is 5.3 feet (Table 1). Tidal range determines the extent of beach exposure and inundation throughout the tidal cycle. Particularly important are the timing and height of high tides coincident with maximum wave heights and surge developed during storms.

Table 1. NOAA Tidal Datums for Monterey Harbor (Station ID: 9413450)

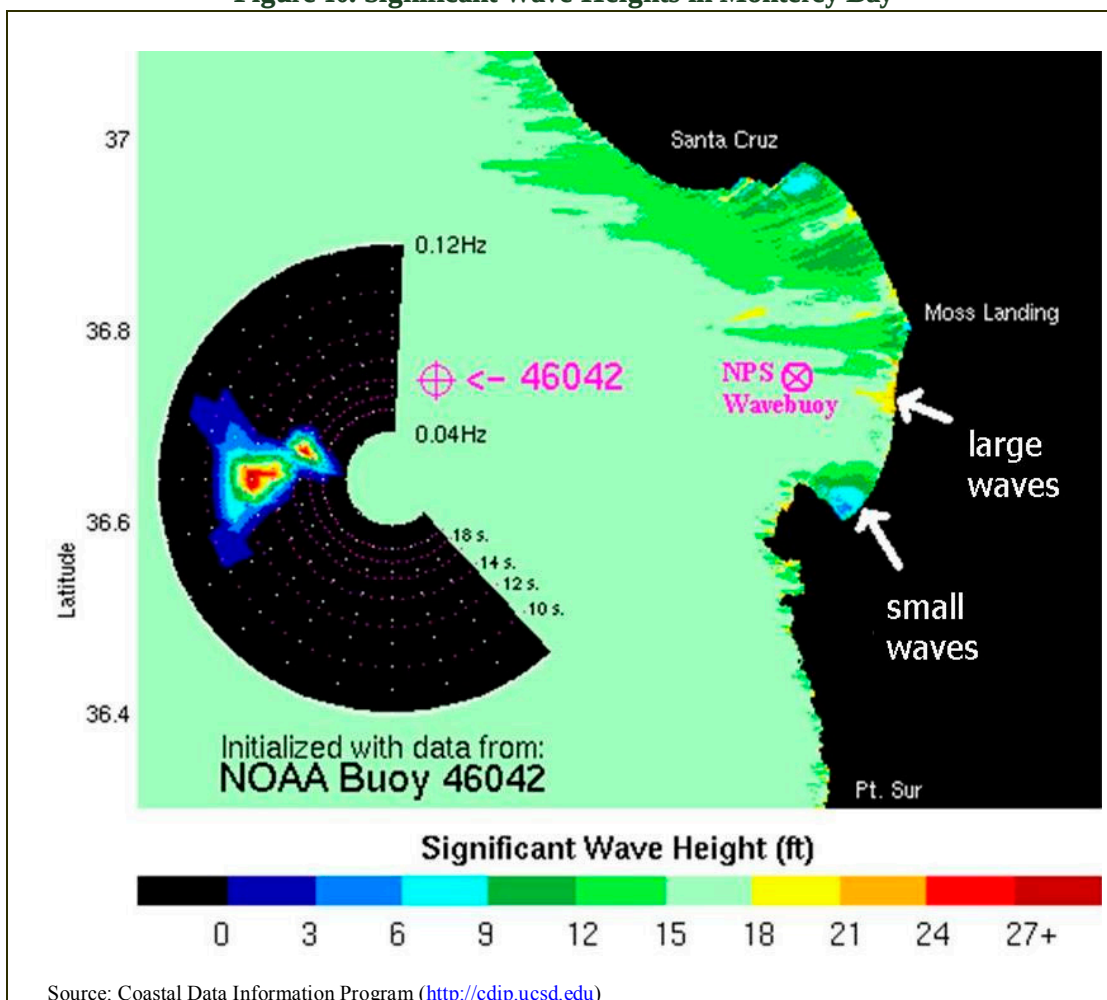
Tidal Datum	MLLW (feet)	NAVD 88 (feet)
Mean higher high water (MHHW)	5.34	5.48
Mean high water (MHW)	4.64	4.78
Mean tide level (MTL)	2.87	3.01
Mean sea level (MSL)	2.83	2.97
Mean low water (MLW)	1.10	1.24
Mean lower low water (MLLW)	0.0	0.14

1.5.2 Wave Climate

With respect to RSM, the wave climate of southern Monterey Bay is important for two reasons. First, differential wave energy alongshore causes variations in the magnitude of erosion due to wave impacts at the dune toe (Section 2.3.3). Second, the direction and magnitude of wave approach relative to the shoreline orientation, controls the direction and strength of alongshore sediment transport (Section 2.2).

The nearshore wave climate of southern Monterey Bay is impacted predominantly by waves from the northwest (Storlazzi and Wingfield, 2005). Xu (1999) reported a time series of wave height, period and energy data between 1990 and 1995 from a gauging station located 0.6 miles offshore from Marina. The time series showed that significant wave heights in winter are greater than in the summer and the highest waves arrive from the northwest in both seasons. Presently, the directional wave spectrum is measured every four hours at the National Oceanic and Atmospheric Administration (NOAA) wave directional buoy (Buoy ID: 46042) offshore of Monterey Bay (Figure 10) as part of the Coastal Data Information Program (CDIP). As a complement to this program, the wave height, direction, momentum flux, and sediment transport have been calculated every 200 m (600 feet) alongshore in Monterey Bay since October 2007 as part of the California Ocean Current Management Program (COCMP). Refraction occurs as the waves pass over Monterey Submarine Canyon focusing wave energy at Marina and Fort Ord (inset) and defocusing energy at Moss Landing. In addition, the shoreline at Monterey and Sand City is sheltered by Point Piños headland from waves from the south and west, resulting in reduced wave energy. The net result is a large alongshore energy gradient with relatively small wave heights at Monterey increasing to relatively large wave heights at Fort Ord and Marina (Figure 10) (Thornton et al., 2007).



Figure 10. Significant Wave Heights in Monterey Bay

Longer term variations in wave climate are linked to large-scale atmospheric variations, particularly El Niño-Southern Oscillation and Pacific Decadal Oscillation (PDO) events. El Niño events are characterized by above average rainfall and large waves generated by Pacific storms, and generally last between six and eighteen months. The two most energetic El Niño's of the past 50 years along the California coastline occurred in 1982-83 and 1997-98. The PDO is a 20-25 year climate oscillation based on sea surface temperature phases, which have implications for ecosystems, physical processes, and beaches (Revell and Griggs, 2006; Adams et al., 2008). The PDO controls the jet stream and storm tracks in the north Pacific, which affects wave direction. During negative phases (relatively low water temperatures), La Niña conditions are more prevalent (dominated by waves from the northwest), while during positive phases (relatively high water temperatures), El Niño conditions are more dominant (more waves from the west). Higher intensity PDO and El Niño events were more common from 1910 to 1940, and after 1978, possibly continuing today, with the 1940 to 1978 period marked by a gentler climate.

The most destructive waves are most common during El Niño events (Storlazzi and Griggs, 2000; Dingler and Reiss, 2002; Storlazzi and Wingfield, 2005) when storms increase in frequency and intensity, producing waves of exceptional height and period at the shoreline. El Niño winter storm waves tend to approach the Monterey Bay shoreline from the west or west-southwest. Waves



from this direction diverge less due to refraction than those created by storms from the northwest, resulting in larger waves at the shoreline. Storlazzi and Griggs (2000) correlated El Niño events and the occurrence of large waves, higher than normal sea-surface elevations, and storms that caused significant erosion at the coast. A higher water surface together with the increased wave setup associated with the higher storm waves elevates the level of wave attack

relative to the bluff toe (inset: photo taken by Steve Moore, CSUMB). The timing of El Niño storms also tends to be later in the winter season when the protective beach is already reduced (Section 2.3.3), further exposing the bluff toe to wave attack. The 1982-83 and 1997-98 El Niño winter storms caused severe beach and dune erosion along central California's coast including southern Monterey Bay (Storlazzi and Griggs, 2000; Thornton et al., 2006).

1.5.3 Base Flood Elevations

The Federal Emergency Management Agency (FEMA) coastal flood studies in southern Monterey Bay (FEMA, 2007) projected the maximum elevations of wave runup and overtopping during a 100-year flood event, denoted by the Base Flood Elevation (BFE) (Table 2). Structures at elevations below the BFE may be subject to damages from direct wave impacts or undermining by wave scour. The BFE estimates do not include a future sea-level rise component and may be low relative to potential future conditions.

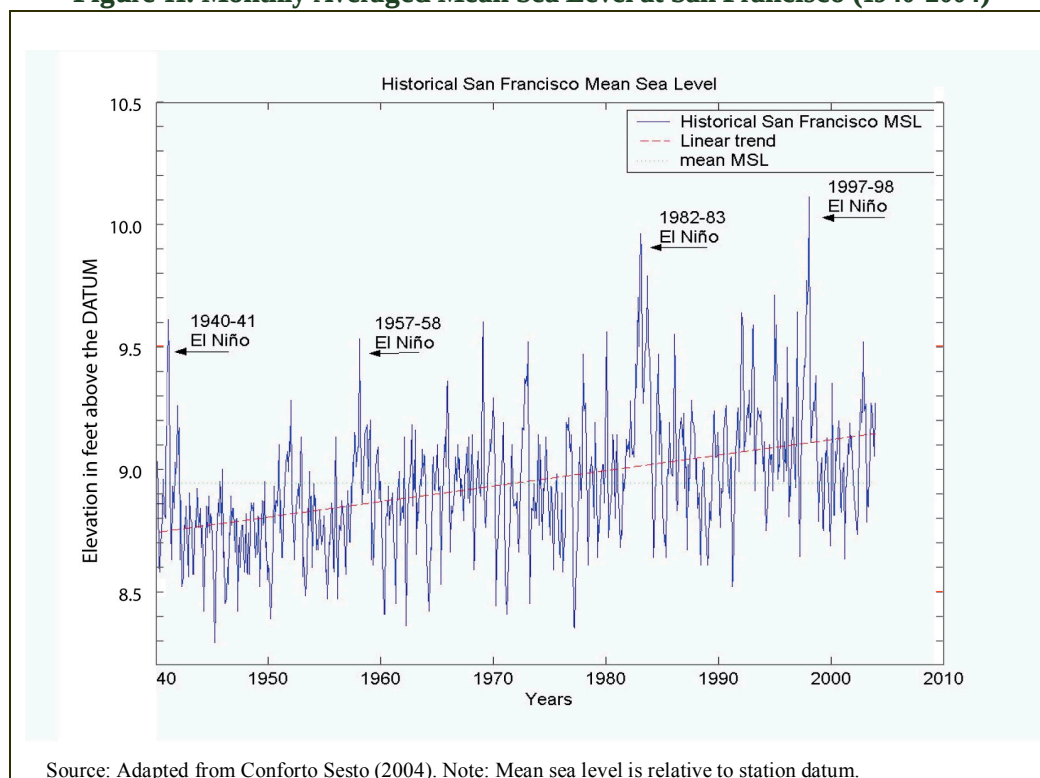
Table 2. FEMA (2007) Base Flood Elevations (BFE)

Location	BFE (feet NAVD)
North of the Salinas River mouth	23-24
Sand City (Tioga Avenue)	27
Seaside Pump Station	27
Monterey Beach Resort	24
North Del Monte Beach (Monterey)	26
Wharf II and South Del Monte Beach (Monterey)	22

1.5.4 Relative Sea-Level Rise

Measurements of monthly-averaged relative mean sea-level rise at Monterey started in 1973, providing a 35-year record for analysis. The Monterey record shows that relative sea-level has risen at a rate of 1.86 mm/year (0.31 ft/50 years) between 1973 and 1999. In order to determine if a longer record could be used to establish the relative sea-level rise rate in southern Monterey Bay before 1973, the Monterey tide gauge data was compared to San Francisco tide gauge data, which started in 1853 and is the longest continuous record in the U.S. The two time series have a high correlation coefficient (>0.9) (Conforto Sesto, 2004), indicating that the San Francisco record can be used to infer relative sea level at Monterey, since the regional land subsidence rates at these tide gauges is low (Battalio and Everts, 1989). The San Francisco record shows that relative sea level has risen at a rate of 2.13 mm/year (0.35 ft/50 years) since 1906. The record shows significant annual variations, and spikes in mean sea level correlate with El Niño events (Battalio and Everts, 1989; Ryan et al., 1999) (Figure 11).

Figure 11. Monthly Averaged Mean Sea Level at San Francisco (1940-2004)



Over the next century, the Intergovernmental Panel on Climate Change (IPCC, 2007) predicted a global rate of sea-level rise between approximately 0.6 and 1.8 feet, although considerable uncertainty surrounds these values. For example, Rahmstorf (2007) projected higher rates of global sea-level rise between 1.6 and 4.6 feet over the next century. The upper end of this range has been recommended for coastal planning in California (CRA, 2008). In this Coastal RSM Plan an average rise of 3.0 feet over the next century is used (one foot over the next 50 years, assuming an exponentially accelerating rise). This estimate is precautionary for long-term planning for sea-level rise and is in line with California Coastal Commission measures which require consideration of a three feet sea-level rise over the next century (Susan Craig, Coastal Commission, personal communication).

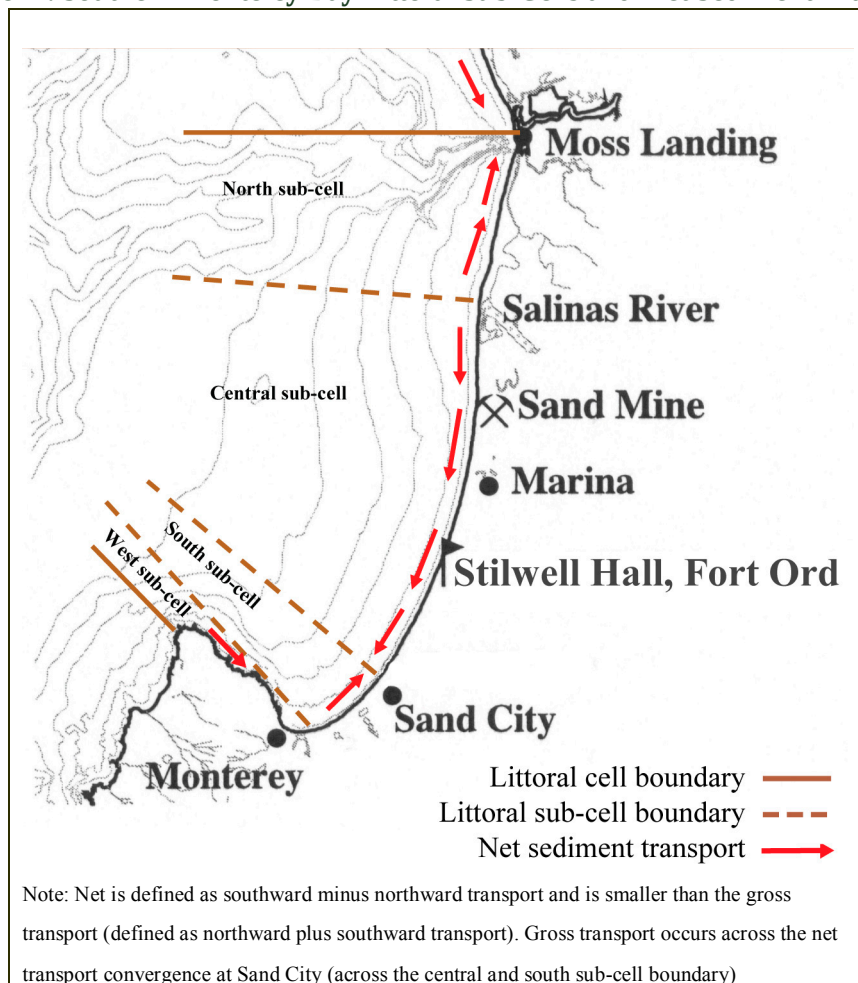
2. SEDIMENT BUDGET

Sediment (sand) budgets are important tools in understanding regional sediment processes (Best and Griggs, 1991; Rosati, 2005) and quantifying the sediment sources (inputs) and sinks (outputs) from a littoral cell; a defined length of shoreline along which the cycle of sediment erosion, transportation, and deposition is essentially self-contained. Sediment enters a cell from one or more rivers (the Salinas River in southern Monterey Bay) draining the coastal watersheds and/or from erosion of coastal bluffs (coastal dunes in southern Monterey Bay). A littoral cell includes the beach above the highest tides, wind-blown sand, and any sediment within the surf/swash zone and out to the depth on the shoreface at which wave energy stops transporting sediment (so-called closure depth). Some of the sediment inputs and outputs are not well defined, such as those in cross-shore directions, and these components are often treated as an unknown and estimated by the residual in the budget.

2.1 DEFINITION OF THE SOUTHERN MONTEREY BAY LITTORAL CELL

Monterey Bay is currently divided into two primary littoral cells; Santa Cruz to the north and southern Monterey Bay to the south (Patsch and Griggs, 2007). The Santa Cruz littoral cell stretches from Point San Pedro to the head of Monterey Submarine Canyon close to the shoreline at Moss Landing. Sediment is transported south within this cell (Best and Griggs, 1991; Eittreim et al., 2002) until it is deflected offshore into Monterey Submarine Canyon by Moss Landing Harbor north jetty, and lost from the littoral system (Wolf, 1970).

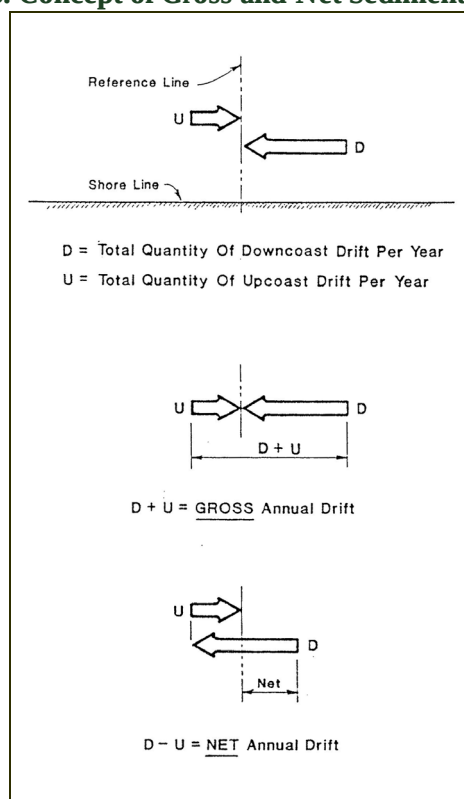
The southern Monterey Bay littoral cell is considered in this Coastal RSM Plan to be comprised of four sub-cells (north, central, south, and west) between Monterey Submarine Canyon and the Point Piños headland, around which no sand enters the Bay (Figure 12). The boundary between the north and central sub-cells is located at the Salinas River mouth. Refraction of waves over Monterey Submarine Canyon (Section 1.5.2) and the relict Salinas River delta results in a net alongshore sediment divide, with a portion of the sand discharged from the Salinas River transported north towards Monterey Submarine Canyon, and a portion transported south towards Sand City (Figure 12) (Habel and Armstrong, 1978). Thornton et al. (2006) suggested seasonal variability in sand transport directions in the central sub-cell. During winter, waves approach from the west and sand is transported to the north, with transport to the south during the rest of the year (waves from the northwest), with an overall net southerly movement. The northerly transport during the winter coincides with the time of year when the Salinas River may be flowing into the Bay and providing sediment input (Section 2.3.1). This suggests that most of the river sediments are transported to the north, supporting the contention of Patsch and Griggs (2007) that most of the sediment from the Salinas River is driven north and potentially lost into Monterey Submarine Canyon at the northern boundary of the littoral cell.

Figure 12. Southern Monterey Bay Littoral Sub-Cells and Net Sediment Transport

A third (south) sub-cell exists between Wharf II and near Sand City (Figure 12). Orzech et al. (2008) showed that the net sand transport at Sand City is to the north, resulting in a convergence with the net southerly transport at Fort Ord (Section 2.2). At the location of convergence, approximately 2.5 miles northeast of Wharf II (although seasonally variable in location), sand may migrate offshore, demarcating the boundary between the central and south sub-cells. Little sand has accumulated against the Wharf II breakwater since it was built in 1932, and the beach sand there appears to be derived primarily from runoff, suggesting little or no net southerly transport at this location.

The net sand transport is defined as the difference between transport to the south and transport to the north (Figure 13). The alongshore transport varies in magnitude and direction in response to incident wave conditions and the actual transport conditions can be different to the net transport shown in Figure 12. In southern Monterey Bay, the net sand transport is much smaller than the gross sand transport, which is defined as the sum of southward and northward transport, and can be greatly affected by sand supply and shoreline orientation changes (Battalio and Everts, 1989) (Section 2.2). This means that gross transport of sand can take place across the net transport boundary between the central and south sub-cells (i.e. large amounts of sand can move south through the boundary).

Figure 13. Concept of Gross and Net Sediment Transport



A fourth (west) sub-cell is defined between Point Piños and Monterey Harbor (Coast Guard Pier) where the alongshore sand transport is to the southeast (Patsch and Griggs, 2007). The shoreline of this sub-cell is comprised primarily of erosion-resistant granite, and hence, has probably not contributed a large amount of sand to the Bay. Monterey Harbor blocks most sand transport from the east with only a small amount passing the breakwater. After the Coast Guard Pier was built in 1959, the breakwater impounded sand such that San Carlos Beach adjacent to the west side of the

pier increased in width to 80 feet by 1990 (Storlazzi and Field, 2000) and has since stabilized at about that width. This implies that the harbor is a barrier to sand transport to Del Monte Beach (Monterey) although the quantities and effects are small.

Monterey Harbor requires periodic dredging. Approximately 4,000 yd³ was dredged in 2003 and it is estimated that approximately 75,000 yd³ could be targeted for dredging in 2010-2011. The sand in the harbor appears to be derived locally based on mineralogy and sand size (Dingler et al., 1985). Sand enters the harbor past the east and west breakwaters, through three runoff outfalls within the harbor, and through an overflow runoff pipe just inside Wharf II.

Based on the potential for sand to be transported from the central sub-cell into the north sub-cell, it is recommended using Monterey Submarine Canyon as the northern boundary of the littoral cell (the littoral cell defined by Patsch and Griggs, 2007) (Figure 12). The 16 miles of shoreline between Monterey Submarine Canyon and Wharf II encapsulates all of the sediment that should be considered in RSM for southern Monterey Bay.

2.2 ALONGSHORE SEDIMENT TRANSPORT

2.2.1 Impacts of Rip Currents

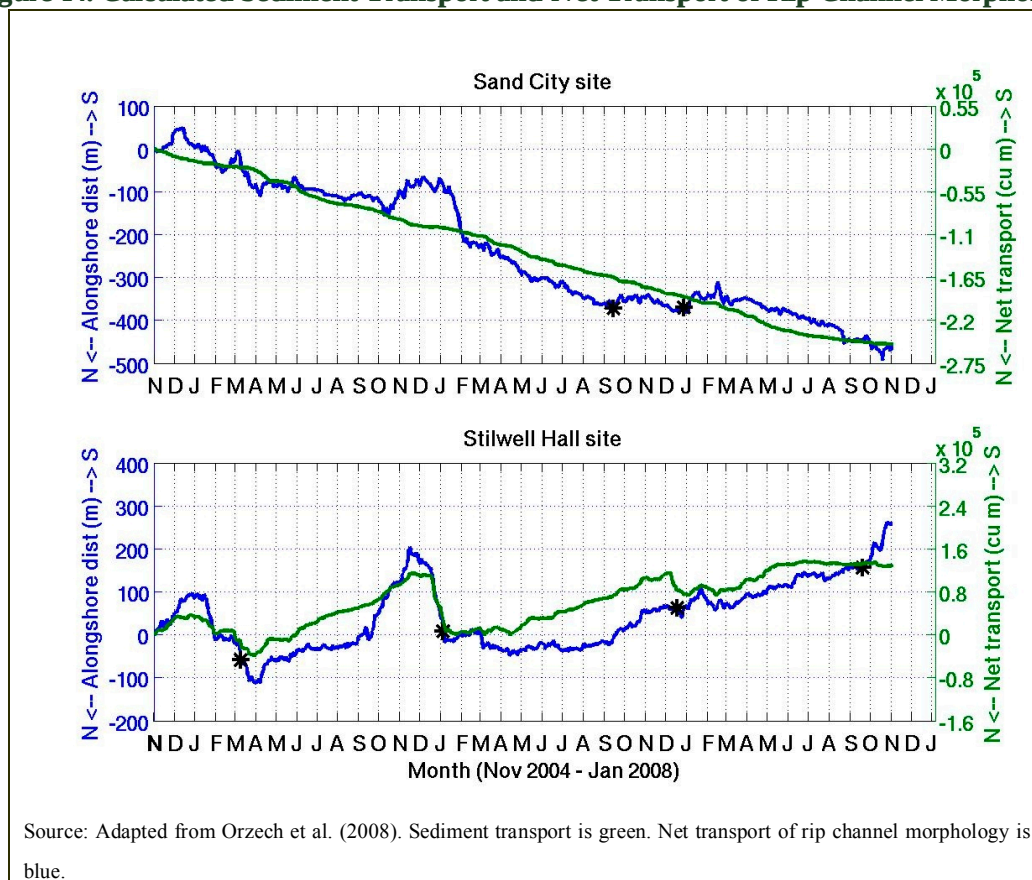
The near-normal incidence of waves approaching the southern Monterey Bay shoreline is conducive to rip current generation and maintenance (Thornton et al., 2007). Rip currents are generated when waves break sooner on nearshore bars (Section 2.3.5) than in the deeper rip channel. This results in greater setup over the bars than in the channel and creates pressure gradients towards the rip channel generating feeder currents from both up coast and down coast directions. The rip current flows offshore at the convergence of the feeder currents, creating a cross-shore component to the sediment transport. The feeder currents both retard and enhance the alongshore sediment transport, but the net affect is a reduction. The amount of reduction (R_c) is dependent on the rip channel width (W_c) compared to the spacing between rip channels (L_c) where $R_c = W_c/L_c$ (Fredsoe and Deigaard, 1992). The reduction to alongshore sediment transport (R_c) ranges from 0.5 at Monterey to 0.2 at Fort Ord and Marina.

2.2.2 Net Sand Transport

Orzech et al. (2008) measured the daily migration of rip current channels (Section 2.3.6) over a three-year period (2005-2008) using time-lapse video images taken at Sand City, Fort Ord and Marina, and hypothesized that the migration was due to alongshore sediment transport. They calculated daily net sediment transport rates over the same three years applying a modified version of the CERC formula (Corps, 1984) on wave spectra refracted from the offshore NOAA

wave directional buoy (Buoy ID: 46042) (Figure 10). They found correlation values of 0.83-0.96 between daily migration distance and calculated net alongshore sediment transport giving confidence in the calculated directions (Figure 14). Sediment transport at Stilwell Hall (Fort Ord) and Marina (not shown in Figure 14 as it is similar to Fort Ord) is seasonally variable with transport to the north during the winter and to the south the rest of the year, with a calculated net rate to the south between 10,000 and 20,000 yd³/year, which includes the reduction factor due to rip currents (Section 2.2.1).

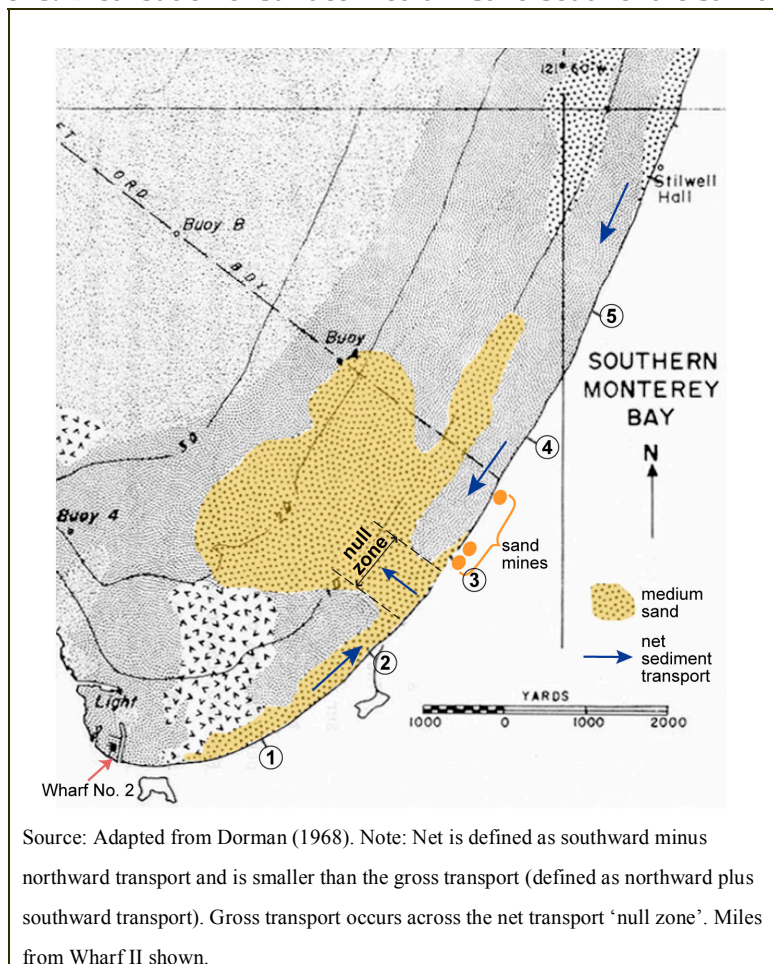
Figure 14. Calculated Sediment Transport and Net Transport of Rip Channel Morphology



An important boundary in the net alongshore sediment transport regime is at Sand City where sand transported south from Fort Ord meets sand transported north from Monterey to form a zone of net convergence. Sediment transport at Sand City is complicated by its sheltered location in the shadow of the Point Piños headland. Wave directionality drives the transport consistently to the north. However, because of its sheltered location, there is also a transport component to the south. The alongshore gradient of wave energy in southern Monterey Bay (Section 1.5.2) creates a pressure gradient driving currents to the south that is seasonally variable and strongest in the winter when waves are largest. The resulting calculated net transport at Sand City, including the

reduction in transport owing to rip currents, is to the north at 8,000 to 20,000 yd³/year. These calculated values closely balance the net transport from the north, suggesting a null zone of small net transport at the convergence (Figure 15).

Figure 15. Distribution of Surface Medium Sand South of the Salinas River



Evidence supporting a net sediment convergence zone is found in Combellick and Osborne (1977) and Hunter et al. (1988). Combellick and Osborne (1977) combined the surface sediment data at the southern end of Monterey Bay of Dorman (1968) and Greene (1970), and found a zone of surface medium sand (particle size 0.25-0.5 mm) extending offshore from Sand City with mineralogy and physical characteristics consistent with the dune and beach sands (Figure 15). The location of the shore-connection of this offshore sand is consistent with the location of the net alongshore sediment transport convergence zone. Hunter et al. (1988) examined this area over a three-year period performing repeated side-scan sonar surveys, obtaining cores, and placing rods on the bottom to measure changes in the bed elevation. They found bands of coarse sand at water depths of 30-60 feet. The coarse sand (0.35-1.0 mm) was approximately three feet lower

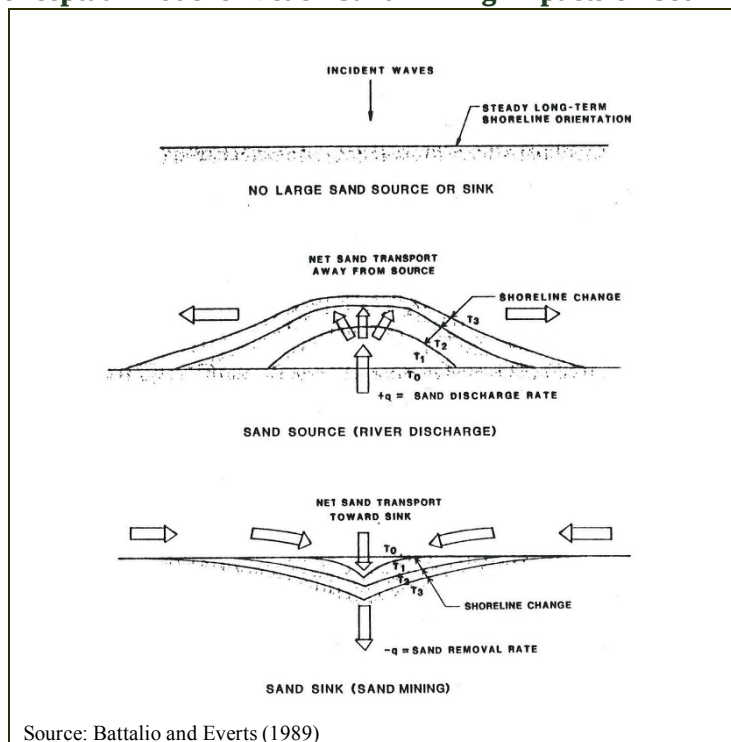
that the adjacent finer sands (0.12–0.35 mm). The cores (20–40 inches in length) recovered unconsolidated sand of recent age (150 years) containing iron and glass fragments, suggesting offshore transport.

2.2.3 Gross Sand Transport

The net alongshore sediment transport rates within the southern Monterey Bay littoral cell are relatively low. This is because waves approach the shoreline at near-normal angles due to refraction across offshore bathymetric contours including Monterey Submarine Canyon, and the evolution of the shoreline in response to the wave climate. Southern Monterey Bay is essentially a hook-shaped bay (a near-equilibrium shape) between Point Piños and Monterey Submarine Canyon. These processes along with the shorelines exposure to the north Pacific, result in large total (gross) alongshore sand transport rates but small net transport rates (Section 2.2.2) over a given period. The gross transport rates are highest towards the center of the Bay (Fort Ord) due to the offshore wave refraction effects. High gross sand transport rates are important because they result in rapid redistribution along the Bay shoreline of perturbations such as beach-sand mining and local bluff erosion (Battalio and Everts, 1989). Hence, mining of sand from the beach in southern Monterey Bay affects sediment transport and supply along the entire shoreline from the Salinas River mouth to Monterey Harbor.

The net sediment transport rates estimated for the south and central sub-cells are expected to be an order of magnitude less than the gross sediment transport rates. Also, the null zone is not a barrier to sand transport, and sand does move through this zone (Section 2.1). The net rate is a calculation affected by sand sources and sinks as well as the change in shoreline orientation resulting from erosion. This implies that the northward net transport shown in Figures 12 and 15 may be a result of sand mining from the beach and coastal erosion. Also, the magnitude of net transport southward near the null zone would likely be effected by sand mining and shoreline response over time.

Mining of sand from the southern Monterey Bay beaches has increased erosion rates, and modified shoreline orientation and sand transport rates. A detailed review of historic shoreline positions and a sand budget indicated that beach-sand mining at Sand City and Marina had caused the shoreline to retreat in the vicinity of the mines, thereby increasing alongshore sand transport toward the mines (Battalio and Everts, 1989). The Fort Ord shoreline experienced the highest erosion rates due to its location between the Sand City and Marina beach-sand mining operations, and also due to greater wave exposure. Battalio and Everts (1989) used a conceptual model and a numerical model to evaluate these processes based on an equilibrium shoreline with small net transport, but large gross (total) transport, where perturbations like beach-sand mining and river discharge result in transport toward and away, respectively, from the perturbation (Figure 16). Therefore, the alongshore sand transport rate has varied over time in response to beach-sand mining, which continues today.

Figure 16. Conceptual Model of Beach-Sand Mining Impacts on Sediment Transport

Apart from the Moss Landing jetties, Wharf II breakwater and Coast Guard Pier at Monterey Harbor, southern Monterey Bay has no shore-normal structures that would act as barriers to alongshore sediment transport. There are also no shore-parallel offshore structures that would inhibit cross-shore transfer of sediment. However, mining of sand from the beach appears to be major barrier to sediment transport.

2.3 SEDIMENT SUPPLY

Sources of sand to the southern Monterey Bay littoral cell are from discharge of the Salinas River, erosion of the beaches and coastal dunes, and possibly transport of sand from offshore.

2.3.1 Salinas River

The quantity of sand that is contributed to the littoral cell by the Salinas River (inset) is a significant uncertainty in the sediment budget of southern Monterey Bay. The Salinas River has the third largest watershed in California (Willis and Griggs, 2003) and processes are characterized by large supply of fine sediments (McGrath, 1987). The sediments are generated from the natural

dryness of the eastern portion of the watershed, from the expansion of agriculture, and from modification of the stream channel. Farnsworth and Milliman (2003) showed that sediment delivery to Monterey Bay from the Salinas River is episodic. During many years, the mouth of the Salinas River is blocked by a sand bar, which changes morphology with seasonal changes in wave climate and rainfall. During periods of low river discharge the bar grows through alongshore sediment transport and interrupts sediment supply from the Salinas River. Breaching of the bar may occur during periodic flood events in winter. Breaching also takes place annually by removal of part of the bar by the Monterey County Water Resources Agency (MCWRA) to prevent flood damage to the surrounding areas. Farnsworth and Milliman (2003) suggested that during major flood events, when the sand bar is breached, sediment concentrations are extremely high (Figure 17).



Figure 17. Salinas River during a Flood and Bar Breach



Source: Unknown

The majority of sediment delivered to the shoreline during flood events is very fine sand and mud that bypass the inner shelf as a plume (Figure 17). The Salinas River discharges on average nearly two million tons of fine sediment annually. After the sediment is introduced into coastal waters, it undergoes intervals of deposition, resuspension, and transport until it is ultimately deposited where it is no longer disturbed (Wright and Nittrouer, 1995). A distinct mid-shelf fine-sediment region is present in central Monterey Bay. This Salinas River mud lobe is a convex bulge in water

depths of 30 to 300 feet covering an area of 28 square miles (Figure 3 (Chin et al., 1988)). Due to the fine particle size of this sediment, it is not a source for beach nourishment.

Willis and Griggs (2003) studied river sediment discharge along the entire California coast, but focused on the Salinas River as a specific example, providing detailed information on this system. In their analysis, they determined suspended sediment concentrations by applying rating curves produced by an empirical power formula using daily measured suspended sediment concentrations and stream flow at Spreckels (11 miles upstream from the river mouth) for water years 1967-1979 and 1986. They then applied the rating curves to the entire time series of measured discharge including the fraction of suspended load for sand particle sizes. However, the bedload was not measured and was assumed to be 20% of the total annual suspended flux, and sand size or coarser. The average annual sand and gravel flux at Speckels was calculated at 490,000 yd³/yr. In this Coastal RSM Plan, this sediment discharge is judged an overestimate for several reasons:

- sand on the beaches of southern Monterey Bay contains little sand finer than 0.25 mm, which is the particle size of the majority of suspended sediments in the Salinas River
- the river is depositional between the measurement location at Spreckels and Monterey Bay
- the assumption that the bedload is equivalent to 20% of the suspended sediment is considered to be an overestimate.

McGrath (1987) argued that the Salinas River no longer contributes substantial beach-size sand to the littoral cell because the river gradient has greatly decreased with rise in sea level, reducing the flow rate. In addition, the dissipation of flood discharge in the channel (for example, during the February 1969 flood, which peaked at 117,000 cfs at Soledad, the flow was only 83,000 cfs at Spreckles further downstream) and the limited capacity of the active river channel provide evidence that the lower river is depositional. The river overflows at a relatively low flood stage (approximately 20,000 cfs) spilling the flow onto the adjacent wide floodplain where the sediment load is deposited and stored. Hence, the Salinas River deposits much of its beach-building sand before it can be carried to the southern Monterey Bay coast.

Further evidence that the Salinas River is depositional is provided by sediment studies. Combellick and Osborne (1977) found that the sediment size in the river decreased downstream towards the mouth suggesting that the coarse-sand fraction is deposited before reaching the Bay. They found that the sand in the river mouth is finer-grained and less well sorted than sand on the beaches, and they estimated that the quantity of medium and coarse sand near the mouth available for discharge into the Bay was less than 5%. Clark and Osborne (1982) performed textural and petrographic analyses to discriminate between the more angular river sands and the more rounded dune and beach sands, and found only a small influence of river sand on the beaches of Monterey Bay south of the Salinas River, even after the major flood of 1978. They concluded that the Salinas River is a minor local sand source to the beaches south of the river, even during periods

of abnormal flooding. Sand contribution to the beaches to the south was limited to within 1.6 miles of the Salinas River mouth.

McGrath (1987) quantified the hydraulic behavior of the Salinas River, and then obtained relationships between stream flow and sediment discharge. He calculated rating curves based on the suspended sediment data for discharge flows greater than 1,000 cfs (similar to Willis and Griggs, 2003), but only included beach-size sand (>0.25 mm) in his rating curves. Rather than assuming bedload to be a percentage of the suspended load, he calculated the bedload transport using a variety of formulations. McGrath (1987) estimated that approximately 50,000 yd³/year of the Salinas River sediment load has large enough particle size for the high-energy beaches of southern Monterey Bay. Since 28% of the suspended sediments are in the range 0.125 to 0.25 mm, the discharge would only increase to 64,000 yd³/year if these particle sizes are included. The study was completed in 1987, so the estimates do not include the water years post-1986, during a time of positive PDO and increased rainfall (Section 1.5.2), which could increase the annual average sediment yield.

For the purposes of the budget used in this Coastal RSM Plan, a beach-size sand supply from the Salinas River to Monterey Bay of 65,000 yd³/year is used (McGrath, 1987). Given the distance over which the Salinas River sands have been found south of the river mouth (1.6 miles) (Clark and Osborne, 1982) and given that sediment transport is generally to the north during the winter when the river is flowing into the Bay (Section 2.1), the budgetary contribution to the south is judged to be relatively small. For this sediment budget a value of 10,000 yd³/year is estimated, leaving approximately 55,000 yd³/year of sand transported north.

2.3.2 Potential Barriers to River Sediment Transport

Reductions in river sediment discharge to the ocean by coastal dams in California were examined by Slagel and Griggs (2006, 2008). Damming of these rivers impounded sediment behind the dams and lowered the sediment carrying capacity by reducing flow in the rivers, particularly during times of floods.

Three dams along the main tributaries of the Salinas River have changed the timing and amount



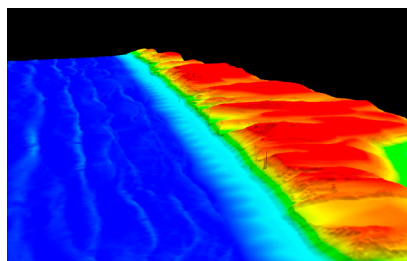
of flow. The Salinas Dam (Lake Santa Margarita) was constructed in 1941 a few miles southeast of the town of Santa Margarita in San Luis Obispo County, close to the origin of the Salinas River. Nacimiento Dam (inset) in northern San Luis Obispo County is a 210-foot high earth-fill dam, built by the MCWRA on the Nacimiento River, which completed construction in 1961. Lake San Antonio in southern Monterey

County is formed by an earth-fill dam on the San Antonio River. The dam is 202 feet high and was constructed in 1965. The lake and dam are owned by the MCWRA and are about 80 miles from the southern Monterey Bay shoreline. Slagel and Griggs (2006, 2008) calculated that at

Spreckles (11 miles upstream of the Salinas River mouth) the impact of these dams has been to reduce the total annual sediment flux by 31%.

2.3.3 Long-Term Dune Erosion

The largest input to the sand budget of the southern Monterey Bay littoral cell is from erosion of the coastal bluffs south of the Salinas River (inset), which are composed of relict dune sand with low cohesion. Erosion occurs during large winter wave events when wave setup and runup coincide with high tides to overtop the beach and undercut the base of the bluff causing the overlying sand to slump



(http://hydro.csumb.edu/dunes_park/retreat/event_080104/index.html). This process causes aprons or cones of loose sand to accumulate at the top of the beach (Figure 4), from where the sediment is redistributed by wind or water, and replenished by further sloughing from the bluff face. The ability of the dunes to recover from erosion is limited. While onshore winds can rebuild active dunes, such as those to the north of the Salinas River (Section 2.5.1), the heights and volumes of the relict dunes south of the Salinas River cannot be re-established at current sea levels. These relict dunes therefore form eroding sandy bluffs behind the beaches.

Long-term erosion of the dunes has been previously measured using a variety of techniques and references. The results of two recent studies undertaken by Thornton et al. (2006) and Hapke et al. (2006) are presented here. Dune erosion was measured by Thornton et al. (2006) using a combination of stereo-photogrammetry (1940 to 1984), LIDAR (1997, 1998) and GPS-walking surveys (2003). Since there was little to no dune erosion during the 2003-04 and 2004-05 winters, the date of the GPS survey was ascribed to 2005. The year 1984 approximately divides the 1940-2005 period into an earlier time when intense sand mining from the surf/swash zone was operational and a later time when it had ceased, except for the ongoing beach-sand mining operation at Marina (Sections 1.4.4 and 2.5.4). The comparative results are presented in Table 3. The dune erosion rates between 1940 and 1984 (1.0 to 6.4 ft/year) equate to an average sand volume of approximately 350,000 yd³/year to the littoral cell (Thornton et al., 2006). Between 1985 and 2005 (0.4 to 4.7 ft/year) this volume decreased to 200,000 yd³/year.

The particle size characteristics of the dune sand provide information on what volume of sediment eroded from the dunes is large enough to remain on the beaches and shoreface. Using the methods of Dean (1974) shows that approximately 25% of the dune sand has particle sizes equivalent to those that reside on the beach. However, according to Dingler et al. (1985), the eroded dune sand contains on average 76% medium-to-coarse sand (>0.25mm) that can remain within the beach and shoreface system. Using an average value of 50%, the retention of sand on the beach and shoreface is approximately 100,000 yd³/year. Approximately 50% of the eroded dune sand (~100,000 yd³/year) is lost offshore.

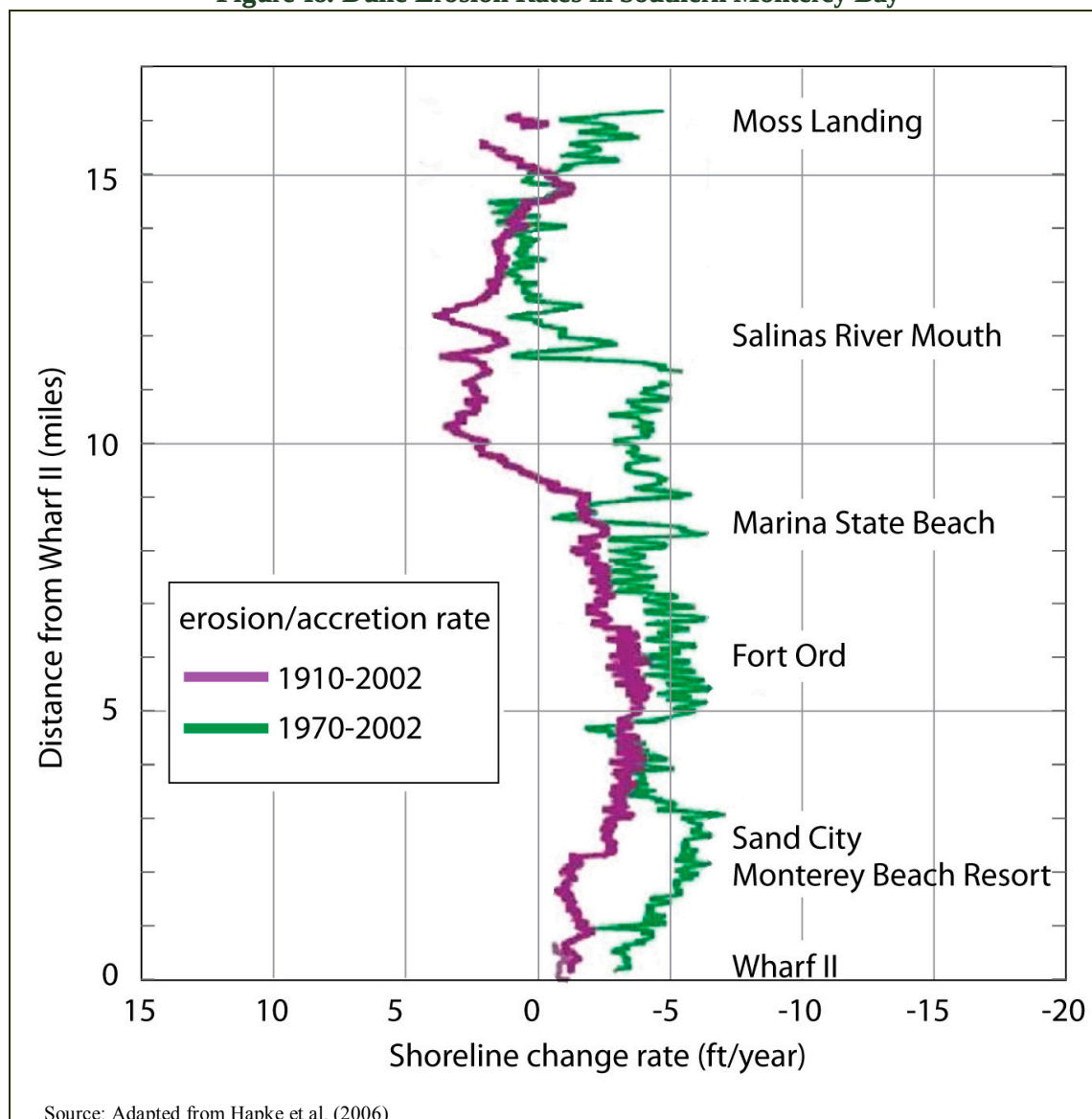
Table 3. Estimated Historic Long-term Average Erosion Rates (ft/year)

Location	Thornton et al. (2006)		Hapke et al. (2006)	
	1940-1984	1985-2005	1910-2002	1970-2002
Moss Landing			+1.2	-1.7
Salinas River			+3.7	0
Marina State Beach	-1.0	-4.7	-1.4 to -2.0	-3.1 to -5.2
Stilwell Hall (Fort Ord)	-5.2 to -6.2		-2.5 to -3.7	-3.7 to -6.6
Sand City	-3.9 to -6.4	-2.7	-1.4	-3.7 to -6.2
Monterey Beach Resort	-2.4	-0.9	-1.4	-3.0
Del Monte Beach	-2.0	-0.4		

Hapke et al. (2006) estimated dune erosion by measuring the movement of the mean high water (MHW) line along the entire California coastline. Average erosion rates were calculated between 1910 and 2002 and between 1970 and 2002. Hapke et al. (2006) calculated an average erosion rate from 1970 to 2002 of 4.0 ft/year for southern Monterey Bay between the Salinas River mouth and Monterey, which was the highest for all of California (and higher than the approximately 3.0 ft/year estimate of Thornton et al., 2006 for 1985 to 2005). Between 1910 and 2002, the shoreline for several miles south of the Salinas River was accretional (Figure 18) whereas from 1970 to 2002 the same stretch of shoreline eroded. This change may be related to the ongoing mining of sand from the beach that began at Marina in 1965 (Section 2.5.4).

A comparison of the 1970-2002 erosion rates using MHW calculated by Hapke et al. (2006) with the dune-top erosion rates calculated by Thornton et al. (2006) during the same time period shows that the results are broadly consistent. Both show that the highest erosion rates are at Fort Ord decreasing to the north and south (Table 3). This pattern is also consistent with the general distribution of wave energy approaching this coast, which is a maximum in the Fort Ord area (Figure 10).

Battalio and Everts (1989) used historic aerial photographs and the ‘wetted bound’ to estimate shoreline erosion rates for the period 1940-1988 that are similar to those of Thornton et al. (2006). The wetted bound is the limit of wet sand often visible in aerial photographs, approximately at the mean high water to mean higher high water elevation associated with beach ground water levels. Optical methods with specialized equipment were used to carefully adjust for photographic distortions.

Figure 18. Dune Erosion Rates in Southern Monterey Bay

2.3.4 Long-term Beach and Shoreface Erosion

Reid (2004) combined the 1930 T-sheet with five aerial photography surveys between 1956 and 2001 to assess 70-year beach width change throughout southern Monterey Bay. He found that while the dune bluff retreated landward, the beach itself maintained a constant width supplied by sand from erosion of the dunes.

Over the long-term the southern Monterey Bay shoreline has migrated landward through space as the dunes erode but the beaches maintained their width, except in locations of coastal armoring such as Monterey Beach Resort and Ocean Harbor House condominiums.

Although the beaches have maintained their width over the long term, there is still a volume loss of sand as the beaches translate landward. Sand is lost from the beach and shoreface, between the toe of the dune and the depth on the shoreface at which wave energy stops transporting sediment (the so-called depth of closure). This loss of sand was calculated as the volume difference between the initial shore profile and the eroded profile displaced landward by the recession rate over the 1940-1984 and 1985-2005 time periods using the height difference between the dune toe elevation and the depth of closure.

The shore recession rates used are the dune erosion rates reported by Thornton et al. (2006) (Table 3), assuming the dunes and beach retreat at the same rate (Reid, 2004). The elevation of the bluff toe was measured from cross-shore profiles every 75 feet using the 1997-1998 LIDAR surveys (Thornton et al., 2007). As a first approximation, the closure depth was estimated using the formula of Hallermeier (1978), where closure depth is a function of an extreme nearshore wave height (H_e) and period (T_e). The empirical formula is based on an offshore sand particle size of 0.2 mm, likely to be comparable to the fine sands in the nearshore of southern Monterey Bay (Section 2.7). Assuming a Rayleigh distribution for wave heights, the extreme nearshore wave height is approximated as $H_e = 2.03 H_s$, where H_s is the average significant wave height. Average significant wave heights in 30 feet of water (Thornton et al., 2007) are used as input to the formulation. A value of T_e of 15 seconds is used, which corresponds to the design wave period for Monterey Bay (Wyland and Thornton, 1991). Owing to the uncertainty in the closure depth formula of Hallermeier (1978), a range of values are calculated based on a range of significant wave heights (established using recurrence values). The H_s , bluff toe elevations, range of closure depths, recession rates and range of beach/shoreface volume losses for locations along the southern Monterey Bay shoreline are shown in Table 4.

Table 4. Beach and Shoreface Change in Southern Monterey Bay

Distance from Wharf II (miles)	H _s (ft)	Bluff Toe Elevation (ft)	Closure Depth (ft)	Beach Recession (ft/year)		Cumulative Volume (yd ³ /year x 1,000)	
				1940-84	1985-05	1940-84	1985-05
1.2	4.2-5.2	9.8	19-23	-2.2	-0.6	-10 to -13	-2 to -3
2.5	5.9-7.3	14.8	26-32	-3.9	-2.7	-32 to -48	-15 to -22
3.0	7.8-9.7	15.4	33-41	-6.4	-2.6	-61 to -91	-27 to -41
3.7	8.6-10.7	16.4	37-45	-6.3	-2.6	-93 to -139	-40 to -60
4.5	9.8-12.2	16.4	41-50	-3.1	-2.3	-134 to -200	-65 to -98
6.2	10.2-12.7	16.4	43-52	-5.7	-3.3	-188 to -282	-99 to -149
7.4	10.2-12.7	14.8	43-52	-5.2	-4.2	-248 to -374	-141 to -213
8.7	10.4-13.0	13.8	44-53	-1.0	-4.7	-273 to -411	-216 to -289
9.9	10.6-13.2	13.1	45-54	-3.9	-4.7	-313 to -473	-241 to -365
11.2	10.6-13.2	13.1	45-54	0	0	-350 to -529	-254 to -384
12.4	10.2-12.7	13.1	43-52	1.3	1.0	-335 to -505	-241 to -366
13.6	8.8-11.0	13.1	38-46	1.3	1.0	-322 to -486	-232 to -351
14.9	5.9-7.3	13.0	26-32	1.2	1.0	-312 to -471	-225 to -340
15.5	5.1-6.4	13.0	23-28	1.0	0.7	-309 to -466	-222 to -337

The closure depth and shoreface height can be estimated in different ways. A comparison of cross-shore elevation profiles is another method. Overlaying multiple profiles taken at different times at the same place will indicate the depth at which elevation changes are limited (where the multiple profiles ‘pinch-out’ to a narrow range of variability), and hence taken as the effective closure depth. This type of analysis was applied by Battalio and Everts (1989) using data from northern Del Monte Beach (northern Monterey). They found the closure depth to be 30 to 33 feet below mean lower low water (MLLW), and the upper beach to pinch out at 16 to 18 feet above MLLW, indicating a shoreface height of approximately 45 to 50 feet. An average shoreface height of 46 feet was used by Battalio and Everts (1989), which is generally consistent with the values shown in Table 4.

2.3.5 Short-term Dune Erosion and Beach Recovery

Erosion of the southern Monterey Bay shoreline is not a consistent process but occurs episodically. Large amounts of erosion have occurred during El Niño winters, followed by several ‘regular’ years producing less erosion, all of which can be summed to provide an average erosion trend (Figure 18). During the winter months, high-energy waves move sand offshore where it forms nearshore bars, and in the process steepening and narrowing the beach profile. Dingler and Reiss (2002) measured at least yearly changes to five portions of the shoreline in southern Monterey Bay between 1982-83 and 1997-98, using traditional survey methods. They showed that at Fort Ord most of the erosion occurred during the El Niño events of 1982-83 and 1997-98, with the beaches eroding then recovering later. Over the 15-year period, the total dune toe erosion was 70 feet, with 25 feet occurring between February and April 1983, and 30 feet over the 1997-98 El Niño winter, with only 15 feet over the remaining 14 years. They found that the beaches took approximately two years to recover both their width and volume after the severe erosion during the 1982-83 El Niño. Thornton et al. (2006) showed that during the 1997-98 El Niño winter storms the beaches lost 1.0 million yd³ of sediment offshore. The 1997-98 El Niño also caused the most severe dune erosion along southern Monterey Bay where the volume of sand eroded was 2.4 million yd³, a seven-fold increase compared to the average annual volume.



As high-energy wave conditions subside in late spring and early summer, the beaches recover as sand is moved onshore to rebuild the beach berm, which flattens and widens the beach profile. At the end of the summer and early fall when typically calm seas occur, the berm is well developed, reaching its peak width.

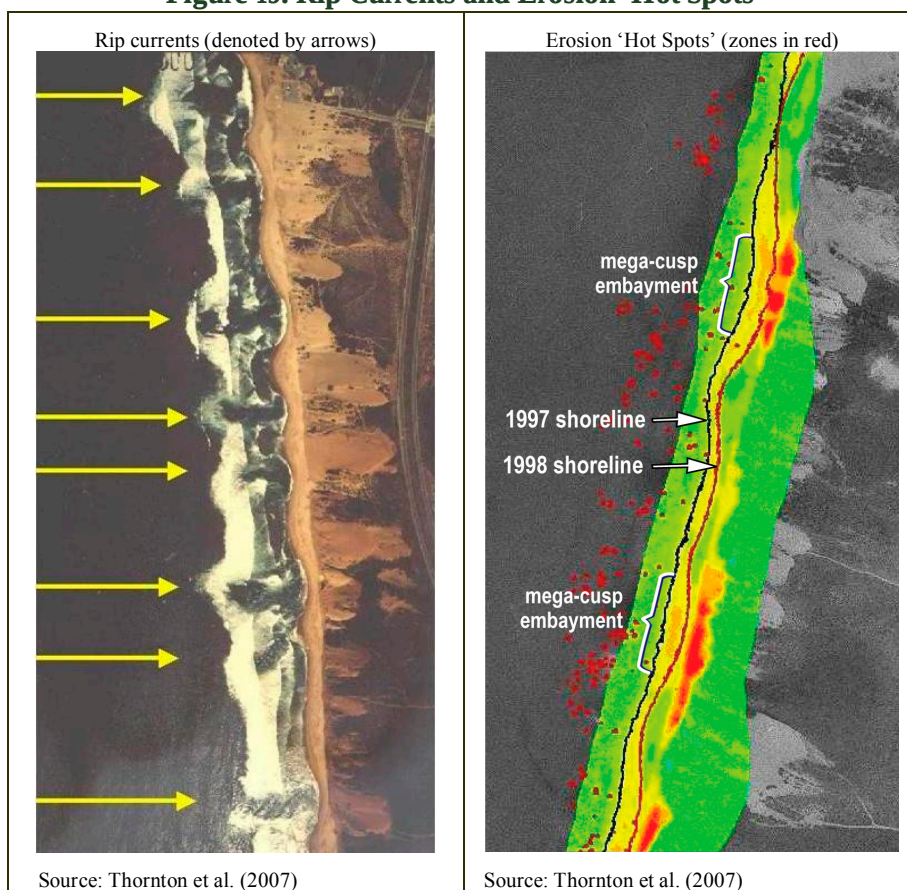
During coincident high water levels and extreme wave conditions, it is possible for sand to be transported offshore into water depths (beyond the shoreface) where summer waves cannot transport it back onshore. Hence, it is possible to have an imbalance in how much sand is transported back to the beaches in summer once winter storms have moved it offshore.

2.3.6 Enhanced Erosion due to Rip Currents

The mean erosion rate in southern Monterey Bay is the highest in California (Hapke et al., 2006). Thornton et al. (2007) hypothesized that erosion in southern Monterey Bay is enhanced by the presence of persistent rip currents and associated large-scale alongshore mega-cusps (order 650 feet alongshore between horns) throughout the year (Figure 19, left panel). Erosion of the dune face is enhanced at the center of the mega-cusp embayment where the beach is narrower and the swash of large waves at coincident high tide can more easily reach the dune toe. ‘Hot spots’ of dune erosion occur at the center of the embayments, as shown by the difference in LIDAR

measurements of dune volumes over the 1997-98 El Niño winter. Figure 19 (right panel) shows volumetric change between October 1997 and April 1998. The rip current channels and mega-cusps migrate moving the hot spots along the shoreline, eroding the dune at an enhanced rate (Orzech et al., 2008). Rip current strength, the spacing between rip channels, and associated alongshore mega-cusp scale are a function of wave height. Therefore, this process of enhanced dune erosion is less effective along the protected shoreline between Monterey and Sand City, and more effective in the Fort Ord and Marina areas.

Figure 19. Rip Currents and Erosion ‘Hot Spots’



2.4 FUTURE EROSION RATES IN RESPONSE TO SEA-LEVEL RISE

One of the most important long-term concerns for RSM in southern Monterey Bay is the physical response of the shoreline to future sea-level rise. Predicting shoreline recession and bluff erosion rates is critical to planning a sediment management strategy, forecasting future problem areas, and assessing biological impacts due to habitat change or destruction. One solution is to assume that historic rates can be projected into the future. However, it is likely that the future recession rate of the shoreline and the erosion rate of the dunes will be affected by higher rates of sea-level

rise than historically (Battalio and Everts, 1989). Higher baseline water levels would result in a greater occurrence of waves impacting the toes of the dune bluffs, increasing their susceptibility to erosion (Ruggiero et al., 2001). However, without proliferation of coastal armoring in southern Monterey Bay, beach widths will be maintained as the dunes erode, continuing to provide recreational, ecologic, and economic opportunities.

One approach for assessing the potential for future shoreline changes is the Coastal Vulnerability Index (CVI) (Thieler and Hammar-Klose, 2000). The CVI uses the physical characteristics of the coastal system (e.g. geology, coastal slope, wave energy, tidal range) to classify the potential effects of sea-level rise. Although this tool allows identification of portions of the shoreline at higher or lower risk relative to other parts of the shoreline, it is not a predictive tool. Southern Monterey Bay between Moss Landing and Wharf II is classified as having a ‘very high’ vulnerability (the highest designation) (Thieler and Hammar-Klose, 2000). This classification indicates that the combination of unstable geomorphology, high rates of historic shoreline change, high wave energy, and moderate tidal range make this area highly susceptible to the adverse effects of sea-level rise.

An approximate quantitative approach for predicting shoreline response to sea-level rise is to multiply the estimated amount of sea-level rise by the ratio of the shoreface width to shoreface height (Everts, 1985; Battalio and Everts, 1989).

$$R = \frac{Y}{X} S$$

where R = recession rate, Y = horizontal dimension of shoreface, and X = vertical dimension of shoreface, and S = sea-level rise.

This procedure is a derivative of the Bruun Rule, neglects possible three-dimensional effects of shoreline position change, and is based on numerous assumptions inherent in the Rule (Cooper and Pilkey, 2004 provide a critique of the Bruun Rule and its derivatives, including sediment budget analysis). It is important to note that the actual recession rate due to sea-level rise could be substantially greater than predicted by this simplified method.

The beach and shoreface between Sand City and the Salinas River slope at approximately 1:40. In general, lower-sloping shorelines should retreat faster than steeper shorelines. Using the recent historic relative sea-level rise rate of about 0.007 ft/year (Section 1.5.4) the above method yields an estimated shoreline erosion rate of approximately 0.3 ft/year. This is small compared to the observed erosion rates, indicating that relative sea-level rise has not been a large factor in shoreline erosion to date. However, sea-level rise is expected to accelerate in response to climate change (Section 1.5.4). Assuming a future relative sea-level rise of 0.5 to 1.5 feet in 50 years and 1.5 to 4.5 feet in 100 years, the corresponding estimates of shoreline recession would be 20 to 60 feet in 50 years and 60 to 180 feet in 100 years. The corresponding shoreline recession rates

would be 0.4 to 1.2 ft/year averaged over 50 years and 0.6 to 1.8 ft/year averaged over 100 years. Given that relative sea-level rise and recession are expected to accelerate but rates and responses are uncertain, it may be more appropriate to distill these ranges to an approximate shoreline recession rate due to sea-level rise for each 50-year period; approximately 0.8 ft/year for the next 50 years and 1.6 ft/year for 50 to 100 years.

This analysis indicates that projected sea-level rise based on climate change forecasts will result in increased shoreline recession in southern Monterey Bay. Over the next 50 years, sea-level rise will increase erosion by about 40 feet (0.8 ft/year), an increase of approximately 20-25% over the historic erosion rates (approximately 3-4 ft/year). The rate increases in the 50 to 100 year time frame, amounting to an additional 80 feet (1.6 ft/year), an increase of 40-50% over historic erosion rates.

2.5 SEDIMENT SINKS

Potential sand sinks in the southern Monterey Bay littoral cell include active dunes, Monterey Submarine Canyon, beach-sand mining (currently only Marina), and offshore transport onto the continental shelf.

2.5.1 Dune and Beach Accretion North of the Salinas River

Hapke et al. (2006) showed that between 1970 and 2002 the shoreline from approximately one mile south of Moss Landing Harbor to the Salinas River slowly accreted (Figure 18). The four miles of beaches have accreted at an average rate of approximately 0.7 ft/year (Figure 18), which equates to a beach-sand gain (sink) of approximately 30,000 yd³/year (Table 4). Active dunes at the Salinas River are about 800 feet wide, then gradually narrow and end against the Flandrian dunes two miles south of the river mouth. The dunes to the north of the river extend to Elkhorn Slough and vary in width from 300 to 600 feet with heights of approximately 20 feet above sea level. Using an average accretion rate of approximately 0.7 ft/year (Figure 18) and a length of four miles equates to a net accretion volume of approximately 10,000 yd³/year of sand.

2.5.2 Dune and Beach Accretion South of the Salinas River

Blow-outs observed in the dunes and sand blowing over the coastal path on to Highway 1, provide evidence of onshore transport of wind-blown sand between the Salinas River and Monterey. Dorman (1968) calculated the transport based on eight years of hourly mean winds measured at Monterey Airport (approximately 1.5 miles inland). He applied the formula of Johnson and Kadib (1964), which estimates onshore transport volume as a function of wind speed and mean sediment particle size on the dune and at mean water level (Table 5). The transport between Monterey and Sand City is the largest because the particle size is smaller along this stretch of shoreline and more easily moved by wind. Dorman (1968) indicated that the calculated values are probably underestimates because the location of the measured onshore winds is

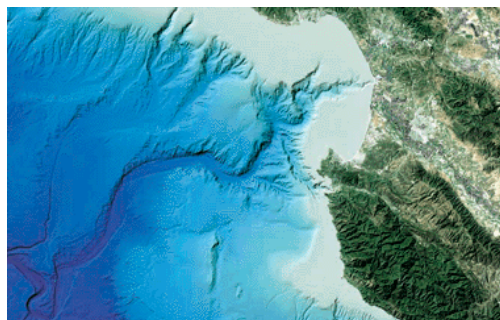
sheltered by Point Piños, reducing the wind speeds compared to those on the open coast north of Sand City.

Table 5. Onshore Sand Transport by Wind South of the Salinas River (Dorman, 1968)

Distance from Wharf II (miles)	Wind Transport (yd ³ /year)
0 – 3.7	14,000
3.7 – 5.7	3,000
5.7 – 7.5	5,000
7.5 – 9.3	6,000

2.5.3 Monterey Submarine Canyon

Monterey Submarine Canyon (inset) marks the boundary between the Santa Cruz littoral cell and the southern Monterey Bay littoral cell (Patsch and Griggs, 2007) (Section 2.1). Given its proximity to the shoreline (Figure 3), the head of Monterey Submarine Canyon is effective at capturing littoral sediments from the north and south that are diverted offshore by the Moss Landing harbor jetties. Smith et al. (2007) examined sequential multibeam sonar images sampled over 29 months and found substantial bedload sediment lost down the Canyon over that short period of time. Patsch and Griggs (2006) estimated that the Canyon captures approximately 300,000 yd³ of sand per year. This Coastal RSM Plan estimates that up to approximately 15,000 yd³/year of sand enters the Canyon from the south, transported alongshore from the discharge of the Salinas River. A potential sediment management alternative could be to capture the sand from both littoral cells before it is lost down the Canyon and beneficially reuse it for beach nourishment (Section 6.5.1).



2.5.4 Historic Sand Mining at Marina and Sand City Using Drag Lines

Sand mining in southern Monterey Bay was not regulated until 1960, when the California State Lands Commission (CSLC) asserted jurisdiction on extractions below MHW, which by law, belongs to the State of California, and began licensing the operations through issuance of leases and charging royalties. The CSLC interest promoted mining, so they imposed a royalty rate with a base minimum mining volume for each company ranging from 26,000 yd³/year to 52,000 yd³/year. In the 1960s, the sand mining companies obtained a court order, which made the volumes of sand mined at specific mines proprietary to each other and the public, ostensibly to

prevent price fixing, and hence, the amount of sand mined was unknown. In 1974, the U.S. Army Corps of Engineers (Corps) also required leases under the Rivers and Harbors Act of 1899, which regulates activities below MHW. They, however, attached maximum mining volumes to their leases ranging from 100,000 yd³/year to 150,000 yd³/year to protect the environment. After the first ten-year lease expired, the Corps concluded that the beach-sand mining caused coastal erosion, and the permits were not renewed.

The actual quantities of sand mined from the beach as reported to the CSLC have now been obtained for this Coastal RSM Plan through a Freedom of Information Act request. A decadal breakdown of the volumes extracted from the beach at each mine is provided in Table 6 based on a yearly breakdown presented in Appendix A. The mines were located either in Sand City or Marina (Figure 9). The amounts reported were audited by the CSLC based on sales receipts and are deemed accurate. Some of the files were missing, which resulted in gaps in the records, which were filled using a ten-year moving average filter (Appendix A).

Table 6. Volume of Sand Mined from Beaches at Sand City and Marina (yd³/year x 1000)

	Sand City				Marina				Total
	MSC ¹	GC ²	PCA ³	Sub-total	MSC ¹	SS ⁴	PCA ⁵	Sub-total	
Distance from Wharf II (miles)	3.0	3.1	3.5		9.1	9.5	9.8		
Years of Operation	1931 to 1990	1950 to 1969	1927 to 1986		1944 to 1986	1957 to 1970	1965 to now		
1940s	37	0	65	102	20	0	0	20	122
1950s	37	22	65	124	33	7	0	40	164
1960s	36	21	61	118	33	8	43	84	202
1970s	34	0	81	115	31	0	98	129	244
1980s	41	0	56	97	21	0	122	143	240
1990s	0	0	0	0	0	0	200	200	200
2000s	0	0	0	0	0	0	200	200	200

¹The Monterey Sand Company (MSC) decreased the reported values by 3% to account for wash loss, and this has been added back into the volumes.

²GC = Granite Construction.

³PCA = Sand City Pacific Concrete and Aggregates was bought by Lone Star Industries

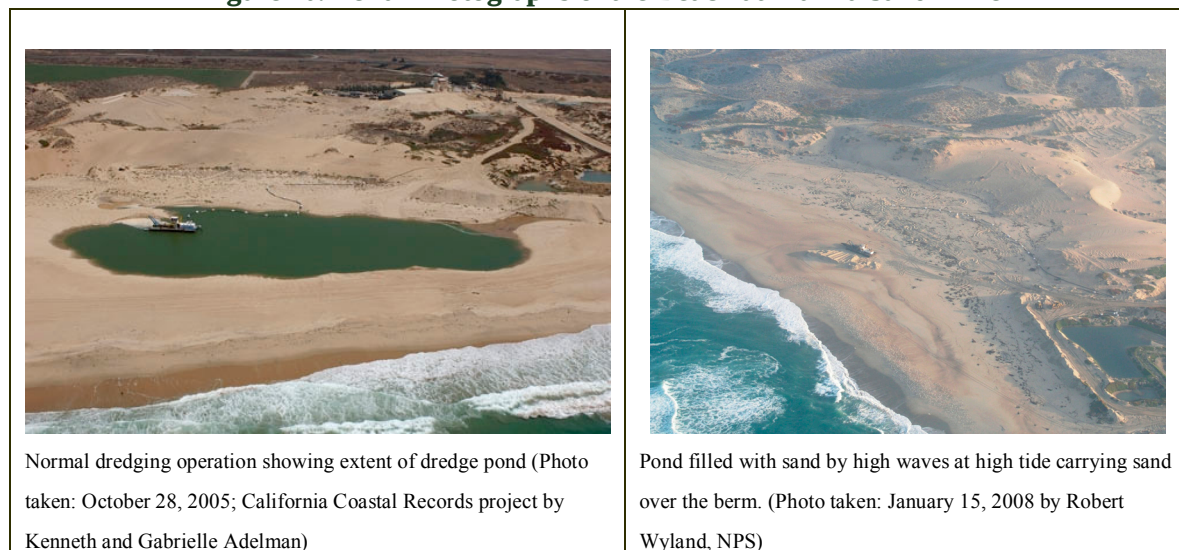
⁴SS = Seaside Sand and Gravel Company was bought by Floyd Bradley in 1970 and then sold to Standard Resources in 1974.

⁵PCA = Marina Pacific Concrete and Aggregates was bought by Lone Star Industries and then by CEMEX in 2005

2.5.5 Ongoing Hydraulic Beach-Sand Mining at Marina

The biggest change in the volume of sand mined from the beach in southern Monterey Bay was the introduction in 1965 of the dredging operation on the back beach at Marina (Table 6). The sand is mined by a floating dredge creating a large pond just landward of the beach berm (Figure 20, left panel). It is then pumped to a dewatering tower, kiln dried, screened and blended at a processing plant on the site. The height of the berm is at a similar elevation to the toe of the adjoining dunes. This beach-sand mining operation efficiently takes advantage of the cross-shore sorting of sediment where coarse sand is washed over the berm to fill the pond during times of high winter waves and high tide. The pond is continuously being filled with sand over time and this sand is continuously dredged. During the storms of January 2008, the pond was completely filled with sediment (Figure 20, right panel). After these storms the wrack line was landward of the pond perimeter indicating the maximum inland extent of the swash carrying sediments onto the beach. This is evidence that the sand being mined from the dredge pond is derived directly from the nearshore and constitutes a loss of sand from the littoral system.

Figure 20. Aerial Photographs of the Beach at Marina Sand Mine



Between 1965 and 1970, Pacific Concrete and Aggregates (PCA) mined both the pond and the backing dunes, and when reporting the volumes extracted, differentiated the coarse fraction from the pond ('ocean sand') from the dune sand. The total volumes reported ranged from 68,000 yd³/year to 98,000 yd³/year. After 1970, the volumes of sand mined from the beach at Marina were not reported (Appendix A). The last reported value of 98,000 yd³/year to CSLC was in 1970 and is conservatively used as the estimate for the amount dredged until the mid 1980s when the operation started using an improved larger dredge. It is assumed that the amount of sand extracted

from the beach increased using the larger dredge, and that the mine further increased their extraction after the other mines closed in 1990, to meet consumer demand. The total amount of sand sold annually over the last decade from the ongoing operation at Marina has been between 225,000 and 280,000 tons, or approximately 167,000-207,000 yd³/year, based on an approximate density of 1.35 tons per cubic yard, as reported by CEMEX (the owners since March 2005). In this Coastal RSM Plan budget an extraction rate of 200,000 yd³/year is used for the ongoing mining operation.



2.5.6 Offshore

It is likely that beach-size sand in southern Monterey Bay is transported both onshore and offshore. Swell wave action tends to move sand onshore because the magnitudes of wave-induced onshore velocities and accelerations generally exceed those in the offshore direction. Evidence of the onshore transport of sand during the summer is based on reports by sand miners that the sand in the summer was of smaller particle size at all sites along the shoreline (to the extent that they often ceased mining operations during the summer). Based on the textural characteristics of sand distributions in southern Monterey Bay, Dorman (1968) concluded that sand moved offshore at the convergence of alongshore sediment transport near Sand City (Figure 15). Assuming this zone of sand is three feet thick, the volume of medium sand offshore is approximately seven million yd³, and potentially a large source for beach nourishment sand.

2.6 SAND BUDGET

2.6.1 Sand Inputs and Outputs

In order to understand the sedimentary processes operating in southern Monterey Bay, the sediment budget is broken down into spatial and temporal components. Table 7 presents a sand budget for the portion of the littoral cell between Moss Landing and the Salinas River mouth (north sub-cell). The sand is input by the Salinas River and transported north alongshore; an assumption is made that no sand is transported to the south from Moss Landing or onshore. The outputs are sand blown by wind onto the low accreting dunes backing the beach (Section 2.5.1), and sand lost down Monterey Submarine Canyon (or to the offshore). This length of shoreline has accreted over the last two decades (Table 4) resulting in an increase in the beach and shoreface volume (change in storage, Table 7).

Table 7. Sand Budget for the Littoral Cell between Moss Landing and the Salinas River

Budget Component		Volume (yd ³ /year x 1,000)
(1) Inputs	Salinas River (net alongshore transport from the south)	55
	Dune erosion	0
	Net alongshore transport from the north	0
	Net onshore transport	20
(2) Outputs	Dune accretion by wind	10
	Canyon (and offshore)	15
(3) Change in Storage	Beach and shoreface gain	30
Residual = (1)-(2)-(3)		0

Table 8 presents a sand budget for the portion of the littoral cell between Wharf II and the Salinas River mouth. Budgets are estimated for the 1940-1984 period when drag line beach-sand mining was operational and 1985-2005, during which time drag line mining ceased, but hydraulic mining at Marina increased. The location of sand losses due to beach-mining shifted to the north from Sand City to Marina during the 1985 to 2005 time period. The beach and shoreface loss was calculated using the erosion rate and closure depth information, and indicates that erosion was much greater during 1940-1984 than during 1985-2005 (Table 4). The sand budget indicates that there is a large loss (deficit) of sand from the littoral system to offshore and that the loss (deficit) has increased over the two time periods.

Table 8. Sand Budget for the Littoral Cell between the Salinas River Mouth and Wharf II

Budget Component		Volume (yd ³ /year x 1,000)	
		1940-1984	1985-2005
(1) Inputs	Salinas River (net alongshore transport from the north)	10	10
	Dune erosion	350	200
	Net alongshore transport from the south	0	0
	Net onshore transport	?0	?0
(2) Outputs	Beach-sand mining (Sand City and Marina)	190	200
	Dune accretion by wind	28	28
	Offshore	208-358	268-398
(3) Change in Storage	Beach and shoreface loss	-350 to -500	-250 to -380
Residual = (1)-(2)-(3)		0	0

The impact of mining sand from the beach, either sand mined from the surf zone by drag line or from a pond dredged just over the berm, causes dune erosion to progress at a higher rate owing to what is referred to as an overfill ratio. The overfill ratio refers to the fact that the primary replacement for the sand mined from the beach is from sand eroded from the dunes. The dune sand has a smaller mean particle size than the mined beach sand; hence more dune sand is required to replace the mined beach sand. The larger and heavier sand particles remain in the energetic surf zone while the smaller sands are carried offshore where they can reside in less energetic wave conditions. The overfill ratio has been estimated to range from 25 to 75% based on the particle size distributions of the dune and beach sands (Section 2.3.3). As a result, mining sand from the beach has a greater impact than simply the amount of sand that is mined. Applying a mean overfill ratio of 0.5 would attribute the actual loss of sand due to mining the beach as effectively twice the volume mined.

The sand budget for the portion of the littoral cell covering the shoreline of the Cities of Sand City, Seaside, and Monterey (approximately the south sub-cell) is complicated because the historical sand mines were located adjacent to the boundary between the south and central sub-cells, at 3.0, 3.1 and 3.5 miles from Wharf II (Figures 9 and 15). This boundary coincides with the location of the medium sand stretching into the offshore and a null zone where the net alongshore transports from the north and south converge (Figure 15). The null zone appears to occur

somewhere between 2.5 and 3.0 miles from Wharf II, which is close to the location of historic sand mining in Sand City.

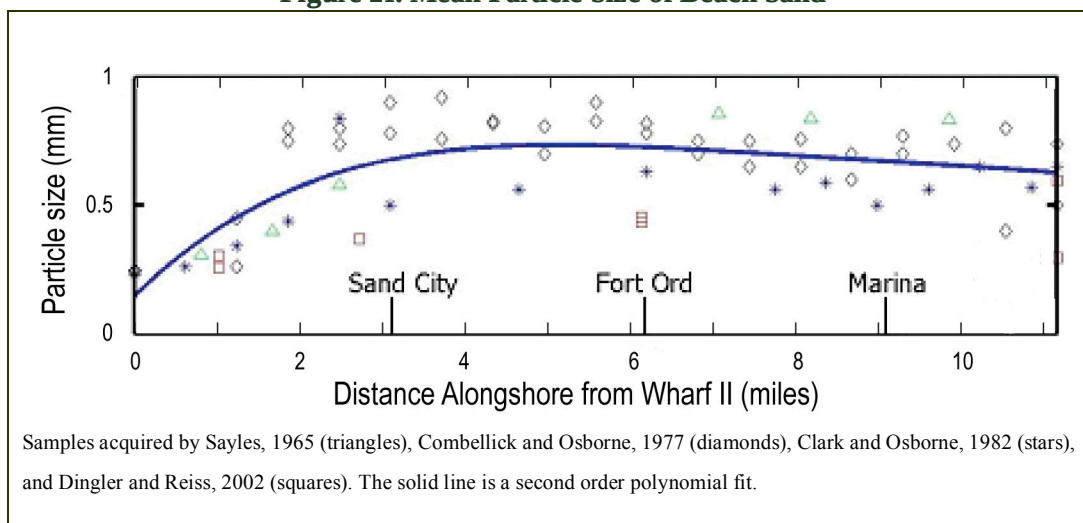
It is important to note that sand transport crosses the null zone (Section 2.1) and that the gross transport in this area is much higher than the net transport that is used to define the null zone. Also, the historic and ongoing mining of beach sand has likely increased the northward transport of sand out of the south sub-cell. The sand supply from the eroding dunes, mostly at Fort Ord, has not mitigated this deficit, resulting in shoreline erosion.

2.7 BEACH AND SHOREFACE SEDIMENT PARTICLE SIZE

The beaches and shoreface of southern Monterey Bay are potential receiver sites for beach nourishment and it is therefore important to characterize their particle size distribution. Discussion of the particle sizes of potential sediment sources, including offshore deposits, is provided in Section 6.

2.7.1 Beach Sand

Beach-sand particle size distributions have been measured in several previous studies (Sayles, 1966; Combellick and Osborne, 1977; Clark and Osborne, 1982; Dingler and Reiss, 2002). The mean particle sizes of the sand by distance from Wharf II are summarized in Figure 21, and Tables 9 and 10. This sand is already part of the active beach and is not a source of sand for nourishment. Clark and Osborne (1982) compared particle-size statistics from a year of low river discharge (February and June 1975) obtained by Combellick and Osborne (1977) to a year of high discharge (June 1978); samples were recovered approximately three feet above MHW. Dingler and Reiss (2002) sampled at mid-tide level during September 1988 and April 1989, and qualitatively related the mean particle size to beach slope and wave climate. Sayles (1966) also collected samples at mid-tide level.

Figure 21. Mean Particle Size of Beach Sand**Table 9. Mean Particle Size of Beach Sand in Sand City, Seaside, and Monterey**

Distance from Wharf II (miles)	Mean Particle Size (mm)	Source
0.0	0.23	Clark and Osborne (1982)
0.0	0.245 ¹ & 0.24 ²	Combellick and Osborne (1977)
0.6	0.26	Clark and Osborne (1982)
0.8	0.307	Sayles (1966)
1.0	0.255 ³ & 0.305 ⁴	Dingler and Reiss (2002)
1.2	0.34	Clark and Osborne (1982)
1.2	0.45 ¹ & 0.26 ²	Combellick and Osborne (1977)
1.7	0.4	Sayles (1966)
1.9	0.44	Clark and Osborne (1982)
1.9	0.8 ¹ & 0.75 ²	Combellick and Osborne (1977)
2.5	0.58	Sayles (1966)
2.5	0.8 ¹ & 0.74 ²	Combellick and Osborne (1977)
2.5	0.84	Clark and Osborne (1982)
2.7	0.37 ³ & 0.37 ⁴	Dingler and Reiss (2002)

¹Sample taken February 1975. ²Sample taken June 1975. ³Sample taken September 1988. ⁴Sample taken April 1989.

Table 10. Mean Particle Size of Beach Sand North of Sand City

Distance from Wharf II (miles)	Mean Particle Size (mm)	Source
3.1	0.5	Clark and Osborne (1982)
3.1	0.78 ¹ & 0.9 ²	Combellick and Osborne (1977)
3.7	0.76 ¹ & 0.92 ²	Combellick and Osborne (1977)
4.3	0.82 ¹ & 0.83 ²	Combellick and Osborne (1977)
4.7	0.56	Clark and Osborne (1982)
5.0	0.81 ¹ & 0.7 ²	Combellick and Osborne (1977)
5.6	0.83 ¹ & 0.9 ²	Combellick and Osborne (1977)
6.2	0.455 ³ & 0.435 ⁴	Dingler and Reiss (2002)
6.2	0.63	Clark and Osborne (1982)
6.2	0.78 ¹ & 0.82 ²	Combellick and Osborne (1977)
6.8	0.7 ¹ & 0.75 ²	Combellick and Osborne (1977)
7.1	0.86	Sayles (1966)
7.5	0.75 ¹ & 0.65 ²	Combellick and Osborne (1977)
7.8	0.56	Clark and Osborne (1982)
8.1	0.76 ¹ & 0.65 ²	Combellick and Osborne (1977)
8.2	0.84	Sayles (1966)
8.4	0.59	Clark and Osborne (1982)
8.7	0.6 ¹ & 0.7 ²	Combellick and Osborne (1977)
9.0	0.5	Clark and Osborne (1982)
9.3	0.7 ¹ & 0.77 ²	Combellick and Osborne (1977)
9.6	0.56	Clark and Osborne (1982)
9.9	0.835	Sayles (1966)
9.9	0.74 ¹ & 0.74 ²	Combellick and Osborne (1977)
10.3	0.65	Clark and Osborne (1982)
10.6	0.4 ¹ & 0.8 ²	Combellick and Osborne (1977)
10.9	0.57	Clark and Osborne (1982)
11.2	0.5 ¹ & 0.74 ²	Combellick and Osborne (1977)
11.2	0.595 ³ & 0.295 ⁴	Dingler and Reiss (2002)
11.2	0.65	Clark and Osborne (1982)

¹Sample taken February 1975. ²Sample taken June 1975. ³Sample taken September 1988. ⁴Sample taken April 1989.

The smallest mean particle size of approximately 0.2 mm (fine sand) occurs near Monterey Harbor (Figure 21 and Table 9). The mean particle size then increases northwards to a maximum of approximately 0.7 mm (coarse sand) at Fort Ord, followed by a general decrease to 0.6 mm (coarse sand) further north towards the Salinas River mouth (Table 10). The mean particle size range south of Sand City is between 0.2 (fine) and 0.8 mm (coarse), but this range increases significantly approximately two miles north of Wharf II. South of this two-mile marker the range is approximately 0.2-0.4 mm (fine-medium), whereas from mile two to mile three the range is larger at 0.4-0.8 mm (medium-coarse). North of Sand City the particle size range is between 0.5 and 0.9 mm (coarse). The increasing particle size of the beaches from Wharf II to Marina is positively correlated with wave height (Thornton et al., 2007).

Alongshore variability in particle size between studies may be related to sampling at different times of year. Seasonal variations in beach particle size occur with coarser beach sands present during the more energetic winter months, and finer sands during summer months, when smaller particles are moved onshore by milder swell waves. Some of the variability may also be related to different sampling procedures. For example, the mean particle sizes reported by Dingler and Reiss (2002) are smaller than those of the other studies as they were acquired higher on the beach face.

2.7.2 Shoreface Sand

The shoreface is the part of the littoral cell between MLLW and the water depth where sediment is not disturbed by wave action during fair-weather conditions. The sand on the shoreface is likely to be constantly moving, either alongshore, onshore or offshore depending on seasonal wave conditions. Along most of the shoreline to the north of Sand City the sediment particle sizes of the shoreface are finer than on the beach. However, a large region of medium sand occurs on the outer shoreface and further offshore at Sand City (Figure 15), which is comparable in particle size to the beach sands to the south (Section 6.5.2). The sand offshore of the shoreface could be a potential source for nourishment for the southern Monterey Bay beaches at Sand City and Monterey.

3. CRITICAL AREAS OF EROSION

This section provides an analysis of critical areas of erosion within the southern Monterey Bay littoral cell. In order to delineate these areas, two criteria are adopted that are used to prioritize erosion responses over a planning horizon of 50 years; risk of erosion and consequences of erosion.

3.1 RISK AND CONSEQUENCES OF EROSION

The risk of erosion is based on the risk analysis developed by PWA and Griggs (2004). This method establishes our first level of risk assessment over a 50 year period:

- what facility is at risk?
- what is the probability that it will be impacted by erosion?

PWA and Griggs (2004) defined three risk categories to Monterey Regional Water Pollution Control Agency (MRWPCA) facilities between Marina and Wharf II. These risk categories were determined by assuming that current long-term historic erosion rates would continue over the next 50 years. For this Coastal RSM Plan assessment of critical areas of erosion, the historic erosion rate results of Thornton et al. (2006) are used (Table 3) with an increment of approximately 20% added to the erosion rate for potential increases due to future sea-level rise (Section 2.4). The risk categories are:

- **Low risk** - facilities with a low probability of being impacted by erosion over the next 50 years.
- **Moderate risk** - facilities not likely to be affected by chronic erosion over the next 50 years, but potentially susceptible to short-term storm event erosion within the planning horizon.
- **High risk** - facilities that are located seaward of the shoreline position anticipated in 50 years or presently vulnerable to short-term event-based erosion. A high risk designation also applies to facilities with shore protection (presently or approved), where erosion is impacting public safety and access, and reducing the shoreline recreational value.

Future erosion rates could be lower if beach-sand mining ceases (Section 2.5.5). In this case, moderate and high risk facilities would have a larger buffer zone of protection (Section 5.2.3), and management action could be delayed beyond the time lines recommended in this Coastal RSM Plan. Conversely, erosion rates may increase if future sea-level rise accelerates over the predicted estimates (Section 2.4), and management may need to be more immediate.

All the facilities identified as at high or moderate risk of erosion were then assessed as to their future value. This assessment is based on the SMBCEW (2006c) evaluation of the economic

(potential loss of facility), environmental (potential loss of habitat), and safety and human health (potential loss of life) consequences of loss of the facility. The facilities are designated as high consequence, moderate consequence, or low consequence.

3.2 SITE SHORT-LIST

The locations of high to moderate risk, and high consequence critical areas of erosion are shown in Figure 22, summarized in Table 11, and described in detail in Section 3.3. They are also available as GIS data files in CSMWs GIS database.

Figure 22. Location of Critical Areas of Erosion

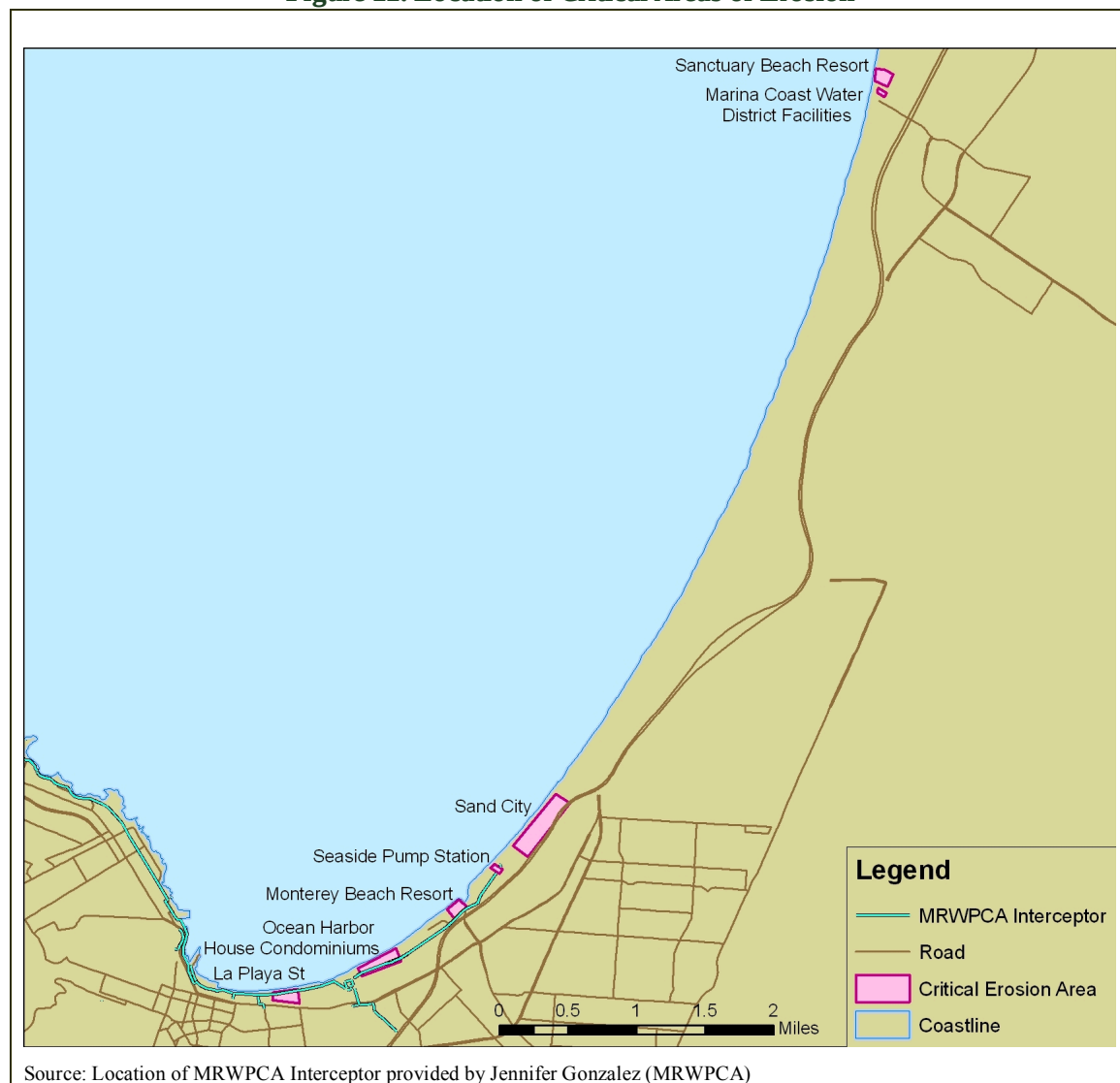


Table 11. Critical Areas of Erosion

Location	Summary of Facility	Erosion Rate (ft/year)	Risk of Erosion	Consequences of Erosion
Sanctuary Beach Resort near Reservation Road	Vacation complex approximately 120 feet from the bluff top	~5.5	High (compromised in approximately 20 years)	High economic
Marina Coast Water District buildings near Reservation Road	Office buildings approximately 70-90 feet from the bluff top	~5.5	High (compromised in approximately 15 years)	High economic (if buildings are converted to other uses)
Sand City and Tioga Avenue west of Highway 1	Bluff top road, storage facility, Highway 1, and proposed hotel developments, and desalination wells	~3.5	High (seaward end of Tioga Avenue eroding)	High environmental safety economic
Seaside Pump Station at Bay Avenue	Raw wastewater pump station approximately 100 feet from the bluff top	~3.0	High (compromised in approximately 30 years)	High economic environmental human health
Monterey Interceptor between Seaside Pump Station and Wharf II	Raw wastewater pipeline approximately 115 to 175 feet from the bluff top or buried mid-beach	~1.0-3.0	High to moderate (some dune portions compromised in approximately 40 years; beach sections exposed in winter)	High economic environmental human health
Monterey Beach Resort, Highway 1 and Resort Access Road	Hotel on Del Monte Beach, Highway 1, and hotel access road	~1.5	High (erosion compromising fronting seawall)	High economic safety
Ocean Harbor House Condominiums/Del Monte Beach Subdivision	Condominium complex and adjacent family homes on the bluff top	~1.0-1.5	High (erosion compromising fronting riprap and homes to the west)	High economic safety
Monterey La Playa Town Homes at La Playa Street	Homes, one of which is 30 feet from the bluff top	~1.0	High to moderate (some homes compromised in approximately 30-50 years)	High economic

3.3 HIGH TO MODERATE RISK AND HIGH CONSEQUENCE AREAS

3.3.1 Sanctuary Beach Resort near Reservation Road

Site

The Sanctuary Beach Resort is located on a 17-acre site between Dunes Road and the coastal bluff fronted by 550 feet of shoreline (Figure 23). The development includes 112 vacation units, a 72-unit hotel, a conference center, retail facilities, a large restaurant, a health club, a recreational building, two tennis courts, a pool, playground and nearly 500 parking spaces. The resort was constructed in the mid 1990s on land formerly owned by the Monterey Sand Company. Because the dunes had been mined for sand for about 45 years (Table 6), the site lies at a lower elevation than adjacent dunes to the north and south. The resort contains buildings and paving on 6.5 acres, landscaping on four acres, and restored dune habitat on 6.5 acres. A boardwalk provides beach access across the southern portion of the dunes. The seaward-facing wall and buildings of the Sanctuary Beach Resort complex are set back approximately 120 feet from the top of the bluff (Figure 23).

Figure 23. Sanctuary Beach Resort and Marina Coast Water District Buildings



Risk

The bluff at this location has eroded approximately 4.5 ft/year over the past 20-30 years (Table 3) (Thornton et al., 2006), and with relative sea-level rise is estimated to erode at approximately 5.5 ft/year over the next 50 years. The erosion rate has increased over the past 20 years compared to pre-1985 (Table 3), which may be the result of increased extraction of beach sand from the mine located only one mile north of the resort (Section 5.2.2). Future dune erosion of 5.5 ft/year would mean that the Sanctuary Beach Resort would be compromised in approximately 20 years time and is therefore designated as a facility at high risk of erosion.

Consequences

The loss of this facility would have high economic consequences to the region as it is a popular tourist destination. The loss of the dunes on this site would also impact endangered western snowy plover, and the black legless lizard (Section 4.2).

The Sanctuary Beach Resort currently raises funds from a restoration fee (currently \$15 per night) to protect endangered species and habitat on its property. The resort has already invested in mitigating threats by installing a 'lizard crossing' beneath the main entry road.

3.3.2 Marina Coast Water District Buildings near Reservation Road

Site

Figure 23 shows the location of a number of Marina Coast Water District (MCWD) buildings. The facilities include infrastructure and offices on a 12-acre site along 400 feet of shoreline. The seaward fence of the site is at the dune bluff edge in places, and buildings and infrastructure are set back 70-90 feet from the fence.

Risk

Using a future erosion rate of 5.5 ft/year the on-site facilities would be under threat of erosion in 10 to 15 years time. Hence, the MCWD site is at high risk of erosion. Indeed, wells on the beach at the end of Reservation Road that used to supply water to a small desalination plant were compromised by coastal erosion and are no longer operational.

Consequences

Although many of the utilities are no longer operational, the future of the office buildings is uncertain. They may be retained and converted into other uses or they may be abandoned and the whole facility removed over the next few years. Given the possibility of their continued future use, the MCWD buildings are, at this stage, designated as high consequence facilities.

3.3.3 Sand City and Tioga Avenue West of Highway 1

Site

From 1927 to around 1990 the parcel of dunes west of Highway 1 and for about 0.8 miles north of Tioga Avenue was the location of sand mining operations (Section 2.5.4), which left the site in an environmentally degraded condition. All the mines were closed by 1990, and currently, remnants of a cement mixing facility are located immediately north of Tioga Avenue in Sand City. The facility is now used for temporary storage of construction equipment (Figure 24). Un-engineered structures are holding the shoreline seaward of its natural position creating a peninsula effect (Figure 7) and in the process they block lateral public access (creating safety hazards), prevent natural shoreline recession, and beach area is lost both for recreation and as a habitat. Also, portions of Highway 1 curve seaward towards the dunes at Sand City. This section of the highway is approximately 400 feet from the dune edge and will ultimately be threatened by coastal erosion.

In order to boost the economy, Sand City has, since the 1970s, sought to provide for commercially viable resort and recreational development on designated portions of its shoreline. In the early 1980s, the certified Sand City Local Coastal Program (LCP) (Section 8.2.1) designated the former sand mine dune location for visitor-serving commercial uses, with a density not to exceed 650 units. In 1996, the City of Sand City entered into a Memorandum of Understanding with Regional and State Park agencies (the Coastal Commission was not party to the agreement) to permit visitor-serving and residential uses at two specific areas north of Tioga Avenue, which are still designated as such in the LCP.

Figure 24. Storage Facility at the end of Tioga Avenue, Sand City



Photo taken: September 19, 2007 (Justin Vandever, PWA)

Risk

The future erosion rate of the unprotected dunes adjacent to the Sand City site is estimated to be approximately 3.5 ft/year. Continued loss of beach in front of the structures at Sand City will lead to further undermining, erosion, and eventually total failure. The existing storage facility and part of Tioga Avenue which provides access to the facility and the beach would be lost. Continued loss of beach would also reduce public access, public safety, and the recreational value of the shoreline. The Tioga Avenue/Sand City complex west of Highway 1 is designated as a facility at high risk of erosion.

Consequences

The current land use has a relatively low economic consequence, but a future threat to Highway 1 (approximately 100 years) could have moderate levels of consequence over the 50 year planning horizon. However, there are several proposed development projects at the Sand City site, located along the west side of Highway 1, north of Tioga Avenue, which would increase the economic consequence of erosion. The Sterling Center is a proposed resort on eight acres immediately north of Tioga Avenue. This proposed development would consist of a 136-unit hotel with restaurant, conference and retail space, and parking garage. North of the Sterling Center is a plot of land owned by the Sand City Redevelopment Agency, on which they are pursuing development of a 39-acre resort complex comprising 495 mixed-use units known as the Monterey Bay Shores Resort.

In addition, the City of Sand City is implementing a water project along its coast to address water supply issues in Sand City. The Sand City desalination plant has a directionally drilled horizontal well for discharge of its byproduct water and intake wells between Bay Street and Tioga Avenue. Water is extracted from the shallow, brackish aquifer along the coast where seawater mixes with freshwater. As of October 2007, the City of Sand City completed and certified the Environmental Impact Report (EIR) on this project and achieved unanimous approval by the California Coastal Commission for its coastal development permit. Construction of the plant facilities should be completed by the spring of 2009.

As part of their condition compliance, the City of Sand City submitted an adaptive management plan to address the potential risk to the desalination components that could be subject to shoreline erosion. The plan includes surveying the bluff and shoreline edge at regular intervals to assess the risk to the wells and pipeline infrastructure, as well as monitoring the salinity level of the feed water. At the onset of a 'risk condition' (i.e. when the bluff recedes to within five feet or the salinity level exceeds an established threshold), measures would be taken to relocate the wells to an approved location in consultation with the Coastal Commission. Coastal armoring is not contemplated as a means of protecting the project components and would only be considered as a last resort.

Overall, the potential future consequence of erosion at Sand City and Tioga Avenue west of Highway 1 is high due to potential future environmental, safety, and economic factors.

3.3.4 Seaside Pump Station at Bay Avenue

Site

Seaside Pump Station (completed in 1983) is located at the junction of Bay Avenue and Vista del Mar Street. Seaside County Sanitation District's former wastewater treatment plant was originally located adjacent to Seaside Pump Station. That plant was decommissioned in 1990 when a Regional Treatment Plant was completed north of Marina, and all of the treatment plant tanks and structures were demolished. The bulk of the site was sold to the California Department of Parks and Recreation (CDPR), although MRWPCA retains ownership of the Seaside Pump Station site. The Seaside Pump Station is located approximately 100 feet from the edge of the low-lying dunes that front the facility (Figure 25).

Figure 25. Seaside Pump Station



Photo taken: October 28, 2005; California Coastal Records project by Kenneth and Gabrielle Adelman

Risk

The historic rate of erosion has been approximately 2.5 ft/year (Thornton et al., 2006), and the future rate is estimated at approximately 3.0 ft/year. The facility could be compromised by erosion in about 30 years. However, the site would be vulnerable to significant wave damage and flooding before that time due to the low elevation of the fronting dunes. The top of the dunes are at approximately 25 ft NAVD compared to the base flood elevation (BFE – maximum elevation of wave runup and overtopping during a 100-year flood event) at this location of 27 ft NAVD (FEMA, 2007) (Section 1.5.3). Seaside Pump Station is considered a high risk of erosion facility (PWA and Griggs, 2004).

Consequences

Seaside Pump Station pumps all of the raw (untreated) wastewater from the cities of Pacific Grove, Monterey, Del Rey Oaks, Seaside, and Sand City through the regional wastewater system to the MRWPCA Regional Treatment Plant. The pumps are a key component of the system and need to remain in full operation indefinitely, so erosion would have significant economic, environmental, and human health impacts. A breach of this facility would cause adverse environmental impacts to the dunes and beaches, and water quality impacts within the MBNMS. Seaside Pump Station is therefore designated as a high consequence facility.

3.3.5 Monterey Interceptor between Seaside Pump Station and Wharf II

The Monterey Interceptor pipeline is divided into three segments, each with a different set of erosion concerns; Seaside Pump Station to Monterey Beach Resort, Monterey Beach Resort to Tide Avenue, and Tide Avenue to Wharf II (Figure 8).

Site

The Monterey Interceptor between Seaside Pump Station and Monterey Beach Resort is buried in the dunes, approximately 100 to 175 feet from the dune bluff. Between Monterey Beach Resort and Tide Avenue the pipeline is not under imminent threat of erosion damage (PWA and Griggs, 2004). However, the pipeline could be vulnerable during a large storm event towards the end of the 50-year planning horizon. From Tide Avenue to Monterey Pump Station, the pipeline is located in the dunes a minimum of 115 feet from the shoreline. Between Monterey Pump Station and Wharf II, the Monterey Interceptor was originally buried beneath the back beach, but due to erosion is now at mid-beach.

Risk

Based on approximate future erosion rates of between 1.5 and 3.0 ft/year, the shoreline between Seaside Pump Station and Monterey Beach Resort would be expected to erode 75-150 feet over the next 50 years, and parts of the pipeline between these two locations may be compromised over the next 40 years. The erosion could uncover the pipe and/or manholes and make them

vulnerable to damage. Hence, the Monterey Interceptor between Seaside Pump Station and Monterey Beach Resort is a facility at high risk of erosion (PWA and Griggs, 2004).

Between Monterey Beach Resort and Monterey Pump Station, the future erosion rate is estimated at approximately 1.5 ft/year, and therefore the pipeline would be at low risk of chronic erosion over the next 50 years. However, given the accuracy of the base map (+/- 16 feet) used to define the position of the pipeline in the dunes here (PWA and Griggs, 2004), it is designated as a moderate risk facility with the potential for storm damage towards the end of the 50-year planning horizon.

Between Monterey Pump Station and Wharf II the shoreline is estimated to erode at an average future rate of approximately 1.0 ft/year and the beach has been observed to scour during storms (Dingler and Reiss, 2002). Manhole covers are now sometimes exposed at low tide during the winter and are vulnerable to damage. At this location, the Monterey Interceptor pipeline is under imminent threat of erosion damage and is at high risk of erosion (PWA and Griggs, 2004).

Consequences

The Monterey Interceptor carries all of the raw (untreated) wastewater from the cities of Pacific Grove and Monterey. This flow is pumped through Monterey and Seaside Pump Stations to the MRWPCA Regional Treatment Plant. The pipeline is a vital facility that needs to remain fully operational indefinitely, and the consequences of erosion would be significant economic, environmental, and human health impacts. A breach to this facility would have adverse environmental impacts to the dunes and beaches, and water quality impacts within the MBNMS. The exposure of the pipeline would be a threat to marine resources if erosion caused a spill to occur. The Monterey Interceptor between Seaside Pump Station and Wharf II is therefore a high consequence facility.

3.3.6 Monterey Beach Resort, Highway 1, and Resort Access Road

Site

The 196-room Monterey Beach Resort hotel was constructed on north Del Monte Beach in 1968 and consists of five four-story buildings, a restaurant, meeting rooms, a pool, and parking structures (Figures 6 and 26). It was originally constructed with surrounding seawalls and a large beach area fronting the hotel. This part of Del Monte Beach was a major attraction of the hotel. Since the hotel was built, shoreline erosion has occurred up coast and down coast, and the hotel has become a headland.

Figure 26. Monterey Beach Resort

Photo taken: August 12, 2003; California Coastal Records project by Kenneth and Gabrielle Adelman

Risk

Future erosion rates at the Resort are estimated to be approximately 1.5 ft/year. When the existing seawall was built in 1968, beach elevations in front of the hotel were over three feet higher than today. Erosion has lowered the beach to the extent that during high tides there is now no beach access in front of the hotel. The existing seawall is not embedded deep enough into the sand to withstand further beach erosion. This structure was partially breached during the severe El Niño winter of 1983 when large waves coincident with very high tides surged through the stairwell opening in the wall, and broke through the joints in the wall causing loss of fill behind. In 2004, much of the south wing wall failed with collapse of the fill behind the wall. Emergency riprap was used to fill this void (Figures 6 and 26). Because of the erosion problem the hotel has received approval from the California Coastal Commission to build a new seawall. The seawall has not yet (September 2008) been constructed. It would comprise a 600-foot long sheet-pile metal seawall with a footprint of 1,000 square feet immediately adjacent to the existing seawall. The permitted project would also involve removal of the existing end walls and replacement with sheet-pile walls.

In addition to the Resort, the access road on Sand Dunes Drive and the access ramp from Highway 1 are within the 50-year erosion zone. The Monterey Beach Resort and the road infrastructure are designated as facilities at high risk of erosion.

Consequences

The hotel continues to be a popular tourist destination and loss of this facility would have high economic consequences. In addition, the presence of the seawall has led to loss of the fronting beach for recreational purposes and at high tide there is a public safety issue as lateral access along the beach is compromised. Monterey Beach Resort, access road, and Highway 1 access ramp are designated as high consequence facilities.

3.3.7 Ocean Harbor House Condominiums/Del Monte Beach Subdivision

Site

Beginning in 1968 the first eight buildings (Ocean House) of an apartment complex were constructed on the dunes at Surf Way in Monterey. An additional six buildings (Harbor House) were constructed further landward in 1974. At the time of construction, the City of Monterey allowed the front buildings to overhang the utility easement running parallel to the shoreline in return for all land seaward of the easement, which means the City owns all land up to the edge of the front buildings. Collectively, the 172 units, now converted to condominiums, are called Ocean Harbor House (Figures 6 and 27).

Figure 27. Ocean Harbor House Condominiums



Since its construction, Ocean Harbor House has had a history of erosion problems. Following the 1982-83 El Niño, erosion of the dunes had approached to within 14 feet of the shallow pilings supporting the complex (the bases of the pilings were ten feet above MLLW). Emergency riprap (600 feet of rock alongshore over 20 feet high) was placed on Del Monte Beach to provide protection to the buildings. It was subsequently removed, following completion of an Environmental Impact Report (EIR) in 1984, because of City of Monterey regulations regarding placement of materials on a public beach. The front pilings were later removed and 50-55 foot deep concrete caissons were then poured along with grade beams to support the front row of condominiums. Despite the deep caissons and grade beams, waves continued to erode the dune face landward beyond the two rows of caissons (Figure 6, right panel). Additional emergency riprap was required to protect the condominium units in 2002 and another EIR was completed to assess a number of longer-term alternatives. While the preferred alternative was to remove the front units, the owners of the condominiums preferred to build a seawall to protect their properties. The application was approved by the City of Monterey Planning Commission, the Monterey City Council, and the Coastal Commission, with substantial mitigation fees involving nourishment of the beach in front of the seawall. The seawall will be within the footprint of the existing building foundations, and will not encroach into the City of Monterey (Del Monte Beach) property.

There is no infrastructure to the east of the condominiums, whereas to the west, Tide Avenue with 15 homes runs parallel to the shoreline on the dune top. Tide Avenue is generally greater than 150 feet from the dune edge, although a short stretch appears to be within 50 feet. Landward of Tide Avenue is Del Monte Beach subdivision comprising several apartment buildings and 128 single-family homes, and associated infrastructure. The neighborhood has some problematic storm drain and sewer infrastructure that are targeted for improvements, including abandonment of a sewer main within the open space dune area and the consolidation of storm drain outfalls.

Risk

A new seawall fronting Ocean Harbor House is being engineered to withstand storm wave-attack and is considered a long-term (50-year planning) solution to erosion of the condominiums. However, it is likely that the new seawall would cause the fronting beach to lower in elevation because the armoring will provide a surface for wave reflection. The seawall will also enhance the peninsula effect at this location, with the dunes to the east and west continuing to erode. Because of the seaward position of Ocean Harbor House and the limited set back of the Tide Avenue community, the condominiums and the Del Monte Beach subdivision are designated as facilities at high risk of erosion.

Consequences

The condominiums and properties along Tide Avenue are privately owned and the consequences of their loss would be economically damaging and hazardous to safety, especially to individual owners. There is currently no lateral access along the beach in front of the condominiums at high

tide and the frequency of access loss will increase in the future. A Coastal Commission condition of seawall approval is provision of lateral access around the back of the most seaward condominiums. Any loss of roads could also have impacts to public safety for the access of emergency services. Ocean Harbor House condominiums, Tide Avenue and Del Monte Beach subdivision are designated as high consequence facilities.

3.3.8 Monterey La Playa Town Homes at La Playa Street

Site

The La Playa town homes are located in the dunes at the end of La Playa Street in Monterey, and were originally constructed as apartments in 1964. The buildings were later converted to condominiums (Figure 28).

Figure 28. Monterey La Playa Town Homes



Photo taken: October 28, 2005; California Coastal Records project by Kenneth and Gabrielle Adelman

Risk

The westernmost condominium sits only 30 feet from the dune edge and is protected by a small pile of riprap, with most of the remaining complex over 50 feet from the shoreline. Long-term future erosion rates are estimated to be approximately 1.0 ft/year, and therefore structures towards the western end of the complex are at high risk of erosion over the next 50 years. In addition, the structures could be vulnerable to wave damage and flooding due to the low elevation of the fronting dunes, compared to the base flood elevation (BFE – maximum elevation of wave runoff and overtopping during a 100-year flood event) at this location of 22-26 ft NAVD (FEMA, 2007) (Section 1.5.3).

Consequences

The town homes are privately owned and the consequences of their loss would be economically damaging to individual owners. Lateral access along the beach in front of the westernmost condominiums would potentially be lost and the beach would be hazardous at high tide. The La Playa town homes are considered to be high consequence facilities.

3.4 LOW RISK AND/OR LOW CONSEQUENCE AREAS

Numerous facilities along the southern Monterey Bay shoreline have either a low risk of erosion or a low consequence factor, and are not discussed further in this Coastal RSM Plan. Details of these facilities and the rationale for non-inclusion in the high risk-high consequence list are provided in Appendix B. It is recommended however that these facilities be considered for set back or relocation opportunistically as maintenance or other funds become available. These facilities are:

- Moss Landing spit community including the research facilities of MBARI
- Monterey Dunes Colony
- Ocean outfall pipeline near Marina sand mine
- Fort Ord storm water and sewer outfalls
- Fort Ord monitoring and injection wells
- Bay Avenue storm water outfall
- Roberts Lake/Laguna Grande outfall
- Sand Dunes Drive
- Monterey Pump Station
- Del Monte Lake outfall
- Lake El Estero Pump Station and outfall
- Catellus East property near Wharf II.

3.5 CRITICAL AREAS OF EROSION SHORT-LIST

In summary, the following lengths of shoreline are short-listed as high-risk and high-consequence critical areas of erosion, for three main reasons:

1. Areas where the facility is located on the dune top and is under threat over the next 50 years through continued erosion of the dune face. These critical erosion areas include:
 - Sanctuary Beach Resort near Reservation Road
 - Marina Coast Water District buildings near Reservation Road
 - Seaside Pump Station at Bay Avenue
 - Monterey Interceptor between Seaside Pump Station and Monterey Beach Resort
 - Del Monte Beach Subdivision
 - Monterey La Playa town homes at La Playa Street

2. Areas where the facility is located beneath the beach and is under threat over the next 50 years from exposure due to beach lowering as the shoreline profile migrates landward. These critical erosion areas include:
 - Monterey Interceptor between Monterey Pump Station and Wharf II.

3. Areas where armoring of the facility exists reducing the local supply of sand to the beach, causing passive erosion (Section 5.4.1) and increasing the potential for undermining the armoring once it is impacted by waves, as well as retreat of the beach on either side. These critical erosion areas include:
 - Sand City and Tioga Avenue west of Highway 1
 - Monterey Beach Resort
 - Ocean Harbor House condominiums.

In addition, the section of the Monterey Interceptor from Monterey Beach Resort to Monterey Pump Station is at moderate risk of erosion, with high consequences.

4. CRITICAL SPECIES AND HABITAT

One of the most important functions of the southern Monterey Bay coastal system is its role as a habitat for a unique flora and fauna. The beaches are habitat for numerous invertebrate species, which provide an important food source for shorebirds, seabirds, marine mammals, and fish. The beaches are also important to the endangered western snowy plover for foraging, nesting, and wintering. Subtidal areas contain kelp, eelgrass, and rocky reef, which provide habitat for marine mammals and fish. Dune areas provide habitat for many native plants and the endangered black legless lizard and Smith's blue butterfly. A key factor that needs to be considered as part of any beach nourishment project is the potential for smothering or temporary loss of marine life or habitats when placing the sand. The distribution and significance of critical species and habitat are discussed in this section and their locations are available as GIS data files in CSMWs GIS database. The impacts of beach nourishment on critical species and habitat are described in Section 5.1.1.

4.1 SENSITIVE HABITAT

Sensitive habitat in southern Monterey Bay includes rocky reef, kelp forest, eelgrass meadow, sandy beaches, sandy subtidal, and coastal dunes.

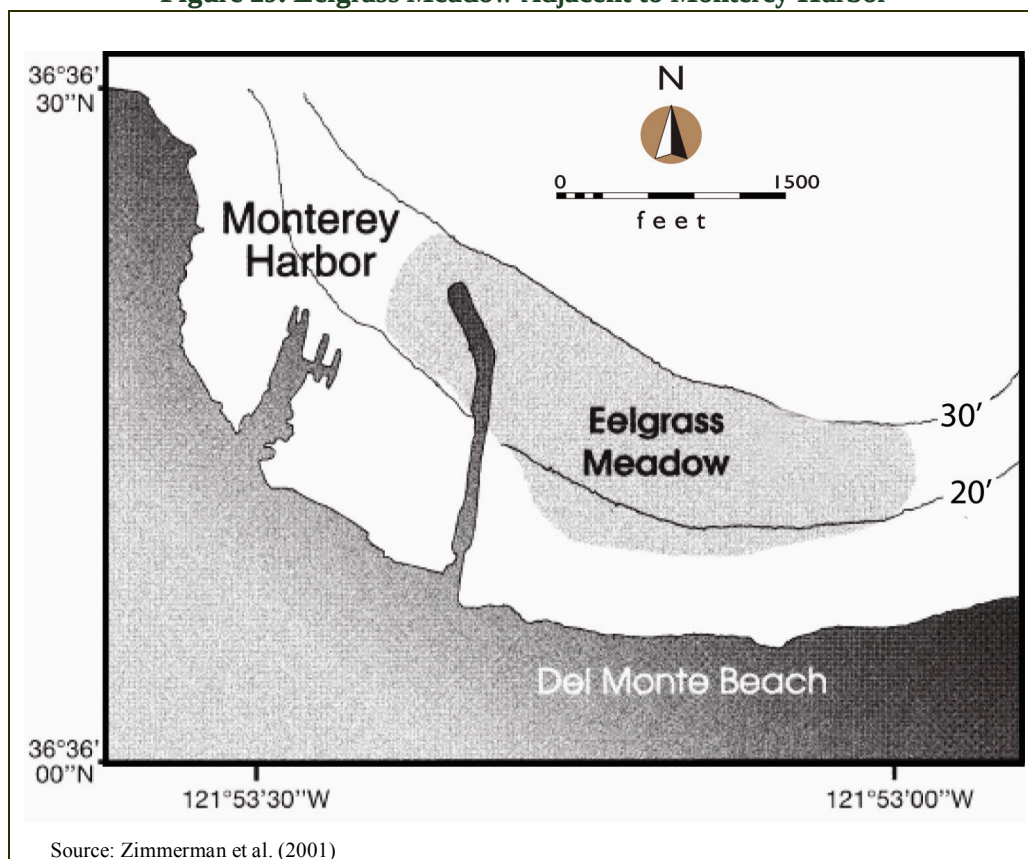
4.1.1 Eelgrass Meadow

Eelgrass (*Zostera marina*) is considered important submerged aquatic vegetation of special interest in California, special aquatic sites (vegetated shallows) under the federal Clean Water Act (SAIC, 2008), and Essential Fish Habitat (NOAA Fisheries and federal and state agency designation). Cutting and disturbing eelgrass is prohibited by California fishing regulations. Eelgrass provides habitat for a variety of invertebrates and fish, including nursery habitat. The primary factors controlling eelgrass growth are light availability, substrate composition, temperature, salinity, nutrient availability, and wave/current energy. Light affects the depth distribution of eelgrass through its role in photosynthesis. The degree to which light is attenuated with depth in the water column is a strong determinant of the lower limit to which eelgrass can grow. Eelgrass can grow in a wide variety of substrates, but generally they flourish in medium to fine sands that contain relatively high levels of organic matter and nutrients.

Prior to 1993, the Del Monte eelgrass meadow covered a continuous 0.1 square miles of the seabed in water depths of 20-30 feet inshore and west of the rocky reef and kelp forest (Figure 29). Zimmerman et al. (2001) indicated that the meadow was fragmented and reduced to less than 50% of its total size following heavy grazing by a southern species of limpet that began in 1993. The prospects for recovery of the meadow to its former size were not considered favorable due to

the limpet grazing. However, data after 2001 are limited and the status of this eelgrass meadow was not known as of 2005 (CDFG, 2005).

Figure 29. Eelgrass Meadow Adjacent to Monterey Harbor



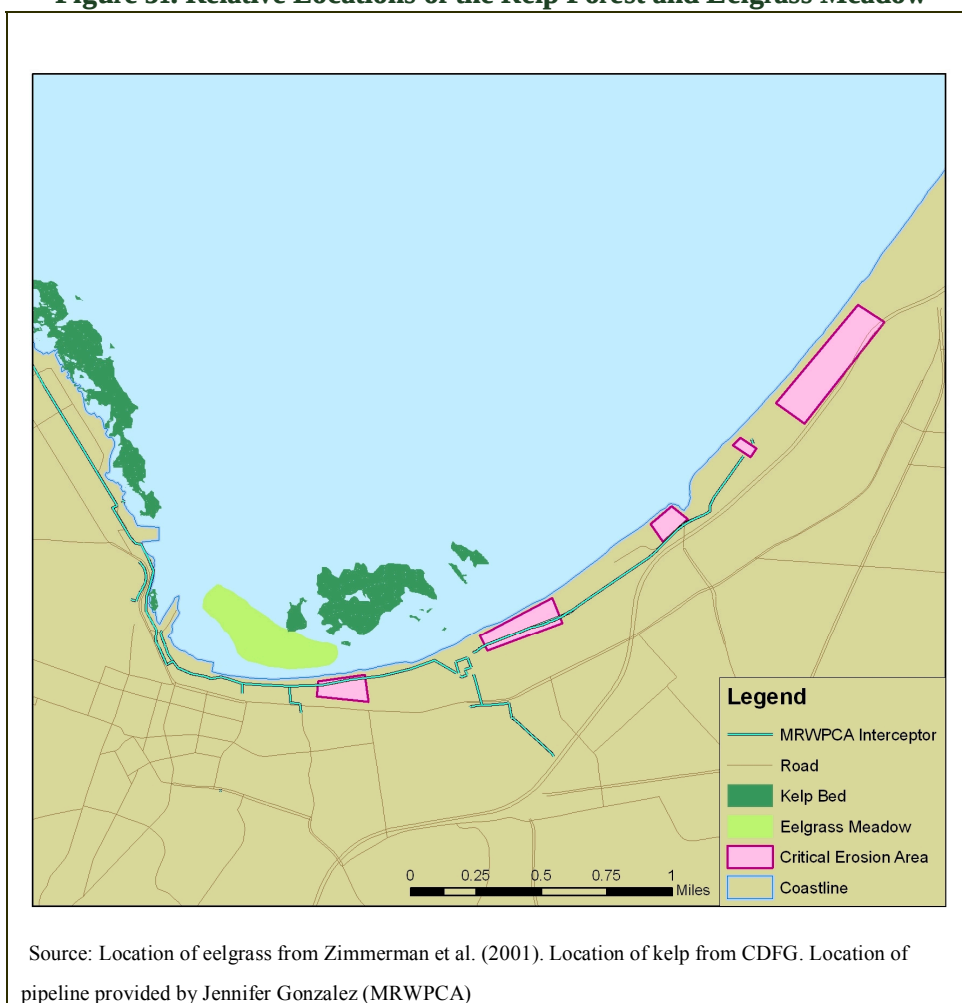
4.1.2 Rocky Reef

A low relief rocky reef of shale known as Del Monte Shale Beds (or Tanker Reef) is situated offshore of the south end of Del Monte Beach (approximately 1.5 miles east of Wharf II and stretching almost to the Monterey Beach Resort), approximately 600 feet from the beach in 30-230 feet of water (Kvitek et al., 2004; Iampietro et al., 2005). The shale outcrop covers an area of over 3.5 square miles (stretching over three miles offshore, Figure 30) and is composed of Miocene Monterey Formation. The inner part of the reef supports a kelp forest and other submerged aquatic vegetation as well as species of fish and invertebrates. In 2005, the Natural Resources Defense Council (NRDC) submitted a proposal to the California Resources Agency which nominated this reef for Marine Protected Area (MPA) status as a marine park. The proposed MPA was not adopted by the CDFG as part of the central coast MPAs and therefore

4.1.3 Kelp Forest

Attached to the inner part of the rocky reef is a kelp forest consisting of giant kelp (*Macrocystis pyrifera*) and bull kelp (*Nereocystis leutkeana*). Kelp favors nutrient-rich, cool clear water through which light penetrates easily, and generally occurs near the offshore limit of wave influence (Figure 31). The kelp forest in the southern bight may support thousands of invertebrate individuals, including polychaetes, amphipods, decapods, and ophiuroids, that are prey for birds and marine mammals, and support commercial fisheries. California sea lions, harbor seals, sea otters, and whales feed in the kelp or escape storms or predators in the shelter of the kelp, which helps to weaken currents and waves. Kelp forests are considered a submerged aquatic vegetation of special interest in California and Essential Fish Habitat. The distribution of this kelp forest likely varies seasonally and from year to year in the southern bight.

Figure 31. Relative Locations of the Kelp Forest and Eelgrass Meadow



4.1.4 Sandy Beaches

Dune-backed sandy beaches exposed to surf are the most prevalent habitat in southern Monterey Bay. These beaches are primary habitat for a variety of invertebrate species including crustaceans, mollusks, polychaetes, and insects, as well as meiofauna that can reach high abundance and biomass. These species are prey resources for fish, seabirds, shorebirds and marine mammals. The beaches also provide roosting areas for shorebirds, pelicans, gulls, and other seabirds, and haul-out habitat for pinnipeds, such as harbor seals and sea lions. Western snowy plovers (a threatened shorebird species) nest and rear chicks on beaches in southern Monterey Bay, and California grunion are known to use these beaches for spawning.

4.1.5 Sandy Subtidal

Extensive sandy subtidal and surf zone habitats bound most of the southern Monterey Bay shoreline. This dynamic habitat can support a diversity of fish and invertebrate species including flatfish, surfperch, amphipods, isopods, mole crabs, Dungeness crabs, swimming crabs, Pismo clams, northern razor clams, sand dollars, sea pansies, sea stars and polychaetes, many of which are prey for seabirds and marine mammals.

Two sandy subtidal benthic infaunal communities are recognized along a gradient of wave activity in southern Monterey Bay. The crustacean zone is closest to shoreline and characterized by strong water motion and sandy sediments. This zone is occupied by small, mobile, deposit-feeding crustaceans, such as amphipods, which do not build permanent burrows. The polychaete zone is in deeper water (60 feet or more), and characterized by more stable fine sand with a significant amount of mud. The zone is dominated by polychaete worms living in relatively permanent tubes and burrows. Many other relatively sessile and suspension-feeding groups, including brittle stars, clams, tube anemones, sea pens, are also common here. The depth limits of these two benthic zones vary with wave activity with zones extending into deeper water with higher wave energy. In southern Monterey Bay, the transition between the two benthic zones is likely to be at a depth of approximately 40 feet.

Subtidal sands are primary foraging and reproductive habitat for a variety of invertebrates and demersal fish including lingcod (inset), white croaker, plainfin midshipman, staghorn sculpin, sand sole, English sole, speckled sand dab and curlfin sole. Marine mammals including otters, pinnipeds, and cetaceans forage on water column and benthic fish and invertebrates over sandy subtidal habitats. Subtidal sands are also important habitats supporting commercial and recreational fisheries for marine invertebrates (e.g. Dungeness crabs, sea cucumbers) and fish (e.g. California halibut, sanddabs).



4.1.6 Coastal Dunes

The coastal dune system of southern Monterey Bay is one of the most important in California. Native coastal strand and dune vegetation is designated as rare in California and much of the area of active sand dunes in southern Monterey Bay (mainly north of the Salinas River) with or without vegetative cover is designated as Ecologically Sensitive Habitat Area (ESHA) (California Coastal Commission designation). Most of the stable vegetated (relict) dunes south of the Salinas River also qualify as ESHA because of the presence of typical sand dune species, species and plants that are ESHA in their own right, and physical substrates that support or could support the above species. Coastal dunes are vulnerable to trampling, erosion, and invasion by exotic species. Dune restoration and conservation is actively ongoing in southern Monterey Bay, including the shorelines of Sand City, Seaside, and Monterey.

4.2 NATIVE ANIMALS

Several native animals inhabiting the dunes and beaches of southern Monterey Bay have special status, are already listed, or are on the candidate list for the federal register. A few other animal species of interest that are prey resources for endangered species or fishery species are also considered.

4.2.1 Western Snowy Plover

The western snowy plover (*Charadrius alexandrinus nivosus*) was listed as a threatened species in 1993 by the U.S. Fish and Wildlife Service (USFWS). In 2005, the USFWS published a final rule on western snowy plover critical habitat along the coast of California, which did not include any of the southern Monterey Bay shoreline. The final recovery plan for the species was published in 2007, in an attempt to remove the Pacific coast population from the list of endangered and threatened wildlife. Although excluded from the USFWS critical habitat designation, southern Monterey Bay provides suitable or potentially suitable habitat for snowy plover foraging and nesting.

Western snowy plovers (inset: photo by Morgan Ball) forage on the shoreline and nest on the beaches and dunes, and are present year-round. Southern Monterey Bay is an important nesting area for snowy plovers, with approximately 60 to 100 nesting birds each year. It is also an important wintering area, with up to 190 birds using this shoreline each winter. Chicks leave the nest to forage soon after hatching, and adults move chicks along the beach (possibly miles) to reach suitable foraging areas. Habitat features essential to the species include areas of sandy beach above and below the high tide line with surf-cast macrophyte wrack and other debris supporting small invertebrates (for nesting and foraging) and



generally open barren to sparsely vegetated terrain (for foraging and predator avoidance). The distribution, including nesting sites, of snowy plover is expected to vary with beach conditions and the dynamics of the population.

At the Sanctuary Beach Resort, the dunes between the bluff edge and resort wall are being preserved to provide dune habitat for the western snowy plover. The dunes to the north of the Ocean Harbor House condominiums are also protected from human and canine disturbance to provide mating and nesting habitat.

4.2.2 Shorebirds



Many species (17) of shorebirds (inset) use the beaches of southern Monterey Bay during migration periods and over the winter months (Table 12). The average abundance of shorebirds is 192 birds per mile of shoreline with peak use occurring between August and March (Neuman et al., 2008). The rich and productive invertebrate prey resources of sandy beaches are important to the survival and success of breeding and non-breeding

shorebirds in coastal ecosystems. Shorebirds have high metabolic rates and relatively high daily energy requirements (Kersten and Piersma, 1987) and are capable of consuming a large percentage (49-65%) of the annual production of invertebrate prey on beaches. The beaches of southern Monterey Bay provide important foraging and roosting habitat for shorebirds particularly when wetlands, such as Elkhorn Slough, are inundated during high tides. Many shorebird populations are declining in the U.S. and the maintenance of high quality foraging habitat is considered important to their conservation.

Table 12. Bird Counts in Monterey Bay (Neuman et al., 2008)

Common name	Scientific Name	Maximum	Density (birds km ⁻¹)	
			Low Tide Mean	High Tide Mean
Sanderling	<i>Calidris alba</i>	6,796	83.70 (37.4)	73.00 (31.8)
Willet	<i>Tringa semipalmata</i>	2,299	19.10 (16.3)	5.40 (6.6)
Marbled Godwit	<i>Limosa fedoa</i>	805	10.50 (5.5)	5.90 (4.4)
Black-bellied Plover	<i>Pluvialis squatarola</i>	497	3.20 (3.5)	1.70 (1.7)
Whimbrel	<i>Numenius phaeopus</i>	535	2.70 (4.2)	1.40 (1.9)
Snowy Plover	<i>Charadrius alexandrinus</i>	330	2.50 (1.7)	3.20 (2.2)
Western Sandpiper	<i>Calidris mauri</i>	1,175	0.78 (1.72)	4.80 (9.7)
Long-billed Curlew	<i>Numenius americanus</i>	94	0.50 (0.64)	0.19 (0.26)
Ruddy Turnstone	<i>Arenaria interpres</i>	42	0.17 (0.29)	0.22 (0.29)
Killdeer	<i>Charadrius vociferus</i>	85	0.17 (0.32)	0.34 (0.68)
Dunlin	<i>Calidris alpina</i>	61	0.14 (0.30)	0.21 (0.41)
Dowitcher spp.	<i>Limnodromus</i> spp.	43	0.14 (0.31)	0.03 (0.06)
Semipalmated Plover	<i>Charadrius semipalmatus</i>	60	0.03 (0.05)	0.30 (0.50)
Red Knot	<i>Calidris canutus</i>	9	0.03 (0.07)	0.01 (0.04)
American Avocet	<i>Recurvirostra americana</i>	14	0.03 (0.10)	0.01 (0.03)
Black Turnstone	<i>Arenaria melanocephala</i>	9	0.02 (0.05)	0.03 (0.06)
Least Sandpiper	<i>Calidris minutilla</i>	89	0.01 (0.02)	0.28 (0.67)
All Shorebirds		7,586	123.80 (44.5)	97.0 (37.6)

NB. Table shows maximum bay-wide count and low-tide and high-tide mean density (standard deviation in parentheses) of the 17 shorebird species observed between November 2002 and April 2003.

4.2.3 Black Legless Lizard

The black legless lizard (*Anniella pulchra nigra*) (inset) is considered a species of concern by the California Department of Fish and game (CDFG) because of its limited distribution. Much of the habitat for this lizard has been lost to agriculture and other development including recreation, especially in coastal dune areas, and by the introduction of non-native plants such as ice plant. It inhabits the Marina and Ford Ord dunes, although the exact distribution of these populations is not known. Kuhn et al. (2005) suggested that standard survey methods may not be effective in establishing presence or absence of this species when densities are low. The Sanctuary Beach Resort has installed a 'lizard crossing' beneath the main entry road to allow the black legless lizard to safely traverse the eastern edge of the property.



4.2.4 Smith's Blue Butterfly



The tiny Smith's blue butterfly (*Euphilotes enoptes smithi*) (inset) is a species of concern and federally protected, and was listed as endangered by the USFWS in 1976 due to loss of dune habitat. At least 12 reserves for this butterfly have been established on Fort Ord. Coast buckwheat (*Eriogonum latifolium*) and dune buckwheat (*Eriogonum parvifolium*) are host plants for this butterfly. They grow in the coastal dunes and are needed by the butterfly for reproduction in their natural

habitat. The distribution of coast buckwheat is limited and patchy in southern Monterey Bay and it has been or is planned to be planted in a number of restoration projects between the Salinas River and Sand City. The emergence of the butterfly is timed to coincide with the blooming of the host plants (approximately 4-6 weeks in late summer-early fall). Each adult butterfly lives about a week, mating and laying eggs on the host plant.

4.2.5 Globose Dune Beetle

The globose dune beetle (*Coelus globosus*) is a Category 2 species of concern for USFWS, meaning it is a potential candidate for listing, but there is insufficient information to support a proposed rule. This species of flightless beetle inhabits coastal dunes usually within 100 feet of the shoreline. They are primarily subterranean as adults and larvae, tunneling through sand underneath dune vegetation such as sand verbena, beach bursage and sea rocket. This species may be absent from southern Monterey Bay; however, the exact status of the population is not known.

4.2.6 Southern Sea Otter

The southern sea otter (*Enhydra lutris nereis*) (inset) inhabits southern Monterey Bay year round. This species is listed as federally threatened and is fully protected by both state and federal regulations. Sea otters require abundant benthic invertebrate prey of large body size including large crabs, sea urchins, abalone, snails, and clams. They feed in rocky and kelp forest habitats as well as low intertidal areas and surf zones of beaches in southern Monterey Bay. Kelp forests are important areas for resting, foraging, and as nursery sites. Hence, sea otters are considered a key factor in the dynamics of kelp forests. The highest density of sea otters occurs in the southern bight (location of kelp) and reproduction of otters as indicated by pup numbers is also relatively high in this area.



4.2.7 California Grunion

The California grunion (*Leuresthes tenuis*) is a beach nesting fish that breeds regularly on Monterey State Beach (Karen Martin, Pepperdine University, personal communication) and possibly on other beaches in southern Monterey Bay. This fish spawns in the upper intertidal zone between March and August, and occasionally in February and September. Peak spawning is late March to early June. Grunion leave the water for four consecutive nights starting the nights of the full and new moons. Spawning begins after high tide and continues for several hours. Eggs



incubate in the sand for two or more weeks and during this period are vulnerable to burial and disturbance. Adult fish inhabit the shallow nearshore from the surf zone to a depth of approximately 60 feet. The most critical problem facing the grunion resource is the loss of spawning habitat caused by beach erosion. By the 1920s the fishery was showing definite signs of depletion and a regulation was passed in 1927 establishing a closed season of three months, April through June. The fishery improved and in 1947 the closure was shortened to April through May. This closure is still in effect to protect grunion during the peak spawning period.

4.2.8 Pismo Clam

The Pismo clam (*Tivela stultorum*) (inset) is a large heavy-shelled long-lived (>50 years) bivalve that inhabits low intertidal and shallow subtidal zones along open sandy coasts from Monterey Bay to Baja California. Southern Monterey Bay is close to the northern limit for this species. This clam can reach shell lengths of greater than six inches and can exhibit zonation by size, with juvenile clams located higher in the intertidal zone than adults.



Pismo clams formerly supported large commercial and recreational (sport) fisheries in the Monterey Bay area and other parts of the California coast until population numbers declined and the fishery collapsed. This clam is important prey for sea otters in southern Monterey Bay.

4.2.9 Beach Invertebrates



Beach invertebrates (inset) including spiny and common sand crabs, beachhoppers, razor clams, polychaete worms, insects, and a variety of small crustaceans can reach high abundance (>30,000 individuals per foot of shoreline) and biomass on the beaches of southern Monterey Bay. These invertebrates are an important prey resource for shorebirds, seabirds, fish, and marine mammals. Many of the invertebrate animals inhabiting the lower intertidal and swash zone can be dispersed relatively long distances as planktonic larvae. The upper shore invertebrates are associated with drift seaweed or wrack, avoiding direct contact with waves. These animals which include beach hoppers, isopods and a number of flightless insects develop directly on the beach and thus can be limited by dispersal and distance from source populations.

4.3 NATIVE PLANTS

Several native plants in southern Monterey Bay are either already listed or are on the candidate list for the federal register of endangered and threatened species. These include Yadon's wallflower (inset), Monterey spineflower, sand gilia, seaside bird's-beak, sandmat manzanita, Eastwood's ericameria, coast wallflower, and Monterey ceanothus. Of these species, Yadon's wallflower (*Erysimum menziesii* ssp. *yadonii*) occurs closest to the shoreline. This endangered species occurs on coastal strand close to high tide, in areas largely protected from wave action, but exposed to strong wind and salt spray. In southern Monterey Bay, this species is reported to be restricted to four occurrences in the vicinity of Marina dunes; two at Marina State Beach and two close to the Marina sand mine. Augmentation, through propagation and reintroduction, has been attempted for populations at Marina State Beach.



Critical habitat is designated by USFWS for the Monterey spineflower (*Chorizanthe pungens pungens*) a threatened annual dune plant that occurs in recent dunes and extends along almost the entire southern Monterey Bay shoreline. Sand gilia (*Gilia tenuiflora arenaria*) grows in the coastal dunes but generally in locations protected from waves, salt spray and strong winds. Sand gilia is both state-listed (threatened) and federal listed (endangered), and ranked by the California Native Plant Society as extremely rare. Seaside bird's-beak is protected under the California Plant Protection Act of 1977.

5. REGIONAL SEDIMENT MANAGEMENT APPROACHES

This section focuses on potential RSM approaches as solutions to coastal erosion problems in southern Monterey Bay. Based on the information outlined in Sections 2 to 4, three main approaches to RSM are considered appropriate. These are:

- beach restoration strategies particularly beach nourishment to slow erosion rates
- eliminate factors that exacerbate erosion
- allow the natural process of dune erosion to continue without intervention.

SMBCEW (2006a) carried out an initial investigation and ranking of a wide variety of erosion response alternatives (including but not exclusively RSM). The list created by SMBCEW (2006a) is presented in Table 13 and includes beach restoration alternatives such as beach dewatering and pressure equalizing modules, sand retention devices and other structures/alternatives, and set backs for any future developments. A full investigation of these methods is outside the scope of this Coastal RSM Plan, but the MBNMS is funding a study for the SMBCEW that further evaluates the higher ranking alternatives, and assesses their role within the RSM framework for southern Monterey Bay.

In addition, CSMW recently commissioned a project to investigate the biological impacts associated with sediment management activities along the California coastline (SAIC, 2008). The draft report is currently under review, and the final document will provide a valuable reference work and appraisal of the potential effects of sediment management on California's natural resources.

5.1 BEACH NOURISHMENT

At locations where it is not considered acceptable to allow natural processes to continue, because the beach resource is being lost and/or important facilities are at risk of erosion, human intervention to alter the shoreline is often considered. In general, there are two types of alteration strategies that are traditionally implemented; soft approaches (a variety of options including beach nourishment) and hard approaches (mainly armoring of different types).

Table 13. Potential Erosion Response Alternatives (SMBCEW, 2006a)

Alternative	Approach	Specific Method	Rank
Approaches to be used when addressing future developments	Prevent or discourage development in areas threatened by erosion	Transfer of Development Credit	20
		Conservation Easements	19
		Fee Simple Acquisition	18
		Present Use Tax	18
	Avoid threats from erosion permanently or for many years	Rolling Easements	19
		Structural or Habitat Adaptation	17
		Set backs for Bluff Top Development	17
		Set backs (Plus Elevation) for Beach Level Development	16
Regional approaches to be used for larger area-wide responses to slow beach erosion		Beach Nourishment - Nearshore Placement	15
		Beach Nourishment – Subaerial-Beach Placement	14
		Beach Nourishment - Dredge Sand from Deep or Offshore Deposits	14
		Dune Nourishment (adding both sand and vegetation)	14
		Pressure Equalizing Modules	14
		Beach Dewatering	12
		Submerged Breakwaters/Artificial Reefs	12
		Inter-littoral Cell Transfers	11
		Perched Beaches	11
		Groins	11
		Emergent Breakwaters	10
Site-specific approaches to be used for existing structures that are threatened by erosion	Move or remove structures away from erosive forces	Managed retreat	18
	Move erosive forces away from the threatened structure	Seawalls	8
		Revetments	8
Approaches that reduce factors that exacerbate erosion	Site-specific (often used in combination with other approaches)	Native Plants	12
		Sand Fencing/Dune Guard Fencing	11
		Controlling Surface Runoff	11
		Controlling Groundwater	11
		Berms/Beach Scraping	9/10
	Regional	Cessation of Mining Sand from the Beach	19

The California Beach Restoration Study (CDBW and SCC, 2002) defines beach nourishment as the introduction of sand on to a beach (inset) to supplement a diminished supply of natural sediment, for the purpose of beach restoration, enhancement, or maintenance. The southern Monterey Bay shoreline has no history of beach nourishment, because the majority of the shoreline is undeveloped and the beaches are healthy, being provided with significant amounts of sand from erosion of the relict dune bluffs (Section 5.3). However, SMBCEW (2006b) strongly recommended analysis of the feasibility of beach nourishment for sites at and south of Sand City to Wharf II, and this Coastal RSM Plan supports that recommendation. Six of the eight areas of critical erosion are located along the stretch of shoreline within the Cities of Sand City, Seaside, and Monterey (defined as the southern bight in this Coastal RSM Plan) where healthy beaches are especially important for recreation and tourism; hence this shoreline could potentially be a receptor for beach nourishment.



The shoreline within the Cities of Sand City, Seaside, and Monterey corresponds with the south sub-cell and the southern extreme of the central sub-cell (Section 2.1), which is the stretch of eroding shoreline impacted by relatively low wave energy and low net sediment transport rates. The clustering of most of the critical areas of erosion within the single relatively short south sub-cell impacted by relatively ‘quiet’ physical conditions provides potential benefits for implementation of beach nourishment strategies:

- The impacts of the nourishment would only be felt within the confines of the south sub-cell with little or no far-reaching impacts to the rest of southern Monterey Bay.
- The nourishment strategy could be implemented on a sub-cell scale and would benefit multiple facilities within the sub-cell region.
- Beach nourishment benefits are enhanced if critical areas of erosion are close together and not separated by large distances within a littoral cell.
- Low wave energy and low net alongshore sediment transport would mean that sand would remain at the receiver site for a longer period of time. This may lead to a reduced frequency of maintenance of the site through further nourishment, reducing costs.
- The location of an apparent alongshore sediment transport convergence close-by (at Sand City) and the associated potential accumulation of sand offshore that is suitable for nourishment would simplify implementation and reduce costs. The south sub-cell is also adjacent to Monterey Harbor providing a second easily accessible potential source of sand.
- The south sub-cell is the most accessible area of southern Monterey Bay for transportation of appropriate sand from inland sources if they become available in the future.

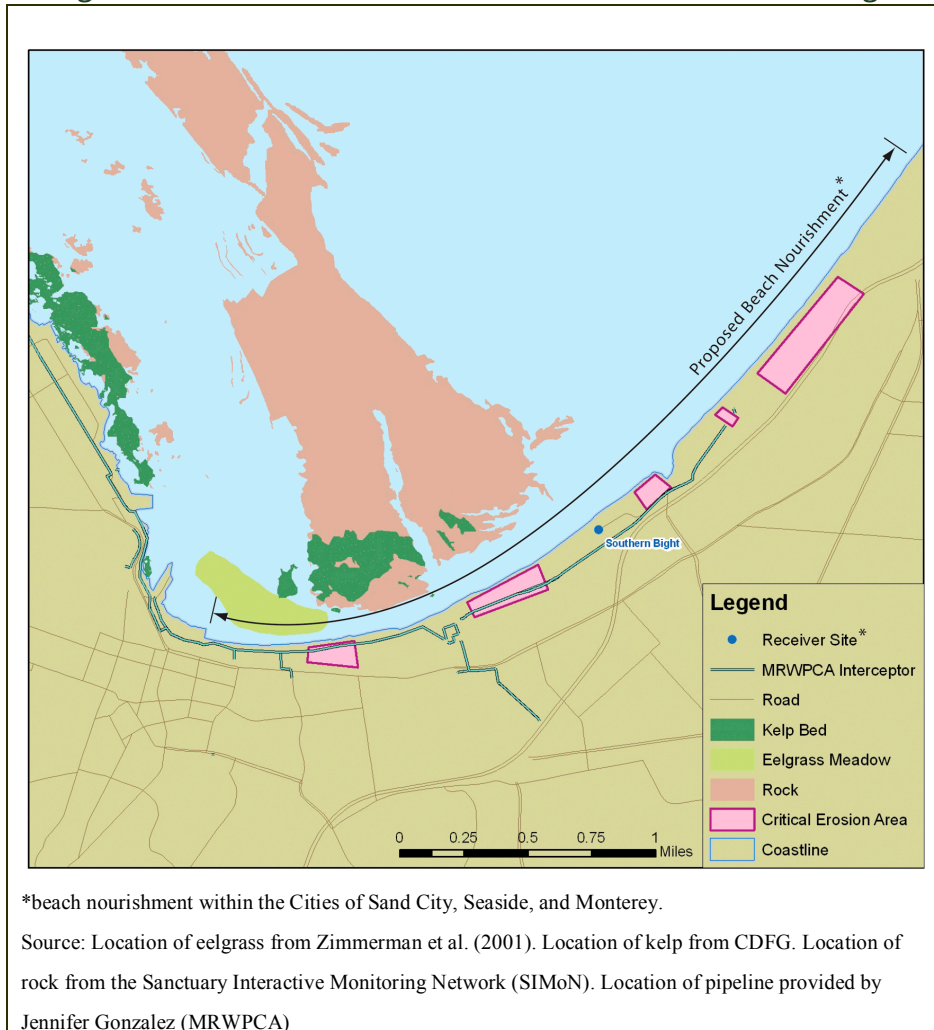
This Coastal RSM Plan recommends investigation of beach nourishment and other beach restoration strategies to ameliorate erosion along the stretch of shoreline within the Cities of Sand City, Seaside, and Monterey.

Two different beach nourishment approaches could be adopted; subaerial placement (on beach), and nearshore placement (in surf zone). Subaerial placement of sand is nourishment of the dry beach and near the water line (CDBW and SCC, 2002), which results in an immediate artificially wide beach. Waves then redistribute the sand across the entire beach and shoreface profile until equilibrium is reached. Through this process the dry beach narrows from its initial nourished width to accommodate the profile adjustment. Nearshore placement nourishes the part of the littoral cell immediately seaward of the surf zone (CDBW and SCC, 2002). The intent is that this sand will buffer waves and at the same time the waves will transport some of the sand onshore to increase the beach width. Nearshore placement of sand should result in a wider dry beach, but at a slower rate than if the same volume of sand is placed directly onto the beach.

The placement location and timing would be important considerations in southern Monterey Bay. Sand placement should occur away from sensitive resources (kelp, eelgrass, rocky reef, Section 4.1), should not take place during bird nesting (such as western snowy plover nesting season, March-September, Section 4.2.1), should not occur at times of high beach use (May to September), and should not be constructed so as to interrupt beach access. A strategy to mitigate placement impacts should be a key objective of the placement design (Section 5.1.2). The Sand Compatibility and Opportunistic Use Program (SCOUP) (Moffatt and Nichol Engineers, 2006) provides guidance and strategies for placement of sand in the nearshore.

5.1.1 Potential Environmental Impacts of Beach Nourishment

A number of sensitive habitats and species are present in southern Monterey Bay (Section 4). The stretch of shoreline where this Coastal RSM Plan supports potential beach nourishment (Cities of Sand City, Seaside, and Monterey), has rocky reef, kelp forest and eelgrass meadow in the nearshore (Figure 32), and may contain endangered birds, plants, and invertebrates as well as grunion spawning habitat in the dune and beach areas. The Corps requires a sensitive habitat survey for beach nourishment projects, which includes pre- and post-project monitoring and proposals for mitigation for any impacts to sensitive habitats adjacent to and down coast of the receiver site.

Figure 32. Beach Nourishment Considerations in the Southern Bight

Impacts of beach nourishment can occur at the site where the sand is placed; as a direct impact and as an indirect impact through dispersal of the sand by alongshore, cross-shore, or wind-driven transport. Impacts to biological resources can be classified into three major categories (Speybroeck et al., 2006):

- impacts directly related to the construction phases of a nourishment project
- impacts related to the characteristics of the sediments used
- impacts related to the quantity of sediment applied.

The magnitude of these impacts is strongly influenced by the place, time, and size of the project, and the strategy of the nourishment activity. Cumulative impacts are also important to consider with respect to the frequency and scale of activity, and for multiple sand management projects.

Impacts of beach nourishment construction activities (both subaerial-beach and nearshore placement) may include direct damage and disturbance, burial of habitat by sand placement at the site, and dispersal to down coast areas (the thickness of sand placed can influence the degree of impacts to biological resources), and water quality effects resulting from resuspension and settling of sediments. Disturbance to wildlife during construction can be both visual and auditory. The use of heavy equipment to transport and arrange sediments can destroy dune vegetation including threatened species, and compact beach sediments negatively affecting vascular plants and invertebrates, as well as affecting air quality.

Disturbance and/or burial associated with either subaerial-beach or nearshore sand placement may affect the mortality of the southern bight benthic community, its potential recovery, and the amount of prey available to higher trophic levels, birds, fish, and marine mammals. Recovery rates vary among species and depend on the scale and timing of the impacts. Periods of six months to greater than two years may be needed for recovery of shorter-lived species depending on the recruitment of planktonic larvae, their survival, subsequent growth, and resulting habitat changes. Recovery of longer-lived species, such as Pismo or razor clams, could take more than 5-10 years. Burial of grunion eggs by a layer of added sediment can prevent successful hatching, and changes in beach profile geometry could reduce spawning activity or potentially trap adult fish above high tide.

Increased turbidity resulting from nearshore and beach placement of sediments in the southern bight could negatively affect vegetation and animals living on the offshore rocky reefs, subtidal sand, eelgrass meadows, and kelp forests (Figure 32). Turbidity could adversely affect kelp recruitment and/or juvenile growth depending on the proximity of the operations, duration of the turbidity related to project size, sediment characteristics, and hydrodynamics. The eelgrass meadow could potentially be disturbed by construction activities, indirect sedimentation and turbidity as well as anchoring of support vessels and other activities. Recovery of kelp and eelgrass can be very slow (2-7 years) and transplantation of eelgrass has been needed in a number of areas where damage to benthic habitat has occurred (SAIC, 2008).

The characteristics of the placed sediment, such as the particle size distribution and proportion of shell fragments can affect habitat quality for burrowing animals and subsequent recovery of the biota and food chain support (Peterson et al., 2000, 2006; Speybroeck et al., 2006). Particle size can also affect beach morphology, compaction, and the subsequent biotic community. Sediments with a high proportion of shell fragments can potentially cement into a pavement, reducing wind-blown and hydrodynamic sand transport and creating a barrier to burrowing animals.

Post-construction transport of sand in the southern bight following placement (both subaerial-beach and nearshore) could negatively affect the adjacent kelp forest, rocky reef, and eelgrass meadow through indirect sedimentation of these habitats, with the magnitude of impact depending on project volume and proximity to the habitat. The Del Monte Shale Beds rocky reef is potentially vulnerable to sand inundation and scour. The kelp forest probably occurs seaward of

the wave impacted seabed; however, inshore portions may extend into shallower waters during years lacking major storms. Sedimentation can adversely affect all life stages of the kelp due to scour and increased mortality of both adults and juveniles.

The beaches and coastal dunes of southern Monterey Bay provide important habitat and resources for the western snowy plover. Management to protect nests, chicks, and adults of this threatened bird is ongoing, particularly during the March to September breeding season. The importance of the area to western snowy plover is high and maintaining prey resources for foraging and chick rearing needs to be considered in beach nourishment activities. The entire southern Monterey Bay was originally proposed for designation as critical habitat for western snowy plover; however, it was removed from critical habitat designations in the final rule for this species (September 2005).

5.1.2 Mitigation Measures

Adverse impacts to the coastal habitats in the southern bight from beach nourishment activities could be reduced by implementing the following mitigation measures:

- match the particle size characteristics of sand used for nourishment with those at the receiver site as closely as possible
- select a placement location that avoids direct impacts to sensitive habitats and species and incorporates buffer distances from kelp forests, rocky reef and eelgrass meadow to minimize potential impacts from turbidity and sedimentation; recommended buffers range from 500 to 1,000 feet (SAIC, 2008)
- time project construction activities to avoid key biological periods; avoid nesting and spawning seasons for western snowy plover and grunion, respectively; avoid recruitment periods for key invertebrates with planktonic larvae, such as sand crabs and clams; avoid peak shorebird migration periods and wintering
- create refuges in project design to reduce impacts, maintain food chain support and facilitate biological recovery by nourishing small sections of beach (less than 2,000 feet) interspersed with undisturbed sections of habitat
- establish no work zones to avoid disturbance by vehicles, equipment, and other activities, and restrict vehicles and pipeline alignments to outside vegetated dune areas and sensitive habitats
- minimize the use of heavy equipment, with use of lighter equipment preferred to reduce mortality and habitat damage from compaction during construction
- implement monitoring and protective measures for sensitive species and habitats during construction (e.g. shorebird, sea otter, grunion)
- conduct pre- and post-project monitoring of ecological responses and recovery for a sufficient time period to inform design of future projects and adaptive management using a modified BACI (Before-After, Control-Impact) approach
- implement mitigation (e.g. restoration, transplantation) to offset any inadvertent and/or unavoidable habitat loss.

5.1.3 Potential Receiver Site in the Southern Bight

Given the location of the critical areas of erosion and the need to avoid adverse impacts to local sensitive habitat, this Coastal RSM Plan recommends a receiver site location for both subaerial-beach and nearshore sand placement between the Monterey Beach Resort and the Ocean Harbor House condominiums (Figure 32). This receiver site is considered suitable for three main reasons:

- The net alongshore sediment transport rate is low and to the north, but the gross transport rate is high in both northerly and southerly directions. This location is fairly central to the southern bight and would allow the sand to be transported most effectively along the whole shoreline (Figure 32). Sand placed at a location further to the north would be unlikely to disperse sufficiently to cover critical areas of erosion towards Monterey Harbor given the overall net transport to the north, and placement further to the south would be too close to the sensitive habitat located offshore.
- This location is far enough away from the sensitive kelp, eelgrass and rocky reef habitat so as not to cause disturbance through sedimentation or turbidity during construction and post-construction phases of the project.
- The location is relatively close to a potential stockpile area proposed at Fort Ord (Section 6.3.1) where inland sediments, if they become available, could be placed temporarily until a beach nourishment maintenance-style project could be developed. Road access to the location is available.

5.2 ELIMINATE FACTORS THAT EXACERBATE EROSION

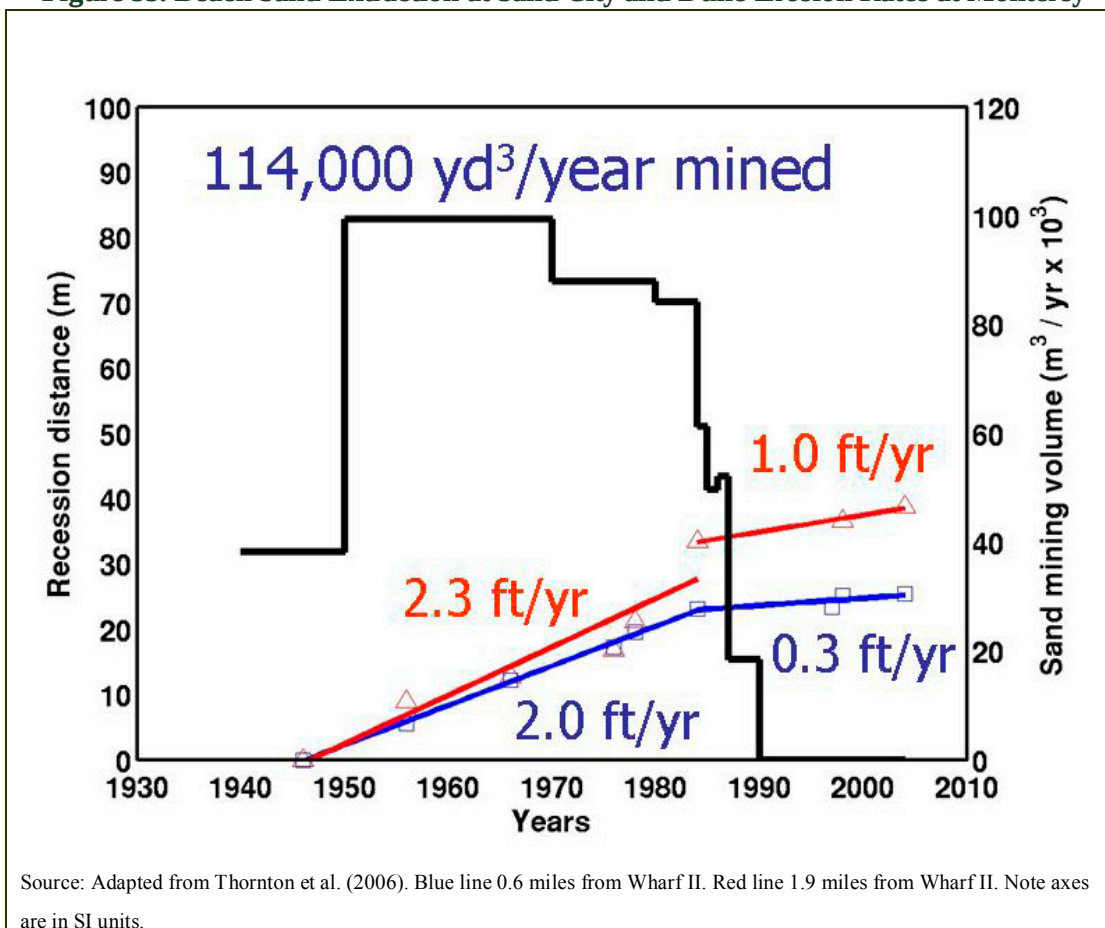
The main human factor that affects the sediment budget, exacerbating shoreline erosion in southern Monterey Bay, is hydraulic sand mining from the beach. Cessation of mining beach sand would allow approximately 200,000 yd³/year of sand (Table 8) to remain in the littoral budget, to supply both up coast and down coast beaches (beach replenishment). Battalio and Everts (1989) determined that the former beach-sand mining operations at Sand City acted as sediment sinks drawing in large quantities of sand from the surrounding littoral zone, and re-orienting the shoreline (Figure 16). They described a process whereby sediment from up coast and down coast moves towards the sink (created by the removal of beach sand by the mines) causing those portions of the shoreline to erode. Battalio and Everts (1989) showed reasonable agreement of their conceptual model with measured shoreline erosion rates (using aerial photograph comparisons) between 1949 and 1988. In this Coastal RSM Plan, the conceptual model is used to explain the impacts to shoreline erosion that mining sand from the beach has had historically and is having currently.

5.2.1 Impacts of Historic Beach-Sand Mining at Sand City

The 1985-2005 dune erosion rates at Sand City and south of Sand City (Monterey Beach Resort and Del Monte Beach) are lower than those during the beach-sand mining period between 1940

and 1984 (Table 3). The decrease in erosion rate is likely to be related to the complete cessation of beach-sand mining at Sand City in 1990 (Section 2.5.4). Figure 33 shows that extraction of beach sand at Sand City peaked at 114,000 yd³/year and during this time erosion rates at Sand City were between 2.0 and 2.3 ft/year. As the amount of beach-sand mining was reduced during the 1980s and finally stopped in 1990, erosion rates at Sand City decreased to between 0.3 and 1.0 ft/year. After the 1980s, the mines ceased to be a sink for sediment from the surrounding littoral zone (Figure 16), the shoreline re-adjusted to the new condition, resulting in lower erosion rates.

Figure 33. Beach Sand Extraction at Sand City and Dune Erosion Rates at Monterey



5.2.2 Impacts of Historic and Ongoing Beach-Sand Mining at Marina

After the Salinas River changed course in about 1910 (Section 1.3), there was significant accretion of the shoreline both north and south of the mouth as measured by the long term (1910-2002) shoreline change (Figure 18, Hapke et al., 2006). However, between 1970 and 2002 the shoreline from the Salinas River to Marina sand mine eroded. The switch from accretion to

erosion is believed to correlate with the start-up and continuation of hydraulic mining of sand from the beach at Marina. The change from accretion to erosion only occurs south of the Salinas River mouth, whereas to the north of the mouth the shoreline continues to accrete (Figure 18). Assuming that the input of sediment from the river has remained constant, the recent losses to the south of the mouth are likely to be related to beach-sand mining, which acts as a sediment sink (Figure 16).

The estimates of Thornton et al. (2006) show that at Marina State Beach (south of the beach-sand mining) there has been a significant increase in erosion rates post-1984 (Table 3). This increase is believed to be related to the increase in extraction rate of beach sand at Marina in the mid-1980s, with further increases in extraction in the 1990s and 21st century (Table 14). The mining acts as a sink effectively drawing in sand resulting in a large loss from the littoral budget. The increase in extraction rate has resulted in less sand being available for transportation up coast and down coast, exacerbating the rate of erosion to the south and north. The erosion diminishes north of the Salinas River mouth, indicating that the offshore depth contours (ancient sediment lobe, Section 1.3) limit the net alongshore transport past this feature.

Table 14. Beach Sand Extraction and Dune Erosion Rates at Marina

Decade	Sand Mined from Beach (yd ³ /year x 1000)	Average Erosion Rate at Marina State Beach (ft/year)
1940s	20	1.0
1950s	40	
1960s	84	
1970s	129	
1980s	143	
1990s	200	4.7
2000s	200	

An aerial photograph of the dredge pond at Marina taken after the storm of January 2008 (Figure 20, right panel) shows how effective the mined area on the beach is at trapping sediment from the littoral zone. Prior to the storm the pond was filled with water (Figure 20, left panel). During the storm, waves and surge overtopped the berm and broke loose the 80-ton dredge that was chained inside the pond. The overtopping waves transported large quantities of sand from the littoral zone, which was deposited in the pond. The photograph in Figure 20 (right panel) was taken on January 15, 2008 and shows the pond has been completely filled with sand. The wrack line is landward of the former pond indicating that swash entered the pond and then swept further inland.

5.2.3 Beneficial Impacts of Stopping Mining of Sand from the Beach

Stopping the mining of the beach would release approximately 200,000 yd³/year of sand to replenish up coast and down coast beaches in southern Monterey Bay. This estimate of sand lost from the littoral cell is equivalent to the volume of sand supplied to the cell from erosion of the 12 miles of dunes between the Salinas River and Wharf II. Using Table 4 to calculate average beach recession rates from volume losses of beach and shoreface sand for the stretch of shoreline between the Salinas River and Wharf II, indicates that mining of 200,000 yd³/year of beach sand is the equivalent of approximately two feet of beach every year. Loss of two feet of beach each year is approximately 50-75% of the ongoing erosion along southern Monterey Bay south of the Salinas River (Section 2.3.3). Hence, retention of the sand that would otherwise be lost from the budget through mining of the beach would have a major benefit for all of southern Monterey Bay.

The main impact of the cessation of beach-sand mining would be an expected increase in the amount of sand available to be transported to the south towards Sand City and Monterey. Thornton et al. (2006) showed that after the cessation of the drag line sand mines at Sand City and Marina the erosion rates significantly decreased in the southern bight. The erosion rates would therefore be expected to further decrease in the south sub-cell if mining of sand from the beach were to completely stop. In addition, gross alongshore sand transport is high throughout southern Monterey Bay enabling effective redistribution of beach-sand mining perturbations along the entire Bay shoreline. Hence, mining of sand from any beach location in southern Monterey Bay affects the entire shoreline from the Salinas River to Wharf II. The beach-sand mining selectively removes the coarser fraction which requires a greater amount of dune erosion to replace (Section 2.6.1). Consequently, the effect of mining sand from the beach, and the benefit of its cessation are likely greater than the beach-sand mining rates indicate.

The mining of sand from the beach disrupts sand transport, and ultimately results in enhanced beach erosion and loss of habitat needed by sensitive species (e.g. loss of western snowy plover breeding and wintering habitat) and other biological resources. Stopping beach-sand mining would result in increased beach widths, reduced erosion and enhanced beach and dune habitats for shorebirds and other sensitive species, as well as the biological resources that support them.

This Coastal RSM Plan recommends cessation of mining of sand from the beach because of its impact on the regional rates of shoreline erosion. Beach and shoreline erosion is particularly acute at the Sanctuary Beach Resort critical area of erosion. This resort is located approximately one mile south of the sand mine and the erosion rates of the dunes on which it is located are directly affected by the extraction of sand from the beach. Replenishment of the beach in front of the Sanctuary Beach Resort with sand that would otherwise be removed from the system would provide a larger and more effective buffer to waves in front of the dunes, reducing the erosion rate.

After confirming the Marina sand mine production rate, the SMBCEW should continue to explore the mining of sand from the beach and its impact on coastal erosion.

5.2.4 Potential Strategies for Reducing Impacts Associated with Mining Sand from the Beach

One of the primary conclusions of this Coastal RSM Plan is that ongoing mining of sand from the beach is contributing significantly to down coast beach erosion; this section of the report offers several options for addressing this issue, both regulatory and non-regulatory. Mining of sand from the beach is a controversial issue due on the one hand to its potential impacts on the environment, and on the other, its provision of jobs and tax revenue. In order to resolve these issues, options that are mutually acceptable to all stakeholders should be explored. This would include the full support of beach-sand mining property owners, and the general community, including business leaders, government officials, and entities concerned about impacts to endangered species and habitat.

In the first instance, the beach-sand mining property owners should be engaged in discussions as to potential futures for their land. For the wider community, the findings of this Coastal RSM Plan should be given wide distribution through official and media channels. A series of articles could be published in the Monterey Herald newspaper and other media outlets. The local communities and businesses that are particularly adversely impacted, such as the nearby Sanctuary Beach Resort and other tourist communities along the entire southern Monterey Bay shoreline, need to be aware of how the negative impacts of mining sand from the beach are directly affecting them.

In order to provide a context to the current mining of sand from the beach, the history of the current Marina sand mine should be investigated in three main areas.

- The sand mine was started in 1965 by Lone Star Industries, who originally reported to the California State Lands Commission (CSLC) under their general permit for mining. Reporting of the mining amounts from the dredging was stopped in 1967. A question to answer is did the CSLC have jurisdiction over this operation originally.
- In 1982, the City of Marina LCP was certified by the California Coastal Commission. The sand mining policy descriptions in the certified LCP should be examined (Section 8.2.1). The City of Marina annexed part of the plant property in 1986.
- In 1987, Lone Star Industries filed a mining restoration plan, which is available through Monterey County Public Works or the California Mining and Geology Board. This document should be reviewed.

Regulatory Options

U.S. Army Corps of Engineers. The Corps has determined that they do not have jurisdiction over the back-beach sand mining operation at Marina. A jurisdictional determination is conducted

prior to the permit review process. In this case, the Corps found that the mining operations did not fall within its jurisdiction. Due to this ‘disclamation’ of jurisdiction, the Corps did not issue a public notice, since it is only required to do so once it is ascertained that a geographic area or activity falls within Corps jurisdiction and the subsequent permitting process. This Corps jurisdictional determination is available for public review upon request.

The Corps determination of non-jurisdiction for the back-beach sand mining may be demonstrably inconsistent with later determinations of jurisdiction the Corps has made (at other beach locations in the San Francisco Corps District) for beach grading and barrier beach breaching to regulate flooding (Peter Baye, personal communication). These determinations indicate that the geographic area in which beach grading and breaching occurs falls within Corps jurisdiction, and the activity of dredging sand from areas that intermittently fall within tidal influence (lagoons that breach) is also within Corps jurisdiction. The mined beach lagoon at Marina has a drift line delineating its edge evident in aerial photographs (Figure 20), and tides in winter capture the lagoon and make it at least temporarily subject to tidal flows. The industrial activity of beach-sand mining and the potential interstate sales of sand (or concrete) obtained from waters of the U.S. supports federal jurisdiction. Hence, the rationale used by the Corps in disclaiming jurisdiction of the beach-sand mining at Marina under Clean Water Act Section 404 and Rivers and Harbors Act Section 10 should be revisited.

California Coastal Commission. Examination of aerial photographs shows that a different dredge with a longer dredge head was introduced at the Marina sand mine sometime after 1979. This allowed deeper dredging and hence increased the dredging capacity significantly. Therefore, the new operation falls under the jurisdiction of the City of Marina, which did not review this significant change in dredging operation. The Marina LCP (Chapter 17.55.040, Section A.4, Permit Limitations) states that ‘no person who has obtained a legal vested right to conduct a surface mining operation prior to January 1, 1976 shall be required to secure a mining permit pursuant to the provision of this chapter so long as such vested right continues, provided that no substantial change is made in that operation except in accordance with the provisions of this chapter.’ This provision is interpreted to mean that a new permit may be required because there was a significant increase in the amount of sand mined from the beach after the introduction of the new dredge after 1979.

U.S. Fish and Wildlife Service. There are many endangered species in the area; for example western snowy plover, black legless lizard, and Yadon’s wallflower. Lone Star Industries did not obtain a take permit for endangered species, such as Yadon's wallflower, which is prevalent in proximity to the sand excavation area (Peter Baye, personal communication). The adverse impacts on endangered species of mining sand from the beach should be investigated under the Endangered Species Act.

Non-Regulatory Options

Alternative mining operation on the property. One alternative to mining sand from the beach could be to mine sand elsewhere on the property outside the littoral zone. It would need to be ascertained if there are sufficient placer sands of the same quality as the beach sands on the property to move the mining operation further landward so as not to ‘take’ sand from the littoral zone. This would be a more expensive mining operation, but would have less of an impact on erosion, and would continue to provide jobs and tax revenue locally.

Purchase the property and/or change the land-use designation. Dialogue with the beach-sand mining property owners could be started to discuss potential purchase and/or change of use. Purchasing the property outright would be expensive, although probably cost effective over the long term. The property could potentially be turned into conservation easement and/or public beaches. Funds would need to be generated for a buy-out. Discussions with land trust organizations (or possibly those entities being economically impacted by aggravated erosion) with a source of funding would need to be initiated if this alternative is to be pursued. The nearby Sanctuary Beach Resort and other affected properties along the southern Monterey Bay shoreline should be encouraged to invest monies in a potential acquisition. Opportunities should also be investigated to use Coastal Commission mitigation fees as another source of funding. For example, the Ocean Harbor House condominiums were required to pay several million dollars as mitigation for the approved seawall project. That money has been earmarked for Monterey Peninsula Regional Park District to purchase dune property.

Alternatives to removing sand from the beach could include development of the property for other uses that would allow the property owners to continue to generate income, jobs and tax revenue. In order to develop the property, the Marina LCP would have to be amended from the present zoned designation within the Coastal Conservation and Development/Coast Permit. One possibility that may be considered is purchase combined with allowing the current owners to retain the rights for development of some portion of the property. This should reduce the purchase price significantly.

5.3 ALLOW DUNE EROSION TO CONTINUE

This ‘no action’ approach allows the natural processes of dune erosion to continue without human intervention. Section 3 shows that within the portion of the littoral cell north of the City of Sand City, there are only two permanent structures or facilities (the Sanctuary Beach Resort and Marina Coast Water District buildings) known to be at risk either on the beach or on top of the dunes. The dunes are also sufficiently wide and high so there is no immediate threat of flooding to the low-lying areas behind the dunes. In addition, erosion of the dunes along this stretch of shoreline is providing large quantities of sand to the littoral system, maintaining the beaches in a healthy condition and providing benefits for sensitive species and habitats (Section 4).

This Coastal RSM Plan recommends that the dunes between Moss Landing and the northern boundary of the City of San Jose be allowed to erode without intervention.

5.4 OTHER POTENTIAL EROSION RESPONSE ALTERNATIVES

5.4.1 Hard Structural Approaches

Hard structural approaches generally refer to armoring the shoreline to prevent erosion, and include seawalls, revetments, and riprap. As coastal development has grown in California, the use of coastal armoring to protect oceanfront property and infrastructure has become more common. For example, ten percent of the entire 1,100 mile coastline of California has now been armored, including 33% of the coastline of the four southern California counties (San Diego, Orange, Los Angeles and Ventura).

Shoreline armoring may lead to physical changes to the beach, ecological impacts, and beach access limitations. Physical impacts include the placement loss of usable beach caused by the footprint of the armoring structure. Armoring prevents erosion of sand from the bluffs that would normally nourish the beach, incrementally increasing erosion potential. Passive erosion is the drowning and narrowing of a beach in front of a structure while adjacent, unarmored shoreline segments continue to retreat (Griggs, 2005). Eventually, a peninsula effect can occur when the armor juts out into the water, impacting alongshore sediment transport, and lateral beach access. In addition, erosion rates tend to be increased at the flanks of the armoring, thus exacerbating erosion of adjacent stretches of shoreline. Armoring also fixes the back beach while the rest of the shoreface erodes. This can change wave energy dissipation and the adjacent shoreline geometry.

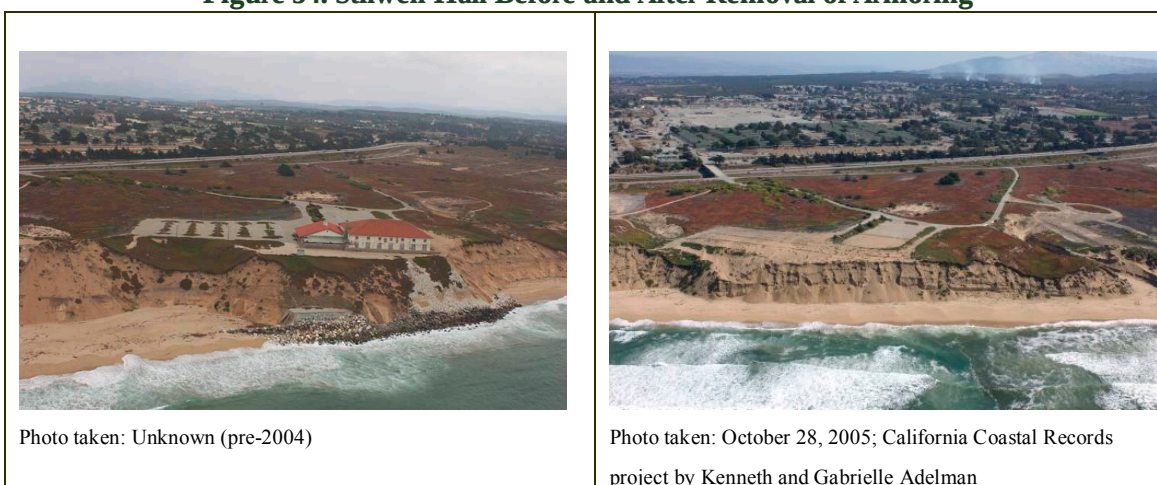
Ecological impacts occur primarily from the enhancement of reflected wave energy from the structure interacting with the incoming waves. This active erosion affects the entire sandy beach ecosystem by reducing the distribution and abundance of wrack, sandy beach invertebrates, and shorebirds (Dugan et al., 2008). From a recreational viewpoint, shoreline armoring reduces the usable beach width and over time, on an eroding shoreline, can significantly reduce lateral beach access. There is also the visual impact of most existing coastal protection structures.



One example of historic shoreline armoring in southern Monterey Bay shows the harm associated with this practice as well as the restoration potential when it is removed. Stilwell Hall (inset) was built in the 1940s as the Fort Ord soldier's club between Sand City and Marina (Figure 1). In 1978, 650 feet of riprap and broken concrete was placed at the base of the bluff to protect Stilwell

Hall from bluff erosion, which was further augmented in 1985 (Figure 34, left panel). The riprap extended out onto the beach (placement loss), reducing the width of the beach in front of the armoring compared to the adjacent beaches. As dune erosion continued on the adjacent shoreline, the beach in front of the structure continued to narrow and disappear (passive erosion), while adjacent to the structure the shoreline and bluff continued to erode. Erosion on the flanks of the structure is increased owing to enhanced energy from waves reflected off the sidewalls of the structure (or bluffs in this case) exacerbating erosion to the shoreline (Figure 34, left panel). Continuing erosion along the adjacent shoreline created a riprap armored peninsula jutting out into the bay, which disrupted public access along the beach as well as reduced alongshore sediment transport. The riprap was eventually removed and Stilwell Hall was torn down in 2004. The now unprotected sandy bluff eroded rapidly during the winters of 2005 and 2006, and has reached a new equilibrium with restoration of the beach in front of the former structure (Figure 34, right panel).

Figure 34. Stilwell Hall Before and After Removal of Armoring



This Coastal RSM Plan recommends that, whenever possible, soft approaches should be adopted for RSM.

5.4.2 Dewatering

Dewatering is defined as the manipulation of groundwater within the beach to increase natural accretion processes. Beach dewatering works on the principle that if the beach face is dry when the wave runup swashes up the beach, then the water can infiltrate into the beach and deposit sediment. If the beach face is saturated, then the infiltration is limited and sediment is transported off the beach with the receding backwash. Dewatering is an effort to lower groundwater levels to

enhance this natural infiltration process. Dewatering can either be active (with pumps and pipes), or passive (without pumps such as the pressure equalizing module - PEM). These dewatering technologies are relatively new to shoreline management and will be investigated as part of the complementary project funded by MBNMS and carried out under the SMBCEW process (Section 1.2.1).

5.4.3 Retention

Sand retention, while often covered under hard structures such as groins or jetties, can also be a soft approach through the use of geotextiles. Retention techniques enhance the ability of the beach to retain sand. They include artificial reefs which can serve dual purposes as habitat and recreation (surfing), and geotextiles placed in a cross-shore orientation acting as ‘soft’ groins, which can accumulate sand on their up coast side while still enabling sediment to overtop, thus avoiding some of the down coast impacts associated with harder groins and jetties. Retention techniques may be investigated as part of the associated MBNMS project (Section 1.2.1).

5.4.4 Bluff Top Development Set Back

Bluff top set back is a technique for locating new development so that it can be safe from erosion and slope failure for some identified time period. Normally the set back is established by determining where the facility can be placed at present, so that it will have an acceptable factor of safety (FS) against slope instability and add to that both the anticipated amount of erosion over the identified time period and a buffer. After the identified time period is over, the facility can be expected to be at risk from erosion and there will be the future question about whether the development should be removed or whether it should be protected. In order to secure the future of new development along southern Monterey Bay this Coastal RSM Plan recommends:

- consideration of an extended planning horizon of 100 years for large cost or long-term projects be incorporated into revised Local Coastal Programs. This planning horizon, however, is not recommended for narrow, urban beach areas adjacent to Highway 1 where a 100 year set back standard would be impractical. This pertains specifically to the coastal zone along the incorporated City of Sand City. Sand City’s existing, certified LCP and related Memorandum of Understanding with the Park agencies establishes a 50-year erosion set back and also allows limited, visitor-serving and residential development.
- development of a strong set back ordinance in the Land Use Plans for oceanfront development that puts high use facilities at an appropriate distance from the ocean.

6. POTENTIAL SEDIMENT (SAND) SOURCES

The potential beach nourishment strategies outlined in Section 5.1 require sources of sand. This section investigates and characterizes potential sources of sediment for beach nourishment including:

- areas of excess sediment such as harbors and wetlands, where sand must be removed to restore function
- flood control projects such as dams and reservoirs where sand may become available as a result of dredging or excavation to restore capacity or close a dam
- inland commercial sand sources, which may become available during new development projects
- dunes at Fort Ord
- offshore sand.

Three main criteria are used as an initial basis for screening source locations; availability of large quantities of beach compatible sand, levels of contamination, and the location of the source relative to the potential southern Monterey Bay receiver site. Sediments with contamination are typically eliminated from further consideration for beach nourishment. Potential sources are then targeted, using the Tier I evaluation criteria of the Sand Compatibility and Opportunistic Use Program (SCOUP) Plan (Moffatt and Nichol Engineers, 2006), for more detailed compatibility studies.

The characteristics of the available source sediment are important in the design of beach nourishment strategies (CDBW and SCC, 2002). The source sediment should be similar in particle size (or larger) to the receiver site, so as to behave in a similar way to the natural beach sediment. Source sediments must be free of harmful chemical and biological contamination. Sediment is appropriate for placement on the subaerial beach if it is sand or possibly gravel, and is found in areas of high energy. Testing protocols for contamination are set out in the Inland Testing Manual (USEPA and Corps, 1998). Sediment that is placed on the beach should contain only a small mud fraction, whereas sediment with a higher percentage of fines or smaller sand particle sizes may be appropriate for placement in the nearshore.

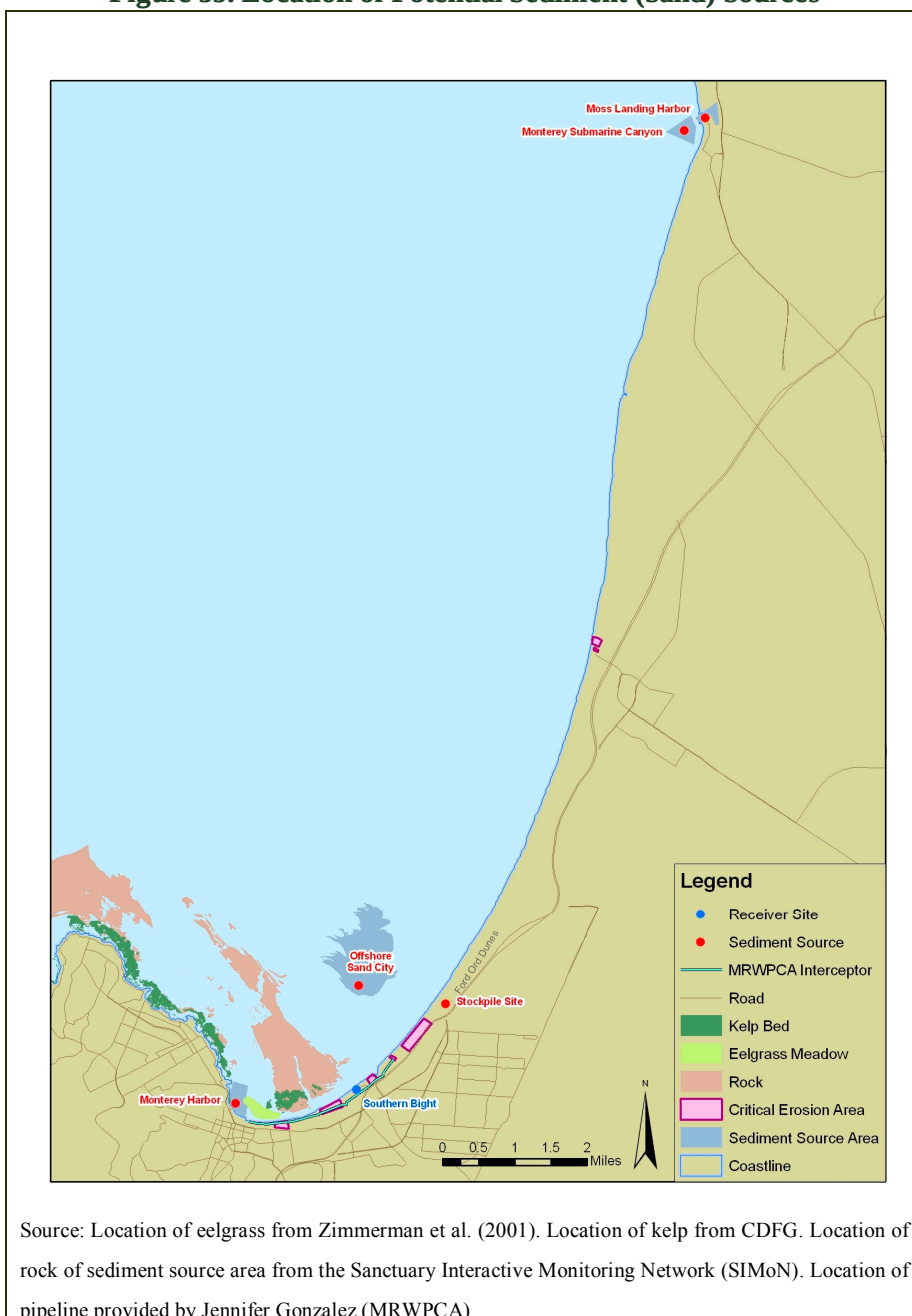
To evaluate source-receiver site particle size compatibility, it is important to determine two parameters; the littoral cell cut-off diameter (LCD) of the receiver site (Limber et al., 2008), and the particle size distribution of the source sediment compared to the composite particle size envelope of the receiver site (Moffatt and Nichol Engineers, 2006).

The LCD is the particle size diameter of the sediment below which it is generally removed from the beach to leave only the sediment with particle sizes greater than the cut-off diameter. The

LCD is strongly controlled by wave energy. Typically, fine-grained sand in the particle size range 0.063 to 0.125 mm does not remain on the exposed beaches of central California because they are high-energy wave environments. For potential beach nourishment projects the LCD is important because any sediment finer than the cut-off that is placed on the dry or subaerial beach would likely move offshore, driven by wave processes. However, finer sands could be placed in the nearshore, where they would support the overall receiver site profile.

Moffatt and Nichol Engineers (2006) recommended determination of a composite particle size envelope to characterize the surface sediment at the receiver site, bracketing the range of particle sizes, from the coarsest to finest fractions (LCD). They also recommended characterization of the wider littoral zone around the footprint of placement in order to understand how the sand may disperse once placed. If the sand gradation of the source falls within the receiver site composite particle size envelope, then the source and receiver sites are compatible with respect to particle size.

In this Coastal RSM Plan, available information was collated on the physical and chemical characteristics of the potential source sediments. The essential data include particle size, and chemical signatures (metals and other analytes). This is defined as a Tier I analysis in the SCoup (Moffatt and Nichol Engineers, 2006). From these data, provisional recommendations are made regarding the suitability of the source sediments for placement at the potential receiver site, which should then be carried forward into a more detailed Tier II analysis. Tier II analysis requires sampling and testing for particle size distribution, chemistry, and physical properties, at each of the source sites and the potential receiver site providing a definitive statement regarding the suitability of the source sediments for placement at the receiver site. The Tier I analysis carried out for this Coastal RSM Plan targets five potential sources of sand for beach nourishment, which are described in Sections 6.1 to 6.5 (Figure 35). These locations are also available as GIS data files in CSMWs GIS database.

Figure 35. Location of Potential Sediment (Sand) Sources

6.1 HARBORS AND WETLANDS

Three coastal harbors are situated in Monterey Bay: Santa Cruz, Moss Landing, and Monterey. Each harbor dredges sediment to keep their navigation channels and berths open for safe passage of commercial fishermen, recreational fishermen, and boaters. Moss Landing Harbor and Monterey Harbor are within the southern Monterey Bay littoral cell (Figure 35) and considered

potential opportunistic sources of sand. Santa Cruz Harbor was not considered further because it is within another littoral cell and the vast majority of the sand is being used to successfully nourish beaches immediately down coast in the same cell. No surplus sand would be available for nourishment of southern Monterey Bay beaches without negatively impacting Santa Cruz beaches. No wetlands with compatible sand for beach nourishment are identified in this Coastal RSM Plan.

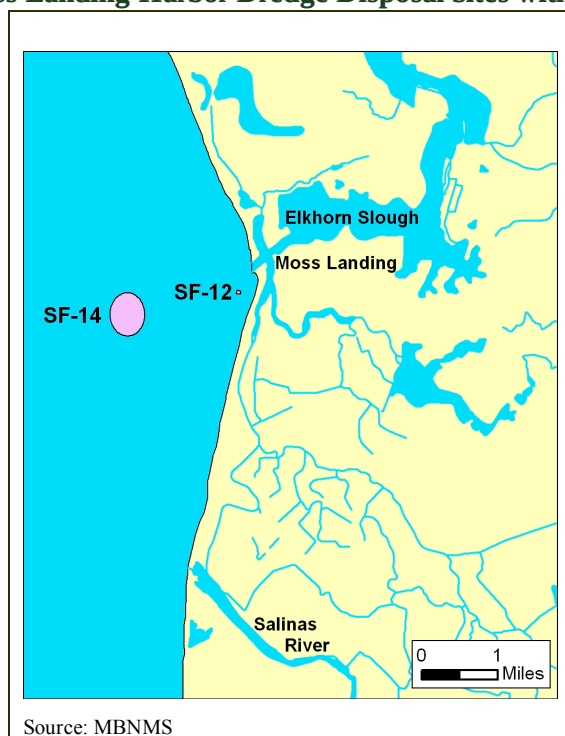
6.1.1 Moss Landing Harbor Entrance Channel

The U.S. Army Corps of Engineers and Moss Landing Harbor District have conducted maintenance dredging of Moss Landing Harbor (inset) since it opened in 1947. Sediment samples collected for the Environmental Assessment for maintenance dredging of the harbor in 2007 (Corps, 2007) showed that sediments in the entrance channel are greater than 90% (medium) sand and free of contaminants. Sediments further into the harbor are predominantly fine-grained



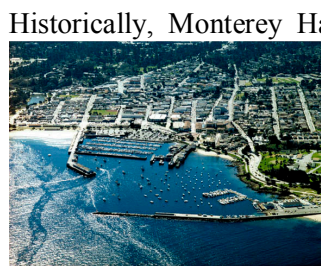
(83-98% silt and clay), approximately 90% of which were contaminant-free in 2007. The primary sediment contamination issue at Moss Landing is chemicals from erosion of agricultural soils in the watershed. Soil loss from the surrounding land results in sediment deposition on roads, drainage channels, and ultimately into the harbor. In addition, Moss Landing Harbor provides haven to over 600 vessels year round, some of which may dispose wastewater into the harbor, or be subject to minor accidental oil spills during routine maintenance. However, chemical testing by Corps (2007) for metals, pesticides (including DDT), and PAHs, showed that the majority of the samples were below the threshold limit for aquatic disposal suitability.

Uncontaminated dredged finer-grained sediments (greater than 20% mud) from Moss Landing Harbor are disposed at two offshore unconfined discharge sites (SF-12 and SF-14) within the boundaries of the MBNMS (Figure 36). When the dredged sediment contains less than 20% fines, it may be placed at a beach disposal site adjacent to the south jetty. Moss Landing Harbor has typically dredged approximately 50,000 yd³ of sediment every three years, although the present permit (California Coastal Commission Permit 3-01-049) allows up to 100,000 yd³/year to be removed. Sand in Moss Landing Harbor is not abundant (Corps, 2007) and if used for beach nourishment purposes in the southern bight, would need to be supplemented with sand from other sources.

Figure 36. Moss Landing Harbor Dredge Disposal Sites within the MBNMS

Given that the Moss Landing Harbor entrance channel sediments meet the Tier I particle size and contamination requirements, the main constraint on their use to nourish southern Monterey Bay beaches is that the sand is already placed on the beach adjacent to the harbor. With additional transportation costs, this sand could be placed elsewhere in the southern Monterey Bay littoral cell. Therefore, Moss Landing Harbor entrance channel has the potential to be a source of sand and is recommended as a target for more detailed Tier II compatibility analysis. It should be noted that Elkhorn Slough (adjacent to Moss Landing Harbor, Figure 36) is rapidly eroding and therefore may also be targeted for receipt of dredged sediments. In addition, placement of sand from Moss Landing Harbor in the southern bight would require modification of the MBNMS Harbors and Dredge Disposal Action Plan for permitting purposes (Section 8.1.1).

6.1.2 Monterey Harbor



Historically, Monterey Harbor (inset) has been dredged approximately every 7-8 years with removal of around 4,000-10,000 yd³ of sediment from the main channels. Most of the sediment has been placed either in shallow water immediately adjacent to Wharf II or on the beach above MHW (Steve Scheiblaue, Monterey Harbormaster, personal communication). Approximately 2,000-3,000 yd³ of the sediment was placed inland. In the future there is the possibility of a dredging

operation to remove up to 75,000 yd³ from the entire harbor basin. The intention would be a complete dredge of the berths and main channels to last for 40 years. Because of its complexity, particularly in obtaining permits to dispose of the sand, this dredging is unlikely to take place before 2010-2011.

Monterey Harbor is a potential source of sand for nourishment of the southern Monterey Bay beaches of Sand City, Seaside, and Monterey. The sediment infilling the harbor is locally derived from around the Coast Guard Pier breakwater, from three runoff outfalls within the harbor, and from an overflow runoff pipe just inside Wharf II. Little sand in the harbor appears to be derived from Del Monte Beach to the east. Monterey Harbor sediments may have potential for minor contamination including agricultural chemicals from runoff, and wastewater and oil discharge from vessel operations.

Sand from Monterey Harbor is not plentiful and would provide only a very small portion of the necessary volume to significantly nourish the southern bight, and would therefore need to be supplemented with sand from other sources. However, Monterey Harbor is recommended as a target for more detailed Tier II compatibility analysis. The AMBAG should coordinate with Monterey harbormaster about near-term dredging activities and the potential use of the sand for beach nourishment.

6.2 FLOOD CONTROL PROJECTS

6.2.1 Sediment Impounded by Dams

There are three dams along the main tributaries of the Salinas River that have sediment accumulated in the reservoirs behind them (Salinas, Nacimiento and San Antonio). Two more dams (San Clemente and Los Padres) are located along the nearby Carmel River but in a different watershed. None of the sediment bodies impounded behind these dams are considered potential sources of sand, for these reasons:



- the reservoirs on the Salinas River and behind Los Padres Dam contain sediment with a high percentage of mud, and so are unsuitable for beach nourishment purposes
- the Salinas Dam is approximately 120 miles from southern Monterey Bay, and the Nacimiento and San Antonio Dams are approximately 80 miles, so transportation of sand would be uneconomical
- although the particle size characteristics of the San Clemente Reservoir sediment may be compatible they are derived from granite rocks in a different watershed and would be unsuitable in terms of mineralogy and/or color (inset)
- although the San Clemente Dam is only 20 miles by road from southern Monterey Bay, it is remote, and access to the source sediment would be difficult, and transporting the sand by truck to southern Monterey Bay would be expensive (approximately \$20-\$30 per yd³).

This cost is approximately two to three times higher per yd³ than the most expensive offshore source (Section 7 provides results of economic analyses for offshore sources).

6.2.2 Salinas River Sand Bar Breaching

In order to prevent flood damage to the surrounding floodplain areas, Monterey County Water Resources Agency periodically removes part of the sand bar fronting the Salinas River mouth. A ten-foot wide notch is cut through the bar to allow water at high tide to pass over the bar and begin a process of scour which eventually creates a breach 150-200 feet wide. The notch is cut with an excavator which disposes the sediment adjacent to the notch. No sand is removed from the littoral cell during excavation and hence no new sand becomes available for nourishment purposes.

6.3 INLAND COMMERCIAL SITES

The SCoup Plan (Moffatt and Nichol Engineers, 2006) provides a generic list of potential inland sources of beach quality sediment, including:

- road and railway construction
- landslides
- quarries
- commercial and residential development.

Currently there are no future major roads or railway construction projects identified in proximity to southern Monterey Bay, and in general most of the sediments yielded through these construction activities would not be suitable for beach nourishment purposes. However, routes that cut through coastal terrain comprised of marine sedimentary deposits may yield beach-compatible sand. In addition, landslides wouldn't likely provide beach-compatible sand or in quantities large enough to consider. However, slides in uplifted marine deposits in coastal regions may prove to be possible sources. Quarried sand and gravel may provide appropriate sediments. Development activities, if conducted in marine terrace or dune fields, could also yield beach compatible sand. These sources would only become available opportunistically and possibly not at a time suitable for immediate use. Hence, the sediment would require relatively rapid identification and characterization to determine compatibility with receiver sites, and then stockpiled for future nourishment needs.

6.3.1 Stockpiling

In order to temporarily store beach-compatible sand from opportunistic inland sources (and potentially from offshore if the nourishment is phased) requires a stockpile site. This Coastal RSM Plan suggests two potential stockpile sites:

- Fort Ord where there are many acres of unused land (recommended, Figure 35)

- a large pit, approximately 600 feet by 450 feet by 90 feet deep, at the north end of Sand City.

For the Fort Ord option, the AMBAG would need to approach the Fort Ord Reuse Authority (FORA) and the County of Monterey to receive permission. The Fort Ord site is large, accessible, and local to the southern bight (the southern end of Fort Ord is adjacent to Sand City), and hence transportation by truck of the stockpiled sand along established routes (Highway 1 and access roads) to the placement area would be relatively straightforward.

The alternative location in north Sand City is between Highway 1 and the shoreline and is a former sand mining pit. This site could accommodate approximately 1,000,000 yd³ of sand.

Although no inland commercial sites with compatible sediments for beach nourishment are identified in this Coastal RSM Plan, it is recommended that the SCOUP process secures part of Fort Ord as a stockpile site where sediment can be stored and accumulated to the appropriate volumes for nourishment projects.

6.4 DUNES AT FORT ORD

There are over 40 square miles of sand dunes (inset) in southern Monterey Bay south of the Salinas River that extend inland as far as five miles at Fort Ord. The dunes north of the Salinas River are less extensive, narrower, and consist of several smaller complexes that total just under nine square miles. Thus, the total southern Monterey Bay dune area is about 50 square miles with 80% of this lying south of the Salinas River mouth (Cooper, 1967).

Although the particle size of the dunes is finer than the beach, the data suggest a potential 76% retention on the beach and shoreface of sediment eroded from the dune bluffs (Section 2.3.3). With over 40 square miles of sand dunes adjacent to the shoreline, derived originally from the beach, they are a large potential source of sand for nourishment of the southern Monterey Bay beaches (Figure 35). There are significant areas of dune sand within Fort Ord that have been disturbed, and do not contain endangered species, that would provide large quantities of compatible sand. Extraction of dune sand would need to be far enough inland of the dune edge so as not to remove sand that would otherwise supply the beaches through dune erosion over the next 50 years. The sand dunes within the Fort Ord complex are recommended as a target for more detailed Tier II compatibility analysis.



6.5 OFFSHORE LOCATIONS

Large volumes of sand exist offshore in southern Monterey Bay (Dorman, 1968; Combellick and Osborne, 1977; Reid et al., 2006; Smith et al., 2007). Offshore sand is a potential source that could be dredged and placed either on the beach or in the nearshore, where it can become part of the littoral cell. The main opportunities with offshore sources include relatively low cost, high placement rates on the receiver beach, and minimal disturbance onshore while the project is underway. One major constraint is that the offshore of southern Monterey Bay is part of the MBNMS, and dredging of the sand may be a complex issue due to a Sanctuary prohibition on alteration of the seabed. However, these activities can be permitted if it is determined that their impacts are neither significant nor long term (Section 8.1.1).

Textural analyses of the offshore surface sediments in southern Monterey Bay reveal major sandy environments based on particle size. The delineation of particle size variations in offshore zones is critical for identifying appropriate source sands for potential beach nourishment. The offshore sand environments of southern Monterey Bay that are potential sources include:

- Monterey Submarine Canyon
- a zone of sand offshore from Sand City
- a nearshore relict sand corridor

6.5.1 Monterey Submarine Canyon

The upper 2.5 miles of Monterey Submarine Canyon experiences both local deposition due to supply from adjacent littoral cells and erosion due to slope failure and landslides (Smith et al., 2007). Frequent episodes of sediment build-up and subsequent down-slope failure transport littoral sediments from the Canyon rim to deeper in the Canyon, where sediment is stored. Hence, the upper Canyon is a temporary storage site for sand.

A study is being undertaken by the U.S. Army Corps of Engineers to examine the feasibility of capturing littoral sediments adjacent to canyons (Moffatt and Nichol Engineers, 2008). Of all the canyons along the California coast, the two identified with the most potential were Monterey and Mugu Canyons. Monterey Submarine Canyon meets three important criteria used in the analysis:

- it meets the minimum critical capture rate of greater than 10,000 yd³/year, determined to be economically worth pursuing
- the location of the sand to be captured is relatively near a critical coastal erosion area as identified by CSMW (southern Monterey Bay)
- there is an additional benefit that the nearby and eroding Elkhorn Slough, a federal reserve, is in need of sediment.

Several means to recover sediment from Monterey Submarine Canyon were considered in the feasibility study. First, the sand that has already been lost down the Canyon could be extracted. Second, it may be possible to intercept the sediment as it moves towards the Canyon head and redirect it back into the littoral system. Several interception alternatives were considered by Moffatt and Nichol Engineers (2008):

- use the Moss Landing north jetty to intercept sediments with an array of stationary jet pumps attached to the breakwater
- a jet pump on a moveable crane on the Moss Landing breakwater
- an offshore breakwater on the south side of the Canyon to impound sediments and provide shelter for a dredge
- use a hopper dredge to create an offshore pit south of the Canyon to serve as a sand trap for future extraction of sand.

The offshore pit approach was suggested to have the least environmental impact with the best benefit-cost ratio for providing sand that could be used for beach nourishment in the southern bight. Identifying an appropriate offshore pit location closer to the critical erosion areas, between the Salinas River Mouth and the Canyon head, could reduce transport costs.

Monterey Submarine Canyon is a large potential source of sand for nourishment of the southern Monterey Bay beaches. Given the proximity of the Canyon head to the nearshore zone (Figure 3), sediment in its vicinity should match the sediment characteristics of the adjacent littoral cell, and be a suitable source with respect to particle size and chemistry. The volumes available are probably sufficient to nourish all the critical erosion areas of Sand City, Seaside, and Monterey. The Monterey Submarine Canyon is recommended as a target for more detailed Tier II compatibility analysis.

6.5.2 Zone of Sand Offshore from Sand City

The possibility that sand is moving offshore from a probable alongshore convergence zone in the vicinity of Sand City (Section 2.2.3) should be investigated in more detail. This repository for sediment could be a potential zone for obtaining sand for beach nourishment purposes. Dorman (1968) and Combellick and Osborne (1977) showed the offshore zone to be comprised of medium sand (particle size 0.25-0.5 mm) (Figure 15). Reid et al. (2006) compiled particle size data for the Pacific coast including southern Monterey Bay. Their data offshore from the southern bight shows a grouping of surface samples in the 0.3 to 0.5 mm mean/median particle size range (medium sand) in a similar location to the medium sand zone of Dorman (1968) and Combellick and Osborne (1977). Particle size data from the offshore zone is presented in Table 15 (Reid et al., 2006).

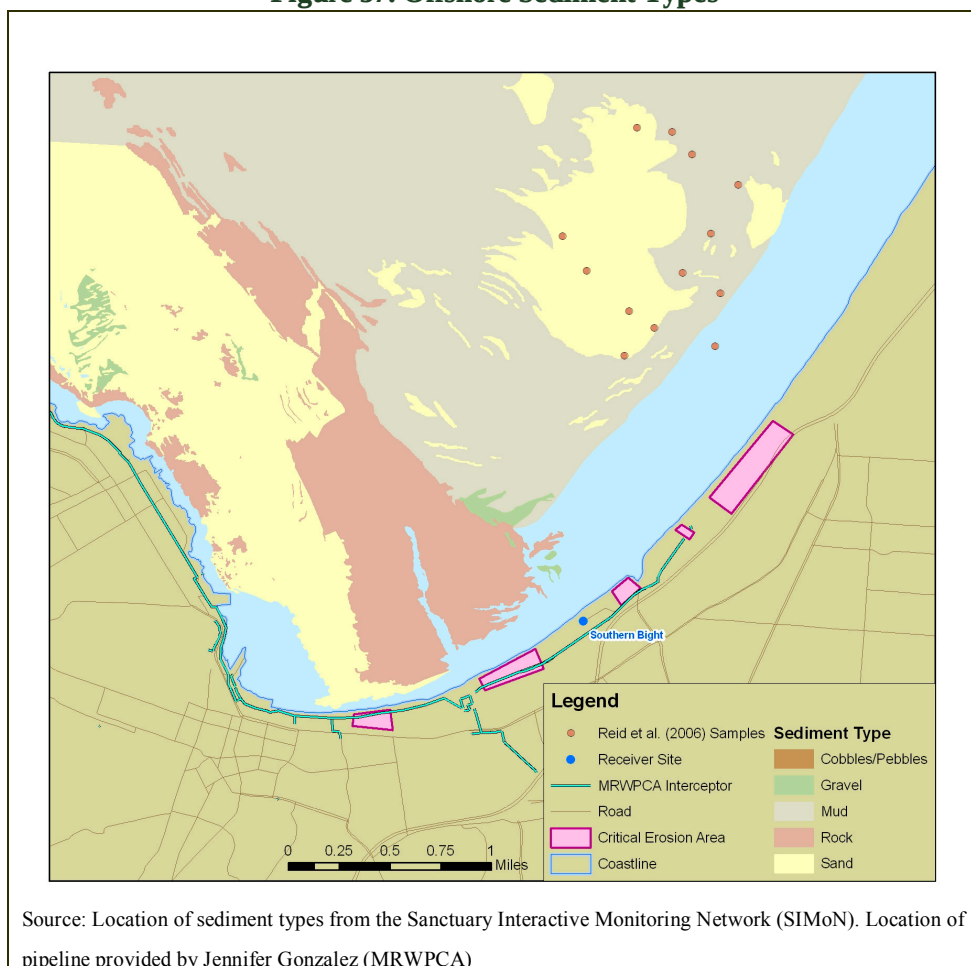
Table 15. Particle Size of Sand Offshore from Sand City (Reid et al., 2006)

Latitude ¹	Longitude ¹	% sand	Particle size ² (mm)
36.64240	121.85500	100	0.38
36.64040	121.85080	100	0.31
36.63683	121.85300	100	0.27
36.63610	121.86610	99	0.31
36.63370	121.86380	100	0.35
36.62780	121.86010	100	0.31
36.63100	121.85990	100	0.33
36.64410	121.86000	99	0.50
36.64390	121.85690	100	0.33
36.63390	121.85530	100	0.47
36.63260	121.85190	100	0.47
36.62880	121.85210	100	0.33
36.62990	121.85760	100	0.33

¹Location of samples is shown on Figure 37.

²Particle size reported as either mean or median.

Data compiled by the NOAAs National Coastal Data Development Center presented as part of the Sanctuary Interactive Monitoring Network (SIMoN) interactive map series also shows a large patch of sand in a similar location to the Combellick and Osborne (1977) and Reid et al. (2006) data sets (Figure 37). The locations of sediment samples taken by Reid et al. (2006) are also shown on Figure 37.

Figure 37. Offshore Sediment Types

The particle size of these offshore sands appears compatible with the southern Monterey Bay beach sands and therefore they are a potential source of sand for beach nourishment. The zone of sand offshore from Sand City is therefore recommended as a target for more detailed Tier II compatibility analysis.

6.5.3 Nearshore Relict Sand Corridor

Relict medium to coarse sand occurs on the inner shelf of southern Monterey Bay as irregularly shaped depressions, approximately three feet deep out to water depths of 200 feet. In shallower water depths of 30-60 feet, these medium-coarse sand trend parallel to the shoreline as bands 60-300 feet wide, alternating with bands of fine-medium sand that are of similar width (Hunter et al., 1988). The medium-coarse sands have a mean particle size of 0.35-1.0 mm, and the fine-medium sands have a mean particle size of 0.125-0.35 mm. Further offshore, patches of the medium-coarse sand are exposed through an overlying mud layer. The source of the sand may be a pre-Flandrian transgressive lag deposit underlying much of the shelf (Chin et al., 1988). It would

appear that these coarse sands do not move onshore and contribute to the sand budget, so they may be a potential source of sand for beach nourishment.

6.6 SEDIMENT (SAND) SOURCE SHORT-LIST

The Tier I screening of potential sand sources for beach nourishment did not identify any suitable opportunistic inland sources. A regional stockpile area somewhere on Fort Ord close to the southern bight is recommended to allow accumulation of appropriate sediment of opportunity to a volume sufficient for a nourishment project, should it become available. The dunes at Fort Ord may themselves provide a suitable source. Of the three harbors in Monterey Bay, Moss Landing Harbor entrance channel and Monterey Harbor contain sand that could potentially be beneficially reused. Potential offshore sand sources include the area between the Salinas river mouth and head region of Monterey Submarine Canyon, and the shelf offshore of the transport convergence zone at Sand City.

In this Coastal RSM Plan, five potential sources of sand are recommended and prioritized for more detailed Tier II compatibility studies.

- **Shelf offshore from Sand City**
- **Sediment captured before entering Monterey Submarine Canyon**
- **Fort Ord dune field**
- **Monterey Harbor**
- **Moss Landing Harbor entrance channel**

All of the potential sand sources for nourishment of the beaches in southern Monterey Bay are in coastal and nearshore locations. It is anticipated that the feasibility of using sand sources from much further inland to nourish the southern Monterey Bay shoreline may change. Feasibility may increase due to increased value of sand for nourishment if future erosion is large enough. Consequently, the feasibility assessments in this Coastal RSM Plan should be updated, as appropriate, in the future.

6.7 ENVIRONMENTAL IMPACTS AT POTENTIAL SOURCE AREAS

Dredging in subtidal sandy habitats to obtain sand for beach nourishment disturbs and removes benthic habitat and results in elevated turbidity (NRC, 1995; Green, 2002) with potential impacts to invertebrates and fish in nearshore and offshore environments. Borrow site dredging removes sediment and associated benthic organisms and has the potential to entrain organisms as a result of near-bottom water being withdrawn by suction dredgers. Generally, complete mortality is assumed for dredge-removed and/or entrained organisms, although a small percentage may survive depending on discharge location (LaSalle et al., 1991).

Recovery of benthic communities following borrow site dredging varies depending on sediment infill rates, hydrodynamics, and dredging method, but can be protracted (SAIC, 2008). In Monterey Bay, Oliver and Slattery (1976) found that dredging in channel areas removed 60% of the benthic animals. Abundance remained low 1.5 years after dredging, but indices of species diversity and evenness were higher than before dredging. They suggested that the timing of dredging in relation to the reproductive cycles and distributive abilities of the benthic organisms in the area affects recovery.

6.7.1 Mitigation Measures

Recovery of benthos may be facilitated by shallow dredging over a larger area rather than creation of deep pits covering a limited area. Dredging shifting sands rather than more stable bottoms, retaining similar surface sediment type, and leaving undisturbed areas within the larger dredged area may also reduce disturbance (Thompson, 1973; Oliver and Slattery, 1976; Hurme and Pullen, 1988; Diaz et al., 2004).

7. ECONOMIC FEASIBILITY OF BEACH NOURISHMENT

7.1 POTENTIAL BEACH NOURISHMENT ALTERNATIVES

This Coastal RSM Plan describes two potential alternatives for nourishment of the southern bight beaches (Table 16):

- Alternative 1: small-scale nourishment using Monterey Harbor as a sand source
- Alternative 2: large-scale nourishment using offshore sand sources.

Alternative 1 considers the use of opportunistic sand sources from Monterey Harbor to nourish the shoreline of Sand City, Seaside, and Monterey. Approximately 75,000 yd³ of sand may become available from dredging of the harbor for placement on the beach (Section 6.1.2). Sand would be placed at a location (or locations) away from the rocky reef, kelp forest and eelgrass meadow (if still present) and be allowed to spread along the shoreline through sediment transport processes (this Coastal RSM Plan recommends a receiver site between Monterey Beach Resort and Ocean Harbor House condominiums, Figure 32). For the purposes of estimating the economic benefits of the nourishment (using a volume of 1.7 yd³ of sediment to nourish one square foot of beach), the increase in beach width along three miles of the southern bight would be approximately three feet.

Alternative 2 is a scenario in which large-scale extraction of sand from offshore sources (offshore Sand City or Monterey Submarine Canyon head) is placed in the southern bight, either as a nearshore or beach placement. Sand would be extracted and transported using a hopper dredge, and be placed at one or more locations (a recommended site is between Monterey Beach Resort and Ocean Harbor House condominiums) in the southern bight away from sensitive habitat. To increase the width of a three-mile equilibrium beach by 75 feet would require approximately two million yd³ of sand.

Two methods of sand placement are considered for Alternative 2; subaerial placement (directly onto the beach); and nearshore placement (in the surf zone). Placement onto the beach creates a wider beach more quickly but is relatively expensive as additional equipment and time is required to move the sand onshore. Nearshore placement simply involves depositing the sand on the seabed as close to shore as feasible, which then takes longer to be worked onto the beach (by wave action). The relative merits of these approaches are further described in Section 5.1. Alternatives using Fort Ord sand dunes or the stockpile site as potential sources are not tested in this Coastal RSM Plan.

Table 16. Potential Beach Nourishment Alternatives for Southern Monterey Bay

Alternative		Receiver Site	Shore Length (miles)	Equilibrium Width (feet)	Required Volume (yd³)	Source Site	Excavation / Dredge Method	Transport Method	Placement Method
1a	Southern	South Sub-cell	3	3	75,000	Monterey Harbor Opportunistic	Hopper Dredge	Hopper	Hydraulic Discharge to Beach
b	Bight Small								Place in nearshore
2a	Southern Bight Large			75	2,000,000	Offshore Sand City			Hydraulic Discharge to Beach
b						Place in nearshore			
c				Canyon Head	Hydraulic Discharge to Beach				
d					Place in nearshore				

7.2 APPROACH TO ECONOMIC ANALYSIS

At this regional scale of analysis the intention is not to determine exact costs and benefits for funding and approval purposes, but to determine the likely economic viability of proposed alternatives. If it can be determined that an alternative is likely to have a benefit to cost ratio robustly greater than 1 (i.e. benefits are greater than costs) then it can be considered viable and appropriate for further investigation and development, as part of the regional planning process.

Costs for the beach nourishment alternatives and recreational benefits of the nourishment have been calculated using a decision support tool developed for CSMW. Benefits associated with prevention of erosion, and hence protection of coastal assets, have been calculated using property values provided by the Monterey County Property Assessor and the Monterey Regional Water Pollution Control Agency (MRWPCA).

The analysis has been carried with the assumption that no future actions, such as constructing new or replacement seawalls or other structures, take place and, furthermore, that existing structures will become ineffective in the absence of additional sand nourishment to protect them beyond their design lives. The assessment of economic benefits is for beach nourishment alone and is not a full analysis of shore protection options. The U.S. Army Corps of Engineers may engage in a more rigorous benefit-cost analysis if/when they conduct a feasibility study for potential beach nourishment projects and will likely determine different benefit-cost ratios for potential projects as a result.

7.2.1 Application of the Coastal Sediment Benefits Analysis Tool

The benefit-cost analysis for beach nourishment in this Coastal RSM Plan uses the Coastal Sediment Benefits Analysis Tool (CSBAT) developed by CSMW (Corps, 2008). The tool is populated with data from southern Monterey Bay to investigate the economics of the small-scale and large-scale alternatives summarized Table 16.

CSBAT was originally developed for use in San Diego County, and the southern Monterey Bay application represents the first outside San Diego. The tool focuses principally on the value of recreational benefits arising from beach nourishment. Consequently, it uses a range of data on both the physical attributes of the source and receiver sites and the economic value of beach visitors.

Where possible, data specific to southern Monterey Bay has been obtained and used in the analysis; however there has been limited study of the economics of beach use in this area, so average and pro-rated values from the San Diego application have been used for many of the attributes. This application of analogous data (from another site within the state) in the absence of locally specific data is considered valid for a regional planning assessment such as this, where it is necessary to determine the likely viability of beach nourishment alternatives. Details of the input data used to run CSBAT and the full outputs are provided in Appendix C. The data provided in Appendix C only considers recreational benefits calculated by the CSBAT tool. The data does not include the benefits provided by beach nourishment to the protection of built assets.

The CSBAT tool allows the user to appraise various beach nourishment alternatives through different combinations of sediment source location, receiver site location, volume of sediment, and mode/s of transportation. Using background attribute data such as unit costs, beach visitor numbers, and other parameters, the tool produces reports containing information such as baseline data on the sites, estimated beach nourishment costs, change in recreational benefits, projected increases in spending and tax value, potential environmental impacts, estimated change in beach width, and cumulative cost/benefits using various transportation routes and scenarios.

The calculation of economic benefits within CSBAT is based on potential changes in the amenity/recreation value of the beach. These benefits are derived from increased visitor numbers due to increased capacity on the wider (post-nourishment) beach, the associated increased visitor spend, increased taxation on that spend, and increased recreational ‘value’ (economic equivalent of the recreational benefit) derived by visitors because of a wider beach. The increase in economic benefit caused by increase in visitor numbers is calculated using King (2001), where visitor surveys at a number of southern California beaches showed that in general respondents preferred wider beaches and would attend wider beaches more often. From the results of King (2001) and the analyses for the San Diego application of CSBAT, it was concluded that doubling beach width would increase attendance by 2.5% and recreational value (per visitor) by 18%. This is an underlying assumption in the CSBAT analysis.

The tool can calculate changes in beach width and hence visitor numbers and recreational benefits for up to a 20 year period from the original beach nourishment. Over time the placed sand spreads laterally along the shoreline, and this process combined with ongoing erosion gradually reduces the width of the beach and hence the additional recreational benefits provided by the nourishment. The tool considers that a 20-year period is a reasonable maximum duration of the positive affect of the nourishment on beach widths.

One of the most important benefit inputs for the CSBAT analysis is beach visitor numbers. Table 17 presents observed visitor numbers from 1995 to 2007 for Monterey State Beach in the southern bight. They show a large degree of fluctuation from year to year, with lower numbers in the early part of the record rising to peaks in excess of one million visitors (2002) before settling to a more consistent level in recent years. CSBAT uses an average annual attendance figure for benefit estimates, so in order to define a value relevant to current beach usage, an average from the last five years has been used. Using the 2002-2007 data avoids the large fluctuations in the earlier years, and is more representative of the present day beach use. The average visitor numbers used in the CSBAT analysis are 644,677 for Monterey State Beach.

Table 17. Annual Visitor Numbers for Monterey State Beach

Year	Number of Visitors
1995	107,946
1996	131,340
1997	251,994
1998	258,771
1999	919,104
2000	457,161
2001	493,170
2002	1,259,688
2003	841,461
2004	834,850
2005	598,204
2006	534,322
2007	414,548
Mean Last 5 Years	644,677

On the costs side of the analysis, generic cost rates defined for the San Diego application of CSBAT are used. It is recognized that the actual cost rates in southern Monterey Bay may be different from those in southern California; however it is considered appropriate to use these rates for this regional plan, as they are adequate to assess the overall economic viability of the nourishment alternatives.

7.2.2 Estimation of Protection Benefits

The CSBAT tool does not calculate the economic benefits arising from the protection of infrastructure and built assets. However, beach nourishment projects not only provide wider amenity beaches, but also slow the rate of beach/dune erosion. Nourishment projects prevent the loss of assets located within areas vulnerable to erosion and depending on the nature and location of coastal development and infrastructure, this can be a major contributor to the overall benefits.

Values for the majority of assets (facilities) at risk of erosion (Section 3) were obtained from the records of the Monterey County Property Assessor. The data provided locations of all property parcels together with value data for all taxable properties. GIS mapping of parcel locations is linked to a database with various property details, of which land value, improvement value (buildings/structures), and land use code, were used in this analysis.

The land and improvement values are summed to create a total asset value for the purposes of the erosion analysis. Where the land use code indicated that the asset was publicly owned no values were provided as they are not taxable uses. Several of the most important built assets are the Monterey Interceptor pipeline and the pump stations associated with the pipeline. Estimates of the replacement value of this infrastructure were obtained from MRWPCA. Approximately five years ago MRWPCA undertook an analysis of the Salinas Interceptor and concluded that a replacement cost of \$600-700 per linear foot would be appropriate for that 36 inch-diameter pipeline. The Monterey Interceptor is 24 inches in diameter and in larger sections, and it was recommended that \$600/foot be used for replacement, taking into account local ground conditions, access and property issues (Jennifer Gonzales, MRWPCA, personal communication). In addition, an estimated replacement cost of \$75 million was recommended for Seaside Pump Station. The recreational benefits of increasing the width of the public beach under which the privately-owned pipeline is located are considered using the CSBAT tool (Sections 7.2.1 and 7.4.1).

Beach nourishment generally has a finite life and only acts to delay the erosion process. Consequently, the true value of the protection benefit is the value of the delay in loss of an asset. The process of evaluating this delay requires the definition of likely time scales for loss due to erosion with and without nourishment, then application of a discount rate to determine the present value of that benefit. The potential timescale until loss of facilities without any beach nourishment are provided in Section 3.3. It was then assumed that nourishment using 2,000,000 yd³ of sand would delay the onset of erosion by 20 years (to be consistent with the time period

considered in the recreation benefits analysis, Section 7.3.2). Discounted values for the loss of the asset (using a 5% discount rate) with and without nourishment were then calculated and the difference between those values is the benefit of the delay. A three-year delay was considered for the 75,000 yd³ nourishment alternative. It was assumed that the delay in erosion would be the same regardless of whether sand was placed on the beach or in the nearshore (even though the dry beach area is less for nearshore placement). The discounting process is described in Appendix C.

7.3 COSTS

Tables 18 and 19 show the costs associated with the potential beach nourishment alternatives.

Table 18. Small-Scale Nourishment of the Southern Bight (Alternative 1)

Cost Component	1a. Beach	1b. Nearshore
Sand Volume (yd ³)	75,000	75,000
Transport Distance (miles)	2.53	2.53
Total Trips	28	28
Construction Period (days)	6	5
Total Transport Cost (\$ x 1,000)	432	194
Mob/Demob. (\$ x 1,000)	600	500
Cost per Yard (\$ x 1,000)	14	9
Total Beach Nourishment Cost (\$ x 1,000)	1,032	694

Table 19. Large-Scale Nourishment of the Southern Bight (Alternative 2)

Cost Component	2a. Sand City Beach	2b. Sand City Nearshore	2c. Canyon Head Beach	2d. Canyon Head Nearshore
Sand Volume (yd ³)	2,000,000	2,000,000	2,000,000	2,000,000
Transport Distance (miles)	1.81	1.81	15.33	15.33
Total Trips	741	741	741	741
Construction Period (days)	151	118	309	265
Total Transport Cost (\$ x 10 ⁶)	11.04	4.83	19.75	10.87
Mob/Demobilization (\$ x 10 ⁶)	0.6	0.5	0.6	0.5
Cost per Yard (\$)	6	3	10	6

Cost Component	2a. Sand City Beach	2b. Sand City Nearshore	2c. Canyon Head Beach	2d. Canyon Head Nearshore
Total Nourishment Cost (\$ x 10⁶)	11.64	5.33	20.35	11.37

The results show that placing sand directly on the beach is substantially more expensive than placing sand in the nearshore. This is to be expected due to the significant increase in effort and equipment required to undertake the beach placement.

7.4 BENEFITS

7.4.1 Recreational Benefits

The benefits generated by CSBAT provide an estimate of the economic value of the improved recreational amenity of southern Monterey Bay beaches. Tables 20-23 present the benefits calculated by CSBAT for the two alternatives. For each alternative, the dollar value of the increase in recreational benefit is calculated in three parts, based on the increased beach width providing for increased visitor numbers and an increased recreational benefit value for all visitors. The parameters presented are:

- beach width increase: this varies dependant on the location of sand placement (subaerial-beach or nearshore) and is used to determine the increase in beach visitors
- increase in state and local spending: the increased spend resultant from more visitors
- increase in state and local taxes: income based on spending
- increase in recreational value: reflects the increased value derived by visitors from a wider beach, plus the increased visitor numbers
- total increase in recreational benefit: the discounted total of the three benefits increases over 20 years (note only the first ten years are presented in Tables 20 through 23).

Table 20. Recreational Benefits of Small-Scale Nourishment of the Southern Bight with Beach Placement (Alternative 1a)

Year	Increases in:			
	Beach Width (ft)	State and Local Spending (\$)	State and Local Taxes (\$)	Recreational Value (\$)
Year-1	3.75	11,243	1,293	38,329
Year-2	0.3	899	103	2,940
Year-3	0.0	0.0	0.0	0.0
Year-4	0.0	0.0	0.0	0.0
Year-5	0.0	0.0	0.0	0.0
Year-6	0.0	0.0	0.0	0.0
Year-7	0.0	0.0	0.0	0.0
Year-8	0.0	0.0	0.0	0.0
Year-9	0.0	0.0	0.0	0.0
Year-10	0.0	0.0	0.0	0.0
Total Increase in Recreational Benefit (\$)		54,995		

Table 21. Recreational Benefits of Small-Scale Nourishment of the Southern Bight with Nearshore Placement (Alternative 1b)

Year	Increases in:			
	Beach Width (ft)	State and Local Spending (\$)	State and Local Taxes (\$)	Recreational Value (\$)
Year-1	0.0	0.0	0.0	0.0
Year-2	0.6	1,799	207	5,877
Year-3	0.98	2,923	336	9,088
Year-4	1.09	3,261	375	9,652
Year-5	0.0	0.0	0.0	0.0
Year-6	0.0	0.0	0.0	0.0
Year-7	0.0	0.0	0.0	0.0
Year-8	0.0	0.0	0.0	0.0
Year-9	0.0	0.0	0.0	0.0
Year-10	0.0	0.0	0.0	0.0
Total Increase in Recreational Benefit (\$)		36,264		

Table 22. Recreational Benefits of Large-Scale Nourishment of the Southern Bight with Beach Placement (Alternatives 2a and 2c)

Year	Increase in:			
	Beach Width (ft)	State and Local Spending (\$)	State and Local Taxes (\$)	Recreational Value (\$)
Year-0	100.0	299,818	34,479	880,495
Year-1	77.76	233,136	26,811	671,330
Year-2	69.15	207,325	23,842	575,432
Year-3	62.84	188,413	21,668	502,571
Year-4	57.94	173,728	19,979	444,523
Year-5	54.01	161,928	18,622	396,936
Year-6	50.56	151,585	17,432	355,752
Year-7	47.11	141,241	16,243	317,382
Year-8	43.66	130,897	15,053	281,655
Year-9	40.21	120,553	13,864	248,411
Year-10	36.76	110,210	12,674	217,498
Total Increase in Recreational Benefit (\$)		8,067,127		

Table 23. Recreational Benefits of Large-Scale Nourishment of the Southern Bight with Nearshore Placement (Alternatives 2b and 2d)

Year	Increase in:			
	Beach Width (ft)	State and Local Spending (\$)	State and Local Taxes (\$)	Recreational Value (\$)
Year-0	0.0	0.0	0.0	0.0
Year-1	16.0	47,971	5,517	152,212
Year-2	26.0	77,953	8,965	231,435
Year-3	29.0	86,947	9,999	244,587
Year-4	15.0	44,973	5,172	123,493
Year-5	11.55	34,629	3,982	91,138
Year-6	8.1	24,285	2,793	61,267
Year-7	4.65	13,942	1,603	33,718
Year-8	1.2	3,599	414	8,343
Year-9	0.0	0.0	0.0	0.0
Year-10	0.0	0.0	0.0	0.0
Total Increase in Recreational Benefit (\$)		1,479,160		

The increased recreational benefits where sand is placed directly on the beach (Table 22) are significantly greater than those for nearshore placement (Table 23). This is because the maximum beach width increase is realized in the first year, and, more importantly, because the overall beach width increase is much greater and lasts longer (as dispersion gradually reduces the beach width over time).

7.4.2 Property Protection Benefits

The protection of built assets from long-term erosion would be a tangible benefit of the beach nourishment proposals. Table 24 estimates the economic value of the assets at risk of erosion along the southern Monterey Bay shoreline (Figure 22) together with an estimate of when they would be lost to erosion without beach nourishment, and when the delayed loss would occur if nourishment was undertaken.

Table 24. Assets Protected by Beach Nourishment

Asset	Land Value (\$M)	Buildings/Facility Value (\$M)	Total Value (\$M)	Approx. Year of Loss		Value of Delay in Erosion (\$M)
				No Project	With 2M yd³ Fill	
Monterey Interceptor (8,600 foot from Wharf II to Monterey Pump Station)	5.16			20	40	1.21
Monterey Interceptor (1,750 foot section south from Seaside Pump Station)	\$76.05M (includes \$75 million for replacement of Seaside Pump Station)			40	60	6.73
Monterey Beach Resort	5.06	13.00	18.04	50	70	4.24
Ocean Harbor House Condominiums	15.93	19.39	35.32	50	70	1.92
La Playa Town Homes	4.78	6.33	11.10	20 (ongoing)	40 (ongoing)	1.45

Note: M = million

Table 24 demonstrates the high value of the oceanfront facilities and properties in southern Monterey Bay, particularly in the southern bight. In addition to the value of the assets, their loss would have significant secondary impacts such as disruption to wastewater facilities for the cities of Pacific Grove and Monterey, as well as major environmental consequences, if the Monterey Interceptor was breached; and impacts to the local tourist economy if oceanfront resorts were lost.

In order to appropriately represent the likely nature of erosion losses at the facilities identified in Table 24, assumptions were made regarding the progression of loss:

- Given its proximity to the shoreline, an 8,600 foot section of the Monterey Interceptor pipeline is considered to be at risk between Monterey Harbor and Monterey Pump Station. Elsewhere the pipeline is sufficiently set back from the shoreline, except near

Seaside Pump Station, where the Station itself and a 1,750 foot section of the pipeline are considered at long-term 50-year risk.

- The existing seawall at Monterey Beach Resort (constructed in 1968) is due to be replaced by a new seawall which has been approved for construction. It is assumed that this new seawall will have a 50-year life and completed in 2008, after which erosion of the property would begin.
- For Ocean Harbor House condominiums it is assumed that the seawall that is due to be constructed will have a 50-year life, after which erosion of the property would be immediate as the fronting beach would be lost and the property outflanked by erosion.
- Twenty six property parcels are identified as being at risk in the Monterey La Playa town homes development. It is assumed that the first losses occur in year 20, with 25% of the at-risk parcels lost every ten years thereafter.

Using the discounting process described in Appendix C the economic benefits of delaying erosion of these assets through beach nourishment with 75,000 yd³ or two million yd³ are calculated (Table 25). The table demonstrates that the erosion delay benefits of the proposed beach nourishment projects could be significant.

Table 25. Assets Protected Benefits

Asset	Land Value (\$M)	Year of Loss			Discounted Value of Asset Loss (\$M)			Benefit of Project (\$M)	
		No Project	75,000 yd ³ Fill	2M yd ³ fill	No Project	75,000 yd ³ Fill	2M yd ³ fill	No Project	With 2M yd ³ fill
Monterey Interceptor (8,600 foot section)	5.16	20	23	40	1.94	1.68	0.73	0.26	1.21
Monterey Interceptor (1,750 foot section plus Seaside Pump Station)	76.05	40	43	60	10.80	9.33	4.07	1.47	6.73
Monterey Beach Resort	18.04	50	53	70	1.57	1.36	0.59	0.21	0.98
Ocean Harbor House Condominiums	35.32	50	53	70	3.08	2.66	1.16	0.42	1.92
La Playa Street Town Homes (assume 25% lost in ten year intervals)	2.78	20	23	40	1.05	0.90	0.39	0.14	0.65
	2.77	30	33	50	0.64	0.55	0.24	0.09	0.40
	2.78	40	43	60	0.39	0.34	0.15	0.05	0.25
	2.77	50	53	70	0.24	0.21	0.09	0.03	0.15
TOTALS	145.67				19.73	17.04	7.43	2.69	12.29

Note: M = million

7.4.3 Ecologic Protection Benefits

Reduction of beach widths associated with seawall construction may result in severe ecologic degradation (Dugan et al., 2008). If beach nourishment is not implemented it is possible that armoring would be installed to protect development. Therefore, beach nourishment would maintain ecology closer to existing conditions. This benefit has not been quantified in this Coastal RSM Plan.

7.5 ECONOMIC VIABILITY OF ALTERNATIVES

Sections 7.1 to 7.3 present the costs and benefits of beach nourishment alternatives in the southern bight of southern Monterey Bay. This section combines these aspects to review the economic viability of the alternatives.

7.5.1 Alternative 1: Small-Scale Nourishment of the Southern Bight

Table 26 presents a summary of the costs and benefits for Alternative 1, the placement of 75,000 yd³ of sand from Monterey Harbor directly on to the beaches of the southern bight.

Table 26. Economic Summary of Alternative 1

Scenario	Total Cost (\$M)	Increase in Recreational Benefits (\$M)	Property Protection Benefits (\$M)	Total Benefits (\$M)	Net Benefits(\$M)	Benefit/Cost Ratio
Beach Placement	1.03	0.05	2.69	2.74	1.71	2.66
Nearshore Placement	0.69	0.04	2.69	2.72	2.03	3.93

Note: M = million

The data demonstrates that there is a clear economic justification to placing sand from Monterey Harbor on to the adjacent shoreline. It is notable that placing this relatively small volume of sand onto this frontage has little benefit in terms of increasing the beach for amenity purposes, and it is the benefits in delaying erosion that provide the justification.

7.5.2 Alternative 2: Large-Scale Nourishment of the Southern Bight

Table 27 presents a summary of the costs and benefits for Alternative 2, the nourishment of the southern bight with 2,000,000 yd³ of sand from two potential offshore sources. Both subaerial-beach and nearshore placement are considered.

Table 27. Economic Summary of Alternative 2

Scenario	Total Cost (\$M)	Increase in Recreational Benefits (\$M)	Property Protection Benefits (\$M)	Total Benefits (\$M)	Net Benefits (\$M)	Benefit/Cost Ratio
Offshore Sand City source to beach	11.64	8.07	12.29	20.36	8.71	1.75
Offshore Sand City source to nearshore	5.33	1.48	12.29	13.77	8.44	2.58
Canyon head source to beach	20.35	8.07	12.29	20.36	0.01	1.00
Canyon head source to nearshore	11.37	1.48	12.29	13.77	2.40	1.21

The economic summary for beach nourishment Alternative 2 demonstrates economic viability. All variants of this alternative have a positive benefit-cost ratio, with the Sand City offshore source proving most cost-effective due to its proximity to the southern bight beaches.

Table 19 shows that the costs of placing sand on the beach are greater than placing in the nearshore; however beach placement also delivers a greater recreational benefit. Considering the benefit-cost ratios (Table 27), the nearshore placement option from offshore Sand City appears most attractive (ratio of 2.58). However, the incremental benefit of placing the sand directly on the beach is greater than one (i.e. the additional cost to place the sand on the beach is \$6.2 million (Table 19) and the additional recreational benefits are \$6.6 million, Table 27), suggesting the additional investment is economically worthwhile. This is supported by the Sand City source to beach placement alternative having the highest net benefit at \$8.71 million.

The results of the economic analysis indicate that there is clear economic justification for undertaking beach nourishment in the southern bight of southern Monterey Bay. Although this analysis does not guarantee funding for these alternatives (Section 9), it has shown that beach nourishment in southern Monterey Bay would deliver net economic benefits to the region.

8. REGULATORY PROCESSES

The Beach Restoration Regulatory Guide (BRRG) (EIC, 2006) details federal and state regulatory processes for implementation of beach nourishment projects in California. The document describes the relevant regulatory requirements and the agencies responsible for administering permits, and should be consulted for California-wide federal and state regulatory processes that are relevant to southern Monterey Bay. However, several regulatory organizations administered by federal or state entities have jurisdiction that is specific to the Monterey Bay region and these are discussed in this Coastal RSM Plan. These organizations are:

- Monterey Bay National Marine Sanctuary (MBNMS)
- California Coastal Commission (Coastal Commission) (related to southern Monterey Bay Local Coastal Programs)
- California Department of Parks and Recreation (CDPR) (Salinas River, Marina, and Monterey State Parks).

This section provides an overview of the regulatory roles of these agencies and their policies regarding potential beach nourishment projects in the region. State and federal regulations other than MBNMS, Coastal Commission, and CDPR are tabulated from the BRRG but are not described in detail. Given the large number of local governmental organizations (coastal cities, counties) and the transitory nature of many of their regulations, the BRRG does not cover local regulatory processes. Hence, all relevant local regulations (principally those in Local Coastal Programs) are described in this Coastal RSM Plan.

8.1 FEDERAL REGULATIONS

Implementation of federal regulatory processes and the issuing of permits for beach nourishment in southern Monterey Bay are the responsibility of several organizations including the Corps, National Oceanic and Atmospheric Administration (NOAA), USFWS, and the U.S. Minerals Management Service (USMMS). Table 28 summarizes federal regulations potentially affecting beach restoration projects in California. Most of these regulations are described in the BRRG (EIC, 2006), and not all will necessarily apply to beach restoration in southern Monterey Bay.

Table 28. Relevant Federal Regulations Affecting Beach Restoration Projects

Policy/Regulation	Requirement	Responsible Agency
National Environmental Policy Act	Compliance	Lead Federal Agency
Coastal Zone Management Act	Coastal Consistency Determination	California Coastal Commission
Rivers and Harbors Act	Section 10 Permit	U.S. Army Corps of Engineers
Clean Air Act	Title V Operating Permit	California Air Resources Board
Clean Water Act	Section 401 Certification or Waiver (401 Permit)	Regional Water Quality Control Boards
Clean Water Act	Section 402 NPDES Permit (NPDES Permit)	Regional Water Quality Control Boards
Clean Water Act	Section 404 Permit (404 Permit)	U.S. Army Corps of Engineers
Endangered Species Act	Section 7 Consultation	U.S. Fish and Wildlife Service
National Marine Sanctuaries Act	Authorization	Monterey Bay National Marine Sanctuary
National Historic Preservation Act	Section 106 Approval	State Historic Preservation Officer
Fish and Wildlife Coordination Act	Coordination Act Report	U.S. Army Corps of Engineers
Magnuson-Stevens Fishery Conservation and Management Act	Assessment of Impacts to Essential Fish Habitat	National Marine Fisheries Service
Outer Continental Shelf Lands Act	Lease Agreement for Utilization of Outer Continental Shelf Sand	U.S. Minerals Management Service

8.1.1 Monterey Bay National Marine Sanctuary

The MBNMS is administered by NOAA, and spans over 5,300 square miles of coastal waters off central California including the waters of southern Monterey Bay. The Sanctuary's boundaries stretch from Marin County to Cambria, encompassing nearly 300 miles of shoreline and extending seaward from mean high water to an average distance of thirty miles offshore. The Sanctuary was designated in 1992, in response to potential offshore oil and gas development, for the purposes of resource protection, research, education, and public use. The MBNMS mission is to understand and protect the ecosystem and cultural resources of central California.

The MBNMS was designated in accordance with the National Marine Sanctuaries Act (NMSA) and their regulatory and enforcement powers are specified in the Act. The MBNMS enforces eleven federal regulatory prohibitions designed to preserve and protect the natural and cultural resources and qualities of the ocean and estuarine areas within its boundaries. Depending upon the nature of the project, three of these prohibitions may directly regulate beach nourishment in southern Monterey Bay:

- Drilling into, dredging or otherwise altering the seabed of the Sanctuary; or constructing, placing or abandoning any structure, material or other matter on the seabed of the Sanctuary.
- Discharging or depositing, from within the boundary of the Sanctuary, any material or other matter.
- Disposal of dredged material from harbors, outside of the existing sites authorized by the U.S. Environmental Protection Agency and U.S. Army Corps of Engineers.

Although some potential beach nourishment projects may be prohibited by MBNMS regulations, it is still possible for projects to be authorized through the Sanctuary's permitting program. Permits or authorizations may be issued by the MBNMS Superintendent under special circumstances for activities otherwise prohibited by Sanctuary regulations, when related to research to enhance scientific understanding of the Sanctuary environment or to improve management decision-making. Authorizations may also be issued under special circumstances for activities otherwise prohibited by Sanctuary regulations if an activity has been authorized by a valid lease, permit, license, approval or other authorization issued after the effective date of MBNMS designation by any federal, state, or local authority, and the Superintendent finds that the activity will not cause long-term or severe impacts to Sanctuary resources. In cases where projects require a Coastal Commission Coastal Development Permit, the MBNMS would review and potentially authorize that permit with special conditions.

MBNMS approval would be required for any beach nourishment project where sand is placed within Sanctuary boundaries, or where sediment is extracted from within Sanctuary boundaries. While it is possible to authorize some beach nourishment projects within the MBNMS, placement of dredged sediments from harbors, outside of those existing sites approved for dredge disposal, will require modifications to the Sanctuary's regulations. MBNMS currently recognizes four sites as approved for disposal of dredged sediment including SF-12, SF-14 (Section 6.1.1), and limited disposal sites at Monterey and Santa Cruz Harbors. However, the Sanctuary's Harbors and Dredge Disposal Action Plan states that if investigations indicate that employment of additional beach nourishment sites using clean dredged harbor sediment would be possible and appropriate, MBNMS may examine whether revision of its regulations may be warranted, or if a beneficial program might occur via MBNMS permit or authorization in concert with other agencies.

In order to obtain an MBNMS authorization, the applicant must submit a permit application to the MBNMS Permit Coordinator; guidelines for submitting applications can be found on the

Sanctuary website at: <http://montereybay.noaa.gov/resourcepro/authorization.html>. Authorization applications must be submitted at least 45 calendar days in advance of the requested effective date to allow sufficient time for evaluation and processing. In order to expedite processing, applicants are encouraged to contact the Sanctuary in advance of submitting a formal application to discuss any questions or issues they feel may complicate or delay the application process. Complete applications are reviewed by Sanctuary personnel, and, when deemed necessary, peer-reviewed by outside experts. Based on the reviews of the application, authorization will be approved or denied. If approved, the Sanctuary Superintendent will issue the authorization. If denied, applicants are notified of the reason(s) for denial and informed of the appeal process.

8.2 STATE REGULATIONS

The main state legislations regulating beach nourishment projects in southern Monterey Bay are the California Environmental Quality Act (CEQA) and the California Coastal Act (CCA). In addition, in 1978, the State of California adopted a Policy on Coastal Erosion ‘to prevent the loss of the state's beaches through coastal erosion and to preserve its coastal resources.’ The primary state agencies involved in regulatory processes and the issuing of permits for beach nourishment in California are the Coastal Commission, California State Lands Commission (CSLC), State Water Resources Control Board (SWRCB)/Regional Water Quality Control Board (RWQCB), California Department of Fish and Game (CDFG), and California Department of Parks and Recreation (CDPR). Table 29 summarizes state regulations affecting beach restoration projects in California. All these regulations are described in the BRRG (EIC, 2006). Details on the Coastal Commission and CDPR regulations specific to southern Monterey Bay are described in Sections 8.2.1 and 8.2.2.

Table 29. Relevant State Regulations Affecting Beach Restoration Projects

Policy/Regulation	Requirement	Responsible Agency
California Environmental Quality Act	Compliance	Lead CEQA Agency
California Coastal Act	Coastal Development Permit	California Coastal Commission
Porter-Cologne Water Quality Control Act	Compliance: Permits under CWA Sections 401, 402, and 404	State Water Resources Control Board Regional Water Quality Control Boards
California State Lands Public Resources Code	Lease Agreement for Utilization of Sovereign Lands	California State Lands Commission
California Public Resources Code Section 1600	Streambed Alteration Agreement	California Department of Fish and Game
California Endangered Species Act	Section 2081(b) Incidental Take Permit (State) Section 2081.1 Consistency Determination (State and Federal)	California Department of Fish and Game
Water Quality Control Plans California Ocean Plan	Consistency Compliance	Regional Water Quality Control Boards
Clean Air Act	Title V Operating Permit	Air Pollution Control Districts Air Quality Management Districts

8.2.1 California Coastal Commission and Local Coastal Programs

The Coastal Commission, in collaboration with local counties and cities, is the primary state agency responsible for planning and regulating the use of land and water within California's coastal zone, in accordance with the specific policies of the CCA. In addition to development within the coastal zone, the Coastal Commission also has jurisdiction over projects requiring federal permits or approval in federal waters. The Coastal Commission was also established to assist local governments in implementing local coastal planning and regulatory powers by adopting Local Coastal Programs.

Local Coastal Programs (LCPs) are basic planning tools prepared and used by local governments to guide development in the coastal zone, in partnership with the Coastal Commission. LCPs contain the ground rules for future development and short-term and long-term conservation and

protection of coastal resources. Each approved LCP specifies appropriate locations, types, and scales of new or changed uses of land and water. Each LCP includes one or more Land Use Plans (LUPs) with goals and regulatory policies, and measures to implement the plan (such as zoning ordinances). While each LCP reflects the unique characteristics of individual local coastal communities, regional and statewide interests and concerns must also be addressed to conform to CCA goals and policies. Following adoption by a city council or county Board of Supervisors, an LCP is submitted to the Coastal Commission for review for consistency with CCA requirements.

After an LCP has been certified by the Coastal Commission, the Commission's coastal permitting authority is transferred to the local government, which applies the requirements of the LCP in reviewing proposed new developments. All project proposals located within the coastal zone will be reviewed for consistency with the LCP or the CCA (where no certified LCP exists) and will require a Coastal Development Permit. Any projects located on sovereign lands below mean high water remain within the Coastal Commission appeal jurisdiction (as are lands between the ocean and the first public road). Therefore, in some cases, two permits may be necessary; one from the local jurisdiction with a certified LCP and one from the Coastal Commission. The beach nourishment projects being evaluated for southern Monterey Bay would require Coastal Commission approval pursuant to Section 30106 of the CCA, which regulates coastal development. The definition of development includes beach nourishment, removal, dredging, mining, or extraction of sediments, and discharge or disposal of any dredged sediment.

Within southern Monterey Bay, the Cities of Marina and Sand City (north of Bay Avenue) and the County of Monterey have certified LCPs. The Cities of Seaside and Monterey have certified LUPs but do not have approved LCPs. Beach nourishment projects in the cities with certified LCPs would require a Coastal Development Permit issued by that city. The details of each LCP and the regulations and policies they contain pertaining to regional sediment management, particularly beach nourishment activities are provided below.

County of Monterey

The Monterey County LCP was certified by the Coastal Commission in 1988, whereby the County assumed permit-issuing authority. Most beach nourishment projects within the jurisdiction of the County of Monterey will require a Coastal Development Permit issued by the County's Planning Department. In addition a Grading Permit and an Erosion Control Permit may be required.

The LCP is composed of four LUPs, including the unincorporated section of southern Monterey Bay between the City of Marina northern boundary and Moss Landing, which is part of the North County LUP. Along this frontage, this Coastal RSM Plan does not identify any critical areas of erosion. The North County LUP (latest update, December 1999) designates the beaches and dunes (except the parking lots of the Salinas River State Beach) as Scenic and Natural Resource Recreation Areas to be maintained at a low level of development to protect dune habitats and preserve the natural character of the shoreline. The LUP recommends that the state acquire

privately-owned dune areas that are offered for sale. The North County LUP does not designate set back requirements for new development like most other local LUPs. The policies from the North County LUP relating to RSM include the following:

- LUP Policy 2.3.2: With the exception of resource dependent uses, all development, including vegetation removal, excavation, grading, filling, and the construction of roads and structures, shall be prohibited in the following environmentally sensitive habitat areas: riparian corridors, wetlands, dunes, sites of known rare and endangered species of plants and animals, rookeries, major roosting and haul-out sites, and other wildlife breeding or nursery areas identified as environmentally sensitive. Resource dependent uses, including nature education and research hunting, fishing and aquaculture, where allowed by the plan, shall be allowed within environmentally sensitive habitats only if such uses will not cause significant disruption of habitat values.
- LUP 2.3.3: A dune stabilization and restoration program should be implemented by the California Department of Parks and Recreation. Damaged dune areas should be replanted with native vegetation. Dune areas of high sensitivity should be protected from disruptive uses and development. The dune area between the City of Marina and the Salinas River should be acquired by the U.S. Fish and Wildlife Service or the California Department of Fish and Game and managed as a wildlife reserve.
- LUP 2.4.2: 1. Further alteration of natural shoreline processes including drainage, erosion, water circulation, and sand transport, shall be limited to protection of public beaches, existing significant structures, coastal dependent development, and the public health and safety.
- LUP 2.4.2: 3. Dredging and spoils disposal should be planned and carried out to avoid significant disruption to marine, estuarine and wetland habitats, and the pattern and volume of water circulation. Dredged spoils suitable for beach replenishment shall be transported for such purposes to appropriate beach areas with suitable longshore current systems. Dredged spoils shall meet all state and federal standards for the protection of the marine biologic environment and shall be disposed of consistent with all current policies and sites.

The southern Monterey Bay shoreline south of the City of Marina northern boundary is under the jurisdiction of City LCPs, apart from Fort Ord, which is within the Monterey County coastal zone in an uncertified area. The Fort Ord Reuse Authority (FORA) has published a Fort Ord Reuse Plan (adopted June 1997) which outlines a set of recommended objectives and associated programs for appropriate land use including the beaches fronting the former base. The following objective and program relates to Monterey County/Fort Ord and RSM:

- Monterey County Objective E: Coordinate open space and recreation land use with other affected agencies at the former Fort Ord, such as the California Department of State Parks and Recreation and the Bureau of Land Management. Program E-1.1: The County of Monterey shall assist the CDPR to develop and implement a Master Plan for ensuring the management of the Fort Ord coastal dunes and beaches for the benefit of the public by restoring habitat, recreating the natural landscape, providing public access, and developing appropriate day use and overnight lodging facilities (limited to a capacity of 40 rooms).

Given the conversion from military to suburban land uses it is important that any future development on the dunes at Fort Ord be sited via set backs or transfer of development rights to avoid future erosion hazards, and that any generated spoils be beneficially reused (e.g. beach restoration).

City of Marina

The City of Marina LCP provides jurisdiction from the northern city limit of Marina to the northern boundary of Fort Ord. Within this length of coast, this Coastal RSM Plan identifies two critical areas of erosion; the Sanctuary Beach Resort and Marina Coast Water District buildings. Also, the LCP covers the sand mine at Marina. The City of Marina LCP was certified by the Coastal Commission in 1982, and the City assumed permit-issuing authority. Several amendments to the LCP have been made in the years up to 2001, with the effective LCP now dated 2002. Further amendments as appealed by the Coastal Commission went to the City Council meeting on November 20, 2007. The policies from the City of Marina LCP that are relevant to RSM include the following:

- LUP Policy 1: to insure access to and along the beach, consistent with recreational needs and environmental sensitivity of Marina coastal area.
- LUP 2: to provide beach access and recreational opportunities consistent with public safety and with the protection of the rights of the general public and of private property owners.
- LUP 8: to prohibit further degradation of the beach environment and conserve its unique qualities.
- LUP 19: to promote restoration and protection of native dune habitat and vegetation.
- LUP 23: to support continuation of the coastal dependent sand mining operations as long as they are economically feasible and their operations are managed with sensitivity to the adjacent dune environment.
- LUP 25: to protect the habitat of recognized rare and endangered species found in the coastal dune area.
- LUP 33: to protect scenic and visual qualities of the coastal area including protection of natural landforms, views to and along the ocean, and restoration and enhancement of visually-degraded areas.

More specific policy is provided in the LCP with respect to the sand mining operations at Marina:

- existing surf zone sand mining operations, as established coastal dependent uses, shall be permitted to continue at their existing locations in substantially the same manner as they are currently being conducted, and have been conducted in the past. All provisions of the LCP (including the Implementation Plan) relating to mining shall be construed and applied in a manner that supports such continuation of existing surf zone sand mining operations, so long as such existing surf zone sand mining operations are in accordance with the LCP.

- further, the City shall establish in its Implementation Plan a method of monitoring shoreline erosion along the Marina coast for the purpose of establishing a continuing project impact analysis. This analysis shall consist of the submission by sand mining operation on an annual basis, of an accurate cronaflex ortho-topographic map, meaningful information on shoreline retreat by way of a benchmark program or other equally effective measurement.
- the City shall not approve or renew a Mining Permit and/or Coastal Development Permit for new surf zone or beach sand mining, if it finds that such new sand mining, either individually or cumulatively, will have significant adverse impacts on shoreline erosion.
- such determination shall be made upon consideration of the results of the continuing project impact analysis, available evidence on the impact of beach and surf zone sand mining on coastal erosion and other relevant social, economic, environmental and technological factors.
- any Mining Permit and/or Coastal Development Permit shall be issued subject to the condition that will permit the City to require that new sand mining activity be reduced to previous levels (prior to the issuance of a Mining Permit and/or Coastal Development Permit) or terminated in the event of a new sand mining operation, if the continuing project impact analysis or other available evidence on the impact of beach and surf zone sand mining on shoreline erosion shows that such operations have a significant adverse impact on shoreline erosion.

The following objective and program from the Fort Ord Reuse Plan also relates to the City of Marina and RSM:

- City of Marina Objective A (also City of Seaside Objective A): Integrate the former Fort Ord's open spaces into the larger regional open space system, making them accessible as a regional resource for the entire Monterey Peninsula. Recreation Policy A-1: The City of Marina (Seaside) shall work with the California State Park System to coordinate the development of Fort Ord Beach State Park.

City of Sand City

Within the City of Sand City jurisdiction are the critical areas of erosion at Tioga Avenue, Seaside Pump Station, and the Monterey Interceptor. The City of Sand City LCP was certified by the Coastal Commission in 1986 with the exception of the part of the city south of Bay Avenue, which has been designated as an area for delayed certification. In 1990, the Coastal Commission issued a report to the City of Sand City (Coastal Commission, 1990) recommending major revisions to the LCP to reduce the amount of development allowed. This report was almost simultaneous with an LCP amendment recommended by the Monterey Peninsula Regional Park District (MPRPD) to make public parks and open space the preferred land use along Sand City's coast. In addition, MPRPD and CDPR sought to acquire coastal land within Sand City for park purposes. The City of Sand City resisted the efforts of MPRPD, because it wished to preserve certain coastal parcels for development to ensure a stable fiscal future for the city.

In 1996, the Sand City LCP was amended to allow public parks and open space over the vast majority of its coastal area. At the same time, MPRPD, CDPR and the City entered into a Memorandum of Understanding, outlining a few remaining ‘development envelopes’ on the coast where visitor-serving development (a priority use by the CCA) could be permitted. One of these envelopes is the area occupied by the former Sand City sand mining operation (Section 1.4.4). Now, MPRPD and CDPR would support reasonable development along the coast that does not block views of Monterey Bay, in exchange for acquisition of the majority of Sand City's coast for sensitive habitat reconstruction, public parks, and general open space.

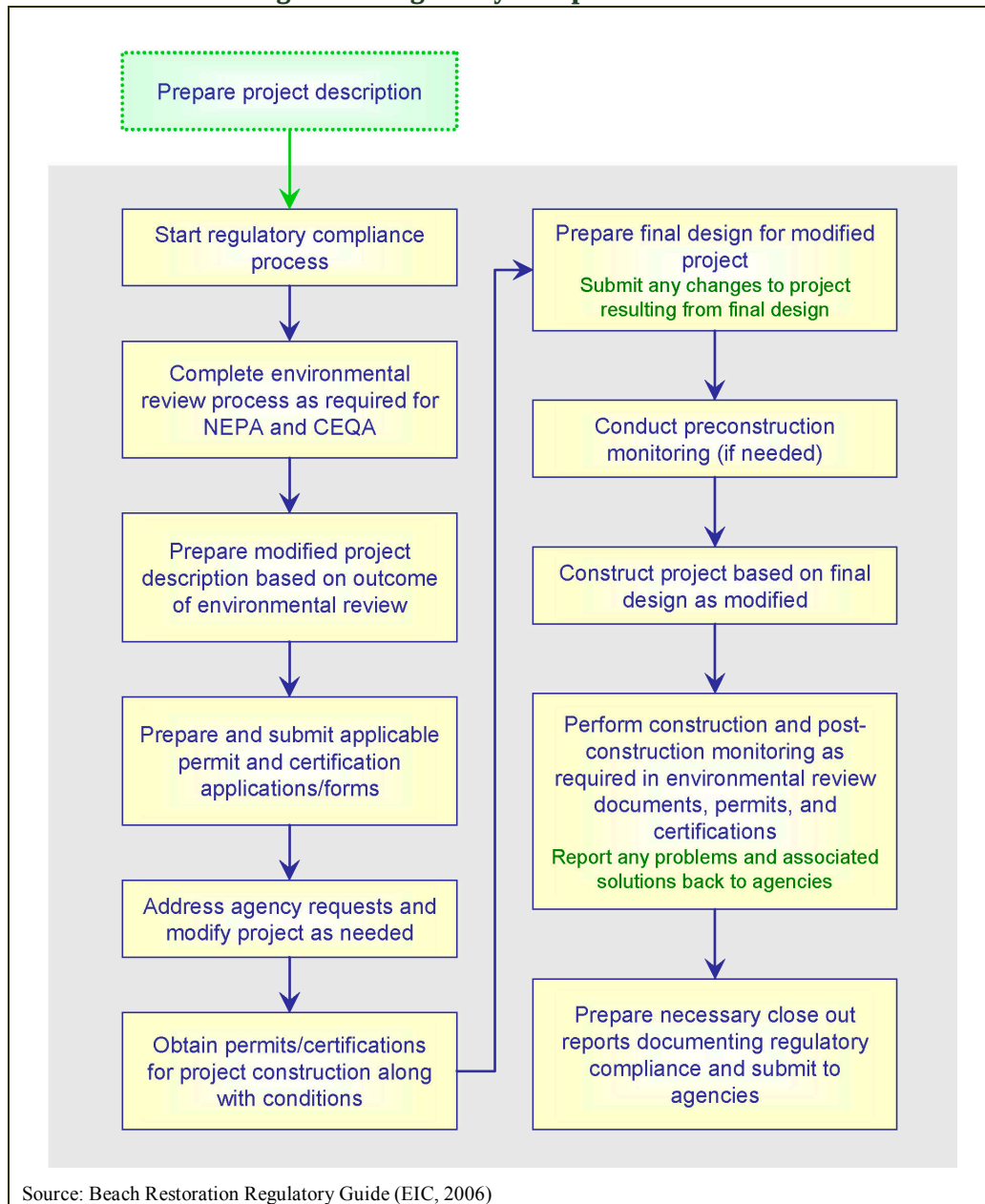
8.2.2 California Department of Parks and Recreation

The CDPR is responsible for the management and protection of natural and cultural resources, and facilitating outdoor recreational opportunities within the State Parks. These include a number of sites in southern Monterey Bay including Monterey, Marina, and Salinas River State Beaches. Any project located on or affecting State Park land would require approval by CDPR in the form of an Encroachment Permit. The CDPR policy on coastal erosion is generally to allow coastal processes (such as wave erosion, beach deposition, dune formation, lagoon formation, and bluff retreat) to continue without interference. The CDPR will not construct permanent new structures and coastal facilities in areas subject to wave erosion and bluff retreat, or areas with unstable bluffs. Structural protection and re-protection of existing developments is appropriate only when the cost of protection over time is commensurate with the value of the development to be protected, and it can be shown that the protection will not negatively affect the beach or the nearshore environment. Where existing developments must be protected in the short term to achieve park management objectives, CDPR would use the most natural-appearing method feasible, while minimizing impacts outside the threatened area.

8.3 REGULATORY COMPLIANCE PROCESS

The regulatory compliance process for beach nourishment projects is described in the Beach Restoration Regulatory Guide (BRRG) (EIC, 2006). In southern Monterey Bay the process would comprise three phases (Figure 38):

- Environmental review
- Permitting
- Compliance review.

Figure 38. Regulatory Compliance Process

Environmental review consists of both National Environmental Policy Act (NEPA) and California Environmental Quality Act (CEQA) compliance, and is typically completed first. NEPA and CEQA documents should be prepared concurrently and are used as the basis upon which the regulatory and resource agencies process permits. The Corps typically serves as the lead agency under NEPA. For CEQA, several state agencies may be involved (such as the Coastal Commission, CDPR), details of which are described in the BRRG (EIC, 2006). However, Figures 39 and 40 provide flow charts of the NEPA and CEQA compliance processes.

Figure 39. NEPA Compliance Flow Chart

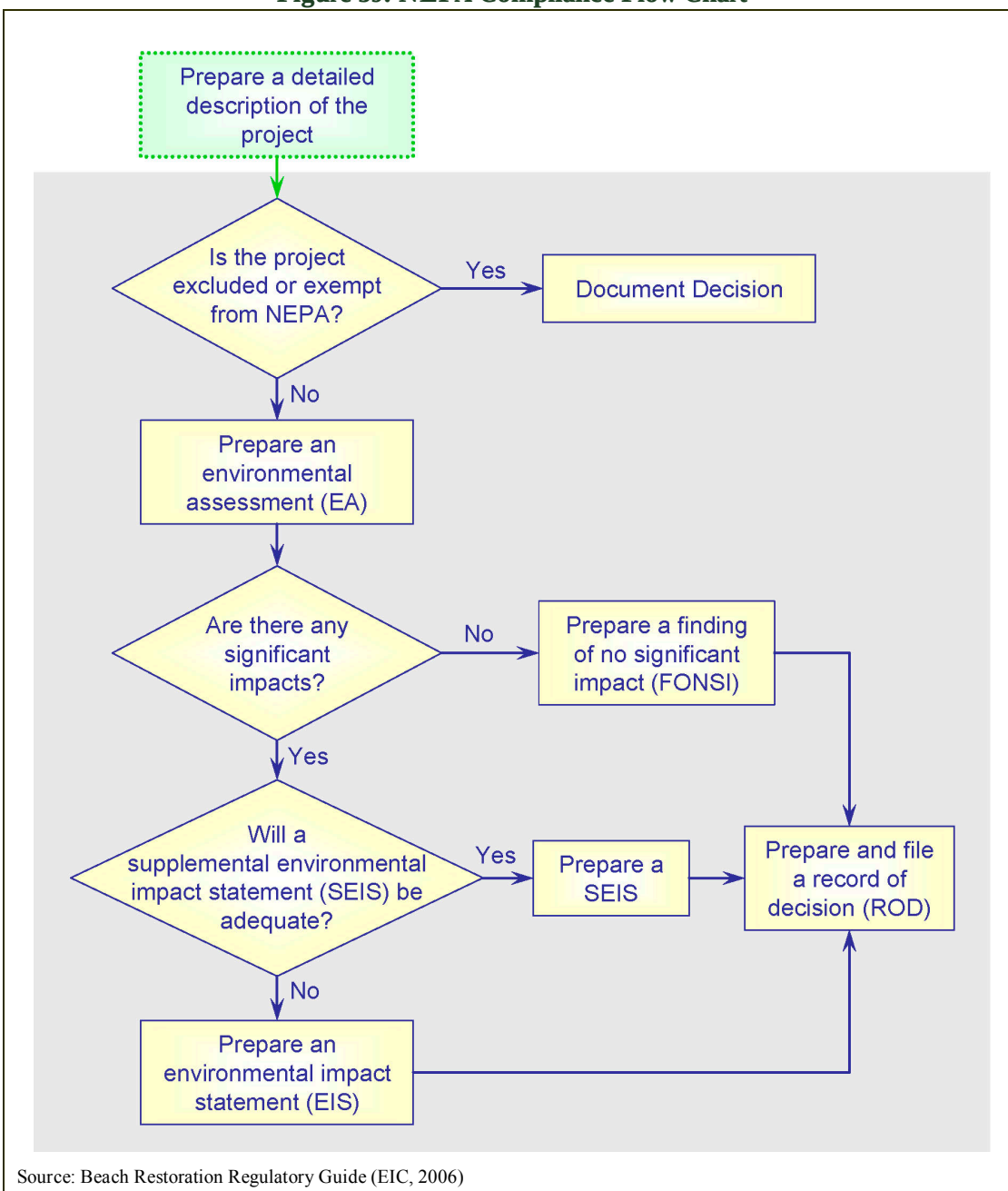
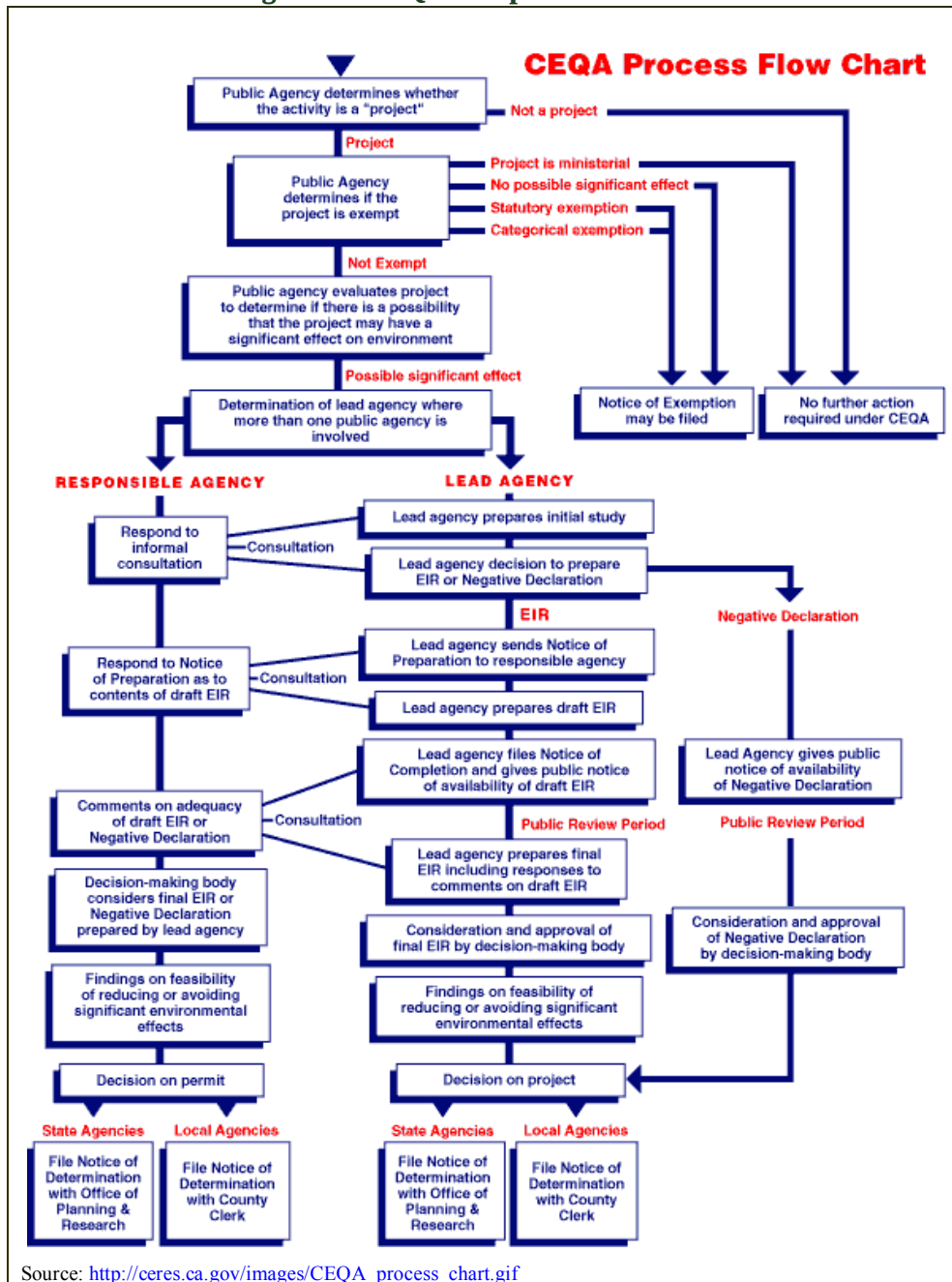


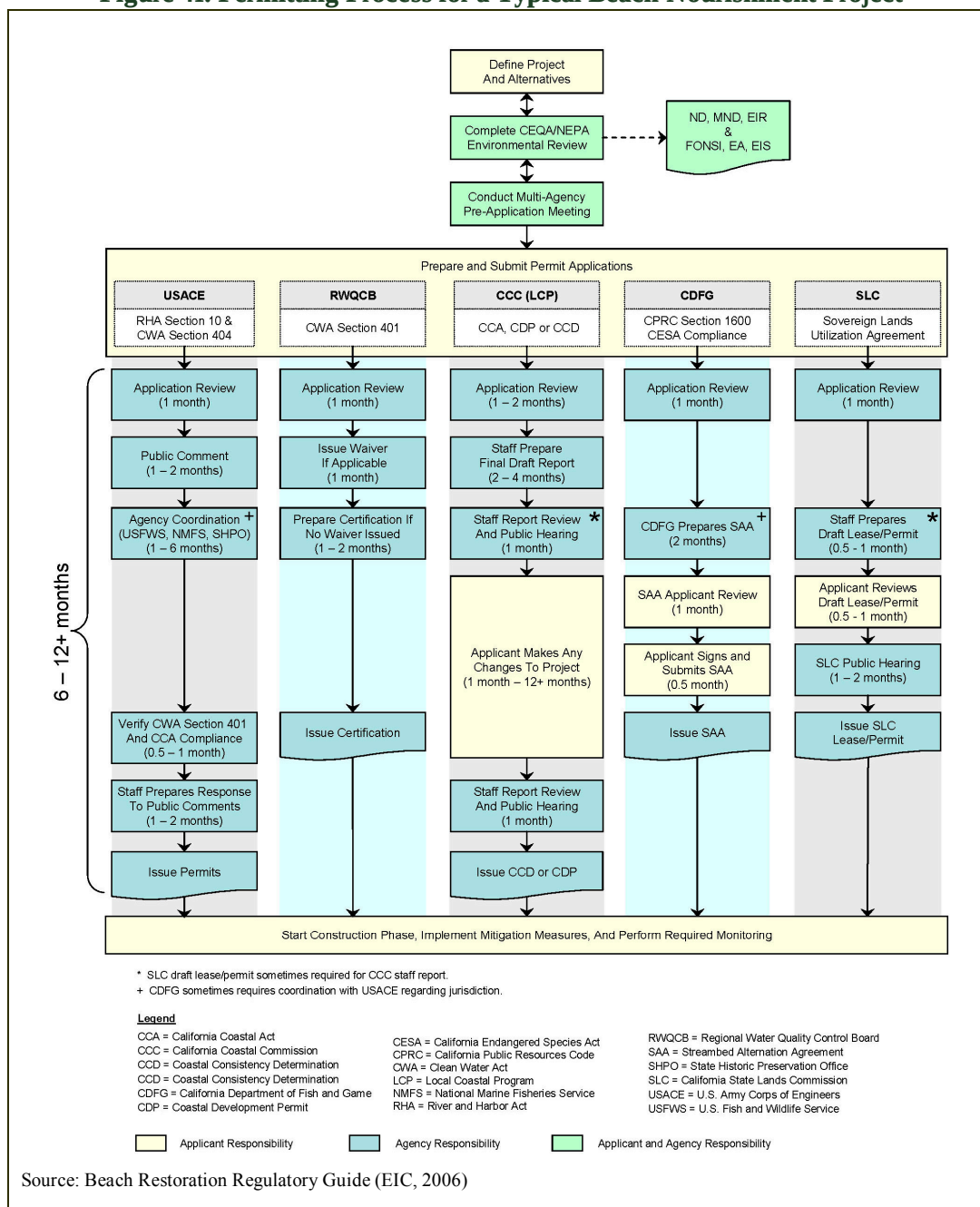
Figure 40. CEQA Compliance Flow Chart



Once the environmental review is completed the permit process begins, and the applicant submits the necessary permit applications to the appropriate agencies. There are many routes that can be taken to receive the permits necessary for a beach nourishment project, depending on the implementing agency and the project applicant. Figure 41 illustrates the milestones for various permit applications for a typical beach nourishment project. In southern Monterey Bay, an additional permit would likely be required through the MBNMS; the process is described in

Section 8.1.1. Beach nourishment projects involve placement of sediment into waters of the U.S., which may result in significant environmental impacts, and hence they receive a high level of scrutiny during the environmental and permitting processes. In order to streamline and potentially shorten the regulatory compliance process, the AMBAG should consider acquisition of a SCoup permit.

Figure 41. Permitting Process for a Typical Beach Nourishment Project



8.3.1 SCOUP Permitting Process

The intent of a SCOUP permit is to establish a process approved by regulatory agencies for environmentally-responsible use of opportunistic sediments to nourish pre-established receiver site(s) when sediment becomes available (Moffatt and Nichol Engineers, 2006). There are two types of SCOUP permit; a single opportunistic permit and an opportunistic use program. The single permit is for a project in which the source sediment is identified and the beach receiver site and method of delivery is permitted (Moffatt and Nichol Engineers, 2006). These are typically applied for by either the developer supplying the sand or the local jurisdiction receiving the sand. The opportunistic use program establishes a predefined program for placement of sediment at beach receiver sites. An approved SCOUP program permit streamlines the regulatory compliance process and enables opportunistically acquired sediments that meet certain criteria to be placed at pre-established receiver sites in various quantities and at times throughout the year with minimal review from the regulatory agencies. Generally, program permits are applied for by a local jurisdiction, county or regional association. This Coastal RSM Plan recommends that the AMBAG pursue a regional SCOUP program permit.

To receive a SCOUP program permit, several steps are required that are described in Moffatt and Nichol Engineers (2006). There are ten federal and state agencies, not including local jurisdictions, which need to be involved in the programmatic permitting; Federal – Corps, USEPA, USFWS; State – CDFG, Coastal Commission, CSLC, CDPR, SWRCB, and RWQCB. In summary, the steps include developing a sediment sampling and analysis plan, used to evaluate potential sources of sand and to identify appropriate receiver sites. For each potential receiver site, components include:

- a sediment budget analysis to establish the need for sand
- a summary of transport mechanisms and routes to identify potential impacts
- monitoring plans for each site including sensitive habitat surveys at established pre, post, and during construction intervals
- environmental review that must receive review and approval from all of the permitting agencies.

As complicated as the process sounds, SANDAG received a program permit on a Mitigated Negative Declaration (MND) which avoided significant environmental impacts by constraining the volume, % of fines, and timing of nourishment activities. In addition, this Coastal RSM Plan has generated much of the background information needed to streamline an application for a SCOUP program permit.

9. POTENTIAL FUNDING SOURCES

This section describes potential sources of federal and state funding and potential matching local funds to implement beach nourishment in southern Monterey Bay. MBNMS (2007a) provided an initial assessment of potential funding mechanisms for short- and long-term shoreline nourishment projects, which is used as a basis for this review.

9.1 FEDERAL FUNDING SOURCES

9.1.1 U.S. Army Corps of Engineers

The Corps is the primary federal agency funding shoreline restoration projects. Funds are available for a wide range of projects and are not limited to beach nourishment or large-scale structural alternatives; for example the Corps can participate in managed retreat projects. Funding mechanisms within the Corps consist of two major programs; the Continuing Authorities Program (CAP) and the General Investigations (GI) approach. For smaller projects, the Corps may act directly under CAP without authorization from Congress. CAP includes a number of standing authorities to study and construct certain specific projects. Projects that are larger in scope require congressional authorization and would fall under GI (i.e. a project larger than the CAP program funding limits). GI recommendations go before Congress for project (construction) authorization and then for funding. Requests for projects with the Corps can be made at any time; however for new starts under the GI program, and the CAP in recent years, the requests are always linked to the budget cycle. All projects funded by the Corps require reconnaissance and feasibility studies prior to implementation to determine whether a federal interest exists in the project, unless the Corps is directed by a member of Congress to move ahead with the project. In either case the Corps will conduct NEPA and/or CEQA environmental documentation prior to implementation.

Continuing Authorities Program

The CAP program is made up of nine individual programs that are categorized by the type of project being proposed. All projects are cost shared between the federal government and a non-federal sponsor. A non-federal partner is a legally constituted public body, such as a city, state, county, or conservancy district, that is capable of financing the project and providing for operation and maintenance of the project once completed. Sections 14, 103, 204, and 206 could potentially provide funding for beach nourishment projects in southern Monterey Bay:

- Section 14 Emergency stream bank and shoreline erosion: This program is authorized by Section 14 of the Flood Control Act and funds shoreline protection projects that protect public facilities including water and sewage treatment facilities, and roads that are in imminent danger of erosion. Private property is not eligible. Cost share requirements are 65% federal to 35% non-federal, and the maximum federal contribution is \$1 million.

- Section 103 Hurricane and storm damage reduction (Beach erosion control): This program is authorized by Section 103 of the Rivers and Harbors Act and funds protection or restoration of public shorelines by the construction of revetments, groins, jetties, and sometimes beach nourishment. Design and construction cost share requirements are 65% federal to 35% non-federal, and the maximum federal contribution is \$3 million.
- Section 204 Beneficial uses of dredged material: This program is authorized by Section 204 of the Water Resources Development Act and allows the use of dredged material from new or existing federal projects to restore, protect, or create aquatic and ecologically related habitats, including wetlands. The total project cost is shared 75% federal and 25% non-federal, and the maximum federal contribution for project development and construction is \$5 million.
- Section 206 Aquatic ecosystem restoration: This program is authorized by Section 206 of the Water Resources Development Act and funds aquatic ecosystem restoration projects that will improve the environmental quality, are cost-effective, and are in the public interest. Although not directly related to beach nourishment, it may be possible to link with projects that restore species habitat such as that of western snowy plovers. The total project cost share requirement is 65% federal to 35% non-federal, and the maximum federal contribution is \$5 million.

General Investigations

In addition to CAP funding, it is possible to get GI funding for larger projects that do not fit within the CAP program, or a collection of several smaller projects. This type of funding requires congressional authorization through either a Senate Resolution (Environment and Public Works Committee) or House Resolution (Transportation and Infrastructure Committee). Alternatively authorization could be accomplished with language in the Water Resources Development Act which, in theory, is passed by Congress and signed by the president every two years. The General Investigations process comprises four phases:

- Reconnaissance Phase: Duration 9-12 months. Corps covers full cost. This phase identifies the Project Study Plan and cost share details.
- Feasibility Phase: Duration 1-3 years. 50% to 50% cost share (up to 50%, either sponsor share or can be in-kind). Average cost \$700,000 to \$1.5 million or more.
- Pre Construction Engineering and Design Phase: Duration 1-2 years. Cost share varies depending on the type of project (typically 65% to 35%, federal/non-federal).
- Construction Phase: Time varies depending on the project. Cost share varies depending on the type of project (typically 65% to 35%, federal/non-federal).

The GI process may take six years to reach the construction phase, once the funds are authorized, and then appropriated. After the reconnaissance phase there is a significant (50%) matching requirement by the local sponsor.

9.1.2 U.S. Fish and Wildlife Service

The USFWS administers a variety of natural resource assistance grants to government, public and private organizations, groups and individuals. One potential source of funding assistance for projects that restore wildlife habitat is the Cooperative Conservation Initiative. This program provides funding for projects that restore natural resources and establish or expand wildlife habitat. A 50% match is required of the project sponsor. The Cooperative Endangered Species Conservation Fund also provides funding for implementation of conservation projects or acquisition of habitat that will benefit federally-listed threatened or endangered species. The required match for this program is a minimum 25% of the estimated project cost by the local sponsor.

9.1.3 Monterey Bay National Marine Sanctuary

The MBNMS occasionally receives settlement funds from Sanctuary violations involving disturbance of the seabed. These funds must be used to protect and restore Sanctuary habitats, and could potentially be used for evaluation, planning and implementation of projects related to retention of beach habitat. Provision of such funds would need to be complemented by funding from other sources.

9.2 STATE FUNDING SOURCES

9.2.1 California Department of Boating and Waterways

The CDBW is the California agency with responsibility for studying and reporting beach erosion issues in the state, and for developing measures to stabilize the shoreline pursuant to Article 2.5 of the Harbors and Navigation Code. Following the passage of the Public Beach Restoration Act (1999) the CDBW is also responsible for allocating funds for beach restoration projects (CDBW has no jurisdiction from a regulatory standpoint). The Public Beach Restoration Program (PBRP) developed as part of the Public Beach Restoration Act provides the funding vehicle for the legislature to support restoration, enhancement, and maintenance of California beaches (CDBW and SCC, 2002). The CDBW primarily funds promotion of boating activities, safety programs and boating access; beach erosion and restoration grants are the organizations only non-boating expenditures.

The PBRP funds beach nourishment projects, dune restoration, biological and sediment transport monitoring, and feasibility and research studies. In many cases, state money has been used to leverage federal Corps funding. The PBRP also allows for 100% funding of project construction costs for beach nourishment at state parks and state beaches, and a maximum (could be less depending on availability of funding) of up to 85% funding for projects at non-state beaches (the local sponsor provides a 15% match). CEQA documentation must be submitted with grant applications, and public beach access must be adequately addressed by the project.

Since the CDBW grant programs are limited fiscally, one possibility would be for various partners to approach state legislators and request funds be earmarked for a nourishment project. The southern Monterey Bay region has a potential advantage over locations in southern California since there is a 60% to 40% split between southern and northern California for funding not assigned to a specific project. While there is intense competition due to the large number of projects in the south, the only major project area competing for funding in the northern part of the state is Ocean Beach in San Francisco. However, funds deposited in the PBRP are often earmarked for specific projects. Regardless, a local source of funding is required to provide matching funds for any project.

9.2.2 California Coastal Conservancy

The California Coastal Conservancy (Conservancy) is a state agency that uses entrepreneurial techniques to purchase, protect, restore, and enhance coastal resources, and to provide access to the shoreline. The Conservancy works in partnership with local governments, other public agencies, non-profit organizations, and private landowners, and has carried out more than 1,000 projects along the California coastline and in San Francisco Bay. The Conservancy funds shoreline protection projects that are consistent with the goals of the CCA. Similar to CDBW grants, the availability of Conservancy grant money is entirely dependent upon availability of funds (mostly bond issues). The Conservancy can fund pre-project feasibility studies, property acquisition, planning (for large areas or specific sites), environmental review, construction, monitoring, and in limited cases, maintenance.

9.2.3 California Coastal Commission

A potential source of funding is fees collected by the Coastal Commission through the Coastal Development Permit (CDP) process, from special conditions on individual permits requiring mitigation fees. The Coastal Commission and SANDAG entered into a cooperative agreement through which a Public Recreation Beach Impact Mitigation Fund was established to make money available for projects that enhance public recreational access. The fund consists of fees collected by the Coastal Commission as mitigation for the adverse impacts on public recreational use of the region's beaches. Monies from the fund will be used to implement projects that provide public recreational improvements, including but not limited to public beach access, bluff top access, viewing areas, public restrooms, public beach parking, and public trail amenities. The role of SANDAG is to collect funds mandated by the Coastal Commission and hold the money in an interest-bearing account. SANDAG staff will work with local jurisdictions to process requests for funds. The use of funds requires local jurisdiction, Coastal Commission, and SANDAG approval. A similar fund could potentially be established to help fund beach restoration projects in southern Monterey Bay, with contributions from various future CDP processes.

In southern Monterey Bay, mitigation fees for a seawall currently being constructed at Ocean Harbor House were allocated by the Coastal Commission to dune acquisition. In order to change the allocation, the recommendation would need to be revisited and approved by the Coastal Commission. Such a change would need to be supported by quantitative projections of the amount of sand estimated to be retained by the proposed project so that it could be compared to the estimated sand lost due to the seawall.

9.3 LOCAL/REGIONAL MATCHING FUNDS

If the southern Monterey Bay area is going to be successful in attracting state or federal funding, some form of revenue stream must be developed at the local/regional level in order to leverage the state and federal funds. The local sponsor is typically required to provide 50% (Corps) or a minimum of (and sometimes more) 15% (CDBW) of costs related to studies and construction. Revenue streams developed elsewhere to generate matching funds include a transient occupancy tax (TOT) levied on hotels (southern California and elsewhere), real estate transfer tax (RETT), tax levied on sporting goods (e.g. Texas), and parking or beach user fees. Other strategies that could potentially be implemented include cost-sharing among project beneficiaries and special assessment districts.

9.3.1 Transient Occupancy Tax

Transient occupancy taxes (TOTs) are hotel taxes levied on visitors. They are the primary source of local funding in several east coast states that have well established beach nourishment programs (e.g. Florida and New Jersey). In Florida, 55% of funding for beach nourishment projects is from local sources, mainly local TOTs. TOTs have recently been implemented by a few municipalities in southern California. The City of Carlsbad estimated that approximately \$1 million could be raised annually by implementing a 1% increase in TOTs. In Solano Beach the City Council voted to increase the TOT by 3% (phased in over three years), of which two thirds will be used for sand replenishment/retention and coastal access projects (estimated to be \$160,000 annually).

Encinitas has a similar program in place. In this case, the Encinitas TOT measure (Measure F) appeared on the city-wide ballot on June 3, 2008 where it was approved. The TOT imposes an 8% tax on short-term lodging rentals in Encinitas; short-term is defined as less than 30 days. There are approximately 130 short-term rentals in Encinitas, and if the tax on those rental units passes, it is expected to accrue about \$250,000 per year for the City. Encinitas spends \$40,000 a year to replenish the sand on its beaches. The ballot language reads ‘Shall an ordinance be approved to amend Section 3.12.030 of the Encinitas Municipal Code to require guests of short term rental units (for 30 days or less) to pay 8% of the rent charged as a transient occupancy tax effective January 1, 2009?’

The Sanctuary Beach Resort currently levies a \$15 per night fee to occupants to fund restoration of habitat on its property.

9.3.2 Real Estate Transfer Tax

Real estate transfer taxes (RETTs) are assessed on real estate when a property changes hands. In California, the RETT is currently 0.11%. RETTs may be applied to residential sales or to other types of real estate transactions including commercial and industrial sales. Revenue raised from a RETT may be added to the jurisdiction's general fund or earmarked for specific uses, which could include beach nourishment.

9.3.3 Tax Levied on Sporting Goods

In 1993, the Texas State Legislature passed a bill for the revenue source for state and local parks to a draw from the general sales tax attributable to sporting goods. There is no separate state tax on sporting goods. Park funding comes from a portion of Texas general sales tax revenue that is 'attributed' to sporting goods. Sporting goods are defined as personal property designed and sold for use in a sport or sporting activity.

9.3.4 User Fees

Many local municipalities on the east coast and in southern California have implemented user fees as a source of funding for beach nourishment projects. This can include parking or beach-use fees, which are often levied on visitors, but not required of local residents. For example the City of Del Mar charges for parking in most areas near the beach.

9.3.5 Cost-Sharing Among Project Beneficiaries

In this strategy, the local share of the cost of a project would be distributed among the various entities that benefit from that project. The cost could be divided proportional to the total benefits attributed to each group (e.g. by the value of the property and the risk being averted). For example, for a project in southern Monterey Bay using this approach, the local costs may be borne by the City of Monterey, the City of San Jose, the private landowners (e.g. Ocean Harbor House homeowners, Monterey Beach Resort), and other potentially affected parties (e.g. MRWPCA, CDPR).

9.3.6 Special Assessments

In this strategy the local government places assessments on properties that would receive a higher proportion of the benefits derived from the project. For example, private property at high risk of erosion damage would be required to pay a special fee that would not be required of other

properties that are not at risk and proportionally higher than those that are at moderate or low risk. In Florida, the state assesses a tax based upon the distance of the structure from the beach.

Geologic Hazard Abatement Districts have been developed in several parts of California, to create a local taxing authority in order to raise funds needed to address geologic hazards. Typically they have been used to address very large, deep-seated landslides and are currently being examined as a means to address flood control when developing on alluvial fans. This process could also be applied to address coastal erosion.

10. GOVERNANCE STRUCTURE

A governance structure provides a framework for the Coastal RSM Plan to be used, including interpretations, updates and implementation of particular actions. The Governance structure represents a coordinated implementation approach that provides a framework for input from citizens as well as federal, state, regional, and local entities. Several existing RSM entities were reviewed and are discussed in this section, along with the recommended governance structure for the southern Monterey Bay Coastal RSM Plan.

10.1 AMBAG AND JOINT POWERS AUTHORITY

A Joint Powers Agreement Authority (JPA) is an institution permitted under the laws of many states whereby two or more public authorities can operate collectively. They are permitted under Section 6500 of the State of California Government Code. JPAs may be used where an activity naturally transcends the boundaries of existing public authorities (such as southern Monterey Bay coastal erosion). It is distinct from the member authorities; the JPA has a separate operating Board of Directors, and the Board can be given any of the powers inherent in all of the participating agencies. In setting up a JPA, the constituent authorities must establish which of their powers the new authority will be allowed to exercise, and a term, membership and standing orders of the Board need to be specified. Also, the JPA can employ staff and establish policies independently of the constituent authorities. JPAs are flexible and can be tailored to meet specific needs, and there are many differences among individual JPAs.

The AMBAG is a JPA governed by a Board of Directors composed of locally elected officials appointed by their respective city council or Board of Supervisors. Each member city has one representative on the Board, while each member county has two. The AMBAG Board of Directors sets policy and oversees a small professional staff. The AMBAG's funding comes from various local sources, including the state and federal governments for mandated planning activities and grant projects. Funding comes from various local sources, including annual membership dues contributed by each member agency.

In order to define a governance structure and implementation for this Coastal RSM Plan using a JPA model we have investigated the governance models adopted by San Diego Association of Governments (SANDAG) and Beach Erosion Authority for Clean Oceans and Nourishment (BEACON).

10.1.1 San Diego Association of Governments

SANDAG comprises 18 cities and county governments and is a forum for decisions on a wide range of issues (not just coastal erosion). Similar to the AMBAG, the SANDAG is governed by a

Board of Directors composed of mayors, council members and county supervisors, as well as advisory members (non-voting) from Department of Defense, Caltrans, San Diego Port District, San Diego Water Authority, and others. In addition to the Board, SANDAG also have a staff of professional planners, engineers, and research specialists. SANDAG builds consensus, makes strategic plans, obtains and allocates resources, plans, engineers, and builds public transportation, and provides information on a wide variety of topics; they have a broader spectrum of responsibilities than the AMBAG. SANDAG also has the ability to issue bonds, as established in specific state legislation (SB 1703, Feb 12, 2002). SANDAG has a Shoreline Preservation Working Group with staff members and a Shoreline Preservation Strategy that was adopted by their Board in 1993. This strategy places a large emphasis on beach nourishment. The Working Group advises the Regional Planning Committee of SANDAG on issues related to the Shoreline Preservation Strategy.

10.1.2 Beach Erosion Authority for Clean Oceans and Nourishment

BEACON is a JPA with member agencies comprising the cities of Carpinteria, Goleta, Oxnard, Port Hueneme, Ventura, Santa Barbara, and the counties of Santa Barbara and Ventura. BEACON was established for the limited purposes of dealing with coastal erosion and beach problems in that coastal region. They have also recently expanded their purview to water quality issues and beach and ocean pollution. BEACON maintains technical staff to assist with coastal engineering issues inherent with beach nourishment.

10.1.3 Joint Powers Authority Options

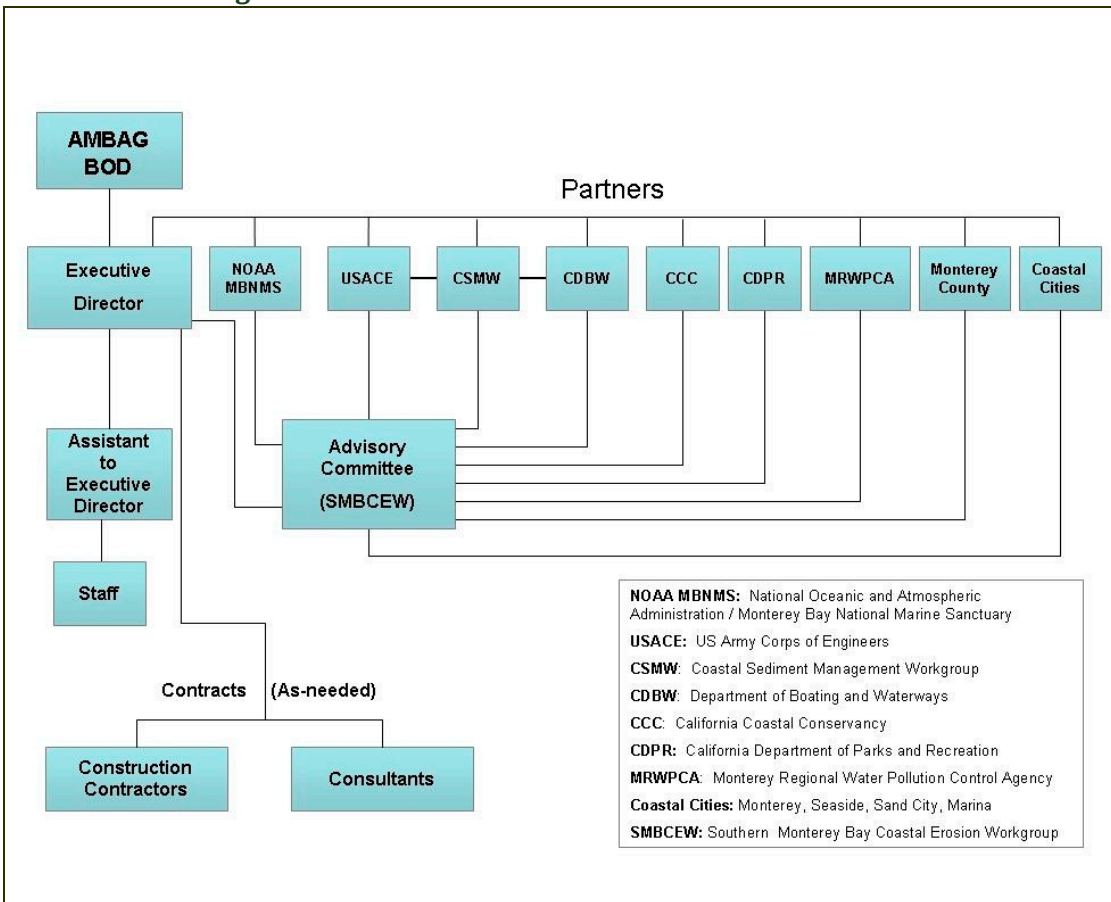
Adopting the SANDAG model, the governance structure would employ the AMBAG as an existing JPA and include a multi-stakeholder coastal erosion committee that advises the Executive Director and Board of Directors. This structure would negate the need to establish a new JPA, it could be extended to other geographic regions in the future (e.g. northern Monterey Bay, Santa Cruz), and the organization would already be set up to receive funding and implement projects. For this option to be adopted the AMBAG Board would need to expand their scope to take on this new coastal erosion/sediment management role.

Adopting the BEACON model would require formation of a new JPA that is only focused on erosion issues in the southern Monterey Bay area, rather than using the AMBAG as an existing JPA. The scope of the new JPA would be limited to erosion/sediment management issues and the geographic area would be limited to southern Monterey Bay, rather than the larger three-county AMBAG region.

10.2 RECOMMENDED GOVERNANCE STRUCTURE

This Coastal RSM Plan recommends a governance structure for implementation of RSM in southern Monterey Bay using the AMBAG as an existing JPA. The recommended governance structure for southern Monterey Bay is outlined in Figure 42.

Figure 42. Recommended AMBAG Governance Structure



In this structure the AMBAG acts as the lead planning and coordinating agency which adopts, seeks funds, administers grants and studies, assists with implementation activities as deemed necessary by the local implementing agencies, and maintains and updates the Coastal RSM Plan. The AMBAG would receive funds, complete environmental documentation, acquire regional permits as appropriate, and plan coastal projects, as appropriate. Local land use decision-making and implementation would remain with the local agencies.

AMBAG is defined as the lead-planning agency for sediment management issues only (i.e. this would not include such issues as seawalls or other interventions involving structural solutions).

As other erosion control measures are defined and proposed, the JPA may, with Board approval, consider expanding its ‘powers’ to govern these measures (perched beaches, groins, dynamic revetments, breakwaters, submerged breakwater, headland enhancement, etc).

This Coastal RSM Plan recommends that the AMBAG investigates hiring a dedicated staff member to assist the Executive Director to specifically manage sediment management issues and co-ordinate staff. This recommendation is conditional upon being able to fund the position. The Executive Director would be advised and guided on regional sediment management issues by a committee comprising representatives from local cities, academic institutions and industry. It is recommended to continue the Southern Monterey Bay Coastal Erosion Workgroup (SMBCEW) in this role. The Executive Director would then report to the Board of Directors.

It is important to note that this structure may be updated as experience is gained with sand management in southern Monterey Bay. The AMBAG may also find, like SANDAG and BEACON, that one or more technical staff may be desired to help local agencies to implement particular projects which require special capabilities in coastal engineering, construction contract administration, and/or monitoring, as needed.

10.2.1 Partners

Three main partners working closely with the advisory committee in the implementation of RSM in southern Monterey Bay are identified in this Coastal RSM Plan. The Coastal Sediment Management Workgroup (CSMW) provides the framework for Coastal RSM Plans throughout coastal California. The California Department of Boating and Waterways (CDBW) is the state department that funds many beach nourishment and erosion control projects, and is a member of CSMW. CDBW could cost share with any public agency that has a Board comprised of elected officials and that has the authority to enter into an agreement. The AMBAG has authority for planning and environmental aspects of beach nourishment. The U.S. Army Corps of Engineers (Corps) is a federal agency that funds many beach nourishment, erosion control, and ecosystem restoration projects, and is also a member of CSMW. The Corps could cost share with any non-Federal public agency, and generally if CDBW can partner with the AMBAG then so can the Corps. To partner with the Corps, the AMBAG would need to sign an agreement and demonstrate an ability to pay.

The AMBAG would enter into contracts for coastal processes studies, planning, environmental review, permitting and engineering as needed. The AMBAG also may enter into construction contracts for beach nourishment, if deemed necessary or desirable by local agencies.

10.2.2 Implementation

Implementation of this Coastal RSM Plan means activation of the AMBAG’s role to coordinate information and funding between the various levels of government and to solicit grant funding for

various shoreline enhancement projects. In order for the Coastal RSM Plan to be considered when sediment management activities are being planned or implemented, the AMBAG should promote referencing of the Plan in individual Local Coastal Programs or Land Use Plans (cities of Monterey, Seaside, Sand City, Marina, and County of Monterey). The AMBAG could pursue implementation of the RSM plan by requesting that the local office of the Coastal Commission begin requiring all sediment management projects along the southern Monterey Bay shoreline be consistent with the Coastal RSM Plan by beneficially re-using surplus sediment for nourishment.

The AMBAG should coordinate with all local agencies (city and County-level) to pursue consistency with specific elements of the Coastal RSM Plan in their zoning ordinances and municipal codes in their General Plans. For example, any project component that requires a grading permit would be asked to show how that project could beneficially reuse surplus sediment (if it has the appropriate quality for nourishment purposes) within the coastal zone rather than for other purposes (such as construction materials or fill). Input from partner cities and the County of Monterey would be received by the SMBCEW, which would then make recommendations to the AMBAG Board of Directors.

The AMBAG should also work with MBNMS to find ways to implement RSM within the Sanctuary boundaries. This would specifically include ways to interpret or modify existing Sanctuary regulations to allow extraction and placement of sand for beach nourishment projects as part of the Harbors and Dredge Disposal Action Plan.

10.2.3 Outreach and Dissemination

In order for the AMBAG to coordinate with the local jurisdictions (County of Monterey, Cities of Monterey, Seaside, Sand City, Marina) and special districts to implement the Coastal RSM Plan, a post-Plan outreach program should be established. The AMBAG should develop existing resources including contact lists to provide a focused outreach campaign to encourage discussion amongst the southern Monterey Bay agencies and stakeholder groups. Public meetings should be also be convened as appropriate in which the AMBAG should seek public input and consensus to guide the implementation of the recommended actions in the Plan. This Coastal RSM Plan should also be supported through publication of brochures, fact sheets, and provision of information on the AMBAG, SMBCEW, and CSMW web pages.

11. DATA GAPS

11.1 SEDIMENT (SAND) BUDGET

Sections 1 and 2 outline the current knowledge about geomorphologic and sedimentary processes in southern Monterey Bay. However, in certain areas the knowledge is incomplete, and assumptions have been made. Two prioritized data gaps are summarized below, which should be filled in order to improve implementation of RSM initiatives.

Regional particle size characteristics and the littoral cell cut-off diameter: Data on regional sediment distribution and character are limited and is considered an important data gap in this Coastal RSM Plan. Filling this gap is important for several reasons:

- littoral cell cut-off diameters for each sub-cell need to be calculated to better assess beach nourishment needs and compatibility of source sediments.
- sediment particle size distributions of potential offshore source areas need to be established for compatibility with potential receiver sites. Side scan surveys to determine detailed bottom type, composition and depth are planned for Monterey Bay. These surveys would provide better information on offshore sand resources.
- the relationship between the particle size distributions of the dunes, beaches and shoreface should be examined to better quantify the amount of eroded sediment that remains in the littoral zone, and the impact of finer dune sand on beach slope and recession rate

Sediment transport calculations: Sediment transport will be calculated every 200 m as part of the COCMP and CDIP. An additional directional wave buoy was installed in southern Monterey Bay in 2007 to define the influence of sea breeze generated wind waves. This has improved the estimates of nearshore waves within southern Monterey Bay. The continually expanding information will provide better estimates on transport and definition of the south sub-cell between Wharf II and Sand City. This is important information for the design of a nourishment plan.

11.2 SENSITIVE SPECIES AND HABITAT

The current knowledge of the distribution of critical species and habitat in southern Monterey Bay is incomplete, and several areas need to be investigated further in order to understand the potential significance of sediment management activities. Two prioritized data gaps are summarized below, which should be filled in order to improve implementation of beach nourishment initiatives.

Distributions of kelp forest and eelgrass meadow: Knowledge regarding the general locations of kelp forest and eelgrass meadow in the southern bight is based on previous surveys undertaken

several years ago. However, these areas could have changed significantly over periods of years and new up-to-date subsurface information on distribution of kelp and eelgrass is needed for use in beach nourishment planning. This Coastal RSM Plan recommends new diver field surveys for project planning and assessment of the sensitivity of these habitats to potential beach nourishment.

Species and habitat of potential offshore borrow sites: Synchronous with the investigation of regional particle size identified as a data gap, the extent and types of benthic communities associated with the potential sand sources (offshore Sand City, Monterey Submarine Canyon) and their relationships to specific substrates is an important data gap. Without these data it is difficult to assess the impacts on these communities of sediment recovery by dredging in the offshore.

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APPENDIX A - SAND MINED FROM THE BEACHES AT SAND CITY AND MARINA

Table A-1. Annual beach-sand mined along southern Monterey Bay (yd³/year x 10³)

Company	Monterey Sand Company ³	Granite Construction	PCA ¹	Sub-total Sand City	Monterey Sand Company ³	Seaside Sand ²	PCA ¹	Sub-total Marina	Total
Location (miles from Wharf II)	3.0	3.1	3.5		9.1	9.5	9.8		
Year	1931-1990	1950-1969	1927-1986		1944-1986	1957-1970	1965-		
40's	37*	0	65*	102	20*	0	0	20	122
50's	37*	22*	65*	124	33*	7*	0	40	164
60	37*	8	14	59	33*	7	0	40	99
61	37*	40	52	129	33*	7	0	40	169
62	37*	33	44	114	33*	12	0	45	159
63	37*	33	41	111	33*	5	0	38	149
64	37*	31	39	107	33*	10	0	43	150
65	37*	31	39	107	33*	7	68	108	215
66	37*	0	78	115	33*	10	94	137	252
67	37*	14	108	159	33*	10	91	134	293
68	13	16	88	117	14	5	98	117	234
69	48	7	106	161	51	8	78	137	298
70	30	0	63	93	30	1	98*	129	222
71	85		59	144	34		98*	132	276
72	43		82*	125	44		98*	142	267
73	27*		82*	109	37*		98*	135	244
74	24		84	108	24		98*	122	230

COASTAL REGIONAL SEDIMENT MANAGEMENT PLAN FOR SOUTHERN MONTEREY BAY

Company	Monterey Sand Company ³	Granite Construction	PCA ¹	Sub-total	Monterey Sand Company ³	Seaside Sand ²	PCA ¹	Sub-total	Total
Location (miles from Wharf II)	3.0	3.1	3.5	Sand City	9.1	9.5	9.8	Marina	
75	30		74	104	31		98*	129	233
76	29		95	124	29		98*	127	251
77	26		91	117	27		98*	125	242
78	26		95	121	27		98*	125	246
79	24*		82*	106	25*		98*	123	229
80	24*		82*	106	25*		98*	123	229
81	24*		123	147	25*		98*	123	270
82	24*		65	89	25*		98*	123	212
83	7		58	65	12		98*	110	175
84	30		60	90	33		131*	164	254
85	22		74	96	60		131*	191	287
86	24		91	115	33		131*	164	279
87	58		7	65	0		131*	131	196
88	135		0	135	0		131*	131	266
89	60		0	60	0		175*	175	235
90	0						200*	200	200
90's							200*	200	200
00's							200	200	200

¹Pacific Concrete and Aggregates (PCA) was bought by Lone Star Industries and then by CEMEX in 2005

²Seaside Sand and Gravel Company was bought by Floyd Bradley in 1970 and then sold to Standard Resources in 1974.

³The Monterey Sand Company had mines at both Sand City and Marina and did not differentiate the total sand volumes reported, so the amount is evenly divided between the two mines.

³The Monterey Sand Company decreased the reported values by 3% to account for wash loss, and this has been added back into the volumes.

*Estimated values

APPENDIX B - LOW RISK AND /OR LOW CONSEQUENCE AREAS

Moss Landing spit communities

The Monterey Bay Aquarium Research Institute (MBARI) consists of a set of two main shoreline buildings connected by a catwalk, a warehouse that contains offices and Phil's Fish Market, and multiple structures to support research and development operations, including parking lots as well as docking facilities in the harbor. The original building was constructed in 1989, and major expansions occurred in 1995 and 2001. MBARI purchased an additional four square miles of land in the early 1990's, and is still in the process of developing plans for expansion and new facilities. The current property is located just south of the entrance to the Moss Landing Harbor, and includes land along the shoreline as well as the harbor. The current facilities span approximately 0.2 miles of shoreline beginning approximately 0.2 miles south of the entrance to Moss Landing Harbor. While the property is located on the beach, the area's erosion rates are strongly accretional in the long term and average to be moderately accretional in the short-term (Hapke et al., 2006). As such, the MBARI property and facilities are designated as low risk.

Monterey Dunes Colony

Monterey Dunes Colony comprises 120 vacation town homes stretched out over approximately 5,550 feet of shoreline. The most seaward units are within 100 feet of the dune edge. There is no information on the long-term movement of the dune face at this location. However, Hapke et al. (2006) showed that mean high water over the short term and long term has migrated seaward indicating beach accretion. The Monterey Dunes Colony is therefore designated as a facility at low risk of erosion.

Ocean outfall pipeline near Marina sand mine

The MRWPCA ocean outfall extends approximately three miles offshore from the beach near the Marina sand mine. The outfall pipeline is five feet in diameter and between the beach and 2,000 feet offshore is bounded on either side by sheet pile walls and capped by concrete. According to construction specifications, the outfall pipeline joins the onshore pipeline at a junction box with a top elevation of -23 feet NGVD. During the El Niño winter of 1998, back beach elevations were about +16 feet NGVD in the vicinity of the junction box. Given the depth of the pipeline at the junction box, it is unlikely that the outfall beneath the beach will be impacted significantly by erosion over the next 50 years. This assessment indicates that the ocean outfall pipeline is a low erosion risk facility (PWA and Griggs, 2004).

Fort Ord storm water and sewer outfalls

As part of the Fort Ord Reuse Plan of 1997, the Fort Ord Reuse Authority (FORA) is to eliminate all storm water discharges to Monterey Bay from Fort Ord. Prior to 2003, storm water from the Fort Ord site that is under FORA jurisdiction was discharged through three deteriorating outfalls.

In 2003, these outfalls were removed from the shoreline and replaced with two infiltration basins landward in the dunes. Although this project is temporary and expected to last about 20 years, a permanent solution is under preparation as part of a long-term drainage master plan and will include percolation galleries east of Highway 1. This project will improve water quality in the MBNMS, and reduce erosion at the former outfall sites, where small canyons have formed by undercutting and vertical failing of the buried pipes. Although remnants of the outfalls remain in the dunes, they are not functional. The land west of Highway 1 has been turned over to the California State Department of Parks and Recreation.

A fourth outfall structure towards the south end of Fort Ord was not removed, since it drains property that was not transferred to State Parks and is currently under Corps ownership. In 2003, the Corps constructed riprap, gabion, and grouted apron as a temporary fix to control erosion at this structure, but it failed during the first winter storm in December 2003. The watershed that drains to this outfall will be redeveloped as part of the Residential Communities Initiative (RCI). This effort was recently started (expected to be phased out over next 10 years), and will ultimately include on-site retention.

Fort Ord monitoring and injection wells

A suite of 13 monitoring wells in Fort Ord west of Highway 1 and north of the former Stillwell Hall exist to monitor the progress of a groundwater trichloroethene (TCE) plume that originated near 12th Street and is migrating seaward. These wells are part of a remediation program that also includes two injection wells into which treated water from the plume is pumped. Both the monitoring wells and injection wells are currently in use, and are owned and operated by the Corps. The wells are located at distance from the cliff edge and are not threatened by erosion.

Bay Avenue storm water outfall

The current 160-foot long concrete-lined Bay Avenue storm water outfall is exposed on the beach, causing aesthetic impacts and restricting public access along the beach. Several improvements to this outfall have been made, including: replacement with an 84 inch plastic pipe and new outlet headwall and overflow structure, with an overall length of 125-feet; removal of previously existing fencing, and installation of a diversion structure and pump station to divert dry-weather flows to the sanitary sewer system. These improvements reduced the length of the outfall on the beach by 35 feet, and improved local water quality by diverting dry-weather flows to a treatment facility. However, the storm drain outlet has not functioned as expected. The outlet is presently buried during normal conditions and has to be excavated before each expected rain so that the storm run-off does not cause floods in Sand City. As the outlet has not functioned as expected, the facility will probably have to be redesigned. The outfall crosses the beach and is therefore under imminent threat of erosion; a facility at high risk of erosion, but of low consequences economically.

Roberts Lake/Laguna Grande outfall

The Roberts Lake/Laguna Grande outfall, which was originally installed by Caltrans when Highway 1 was constructed, is located adjacent to the Monterey Beach Resort. The outfall drains the overflow from Roberts Lake and Laguna Grande, portions of Highway 1, the City of Del Rey Oaks, Fremont Boulevard, and approximately one third of the City of Seaside's storm water runoff. The outfall is located on the back beach at the landward point of the northern end wall of the hotel and is a facility at low risk of erosion.

It is possible that the drainage from this outfall is exacerbating coastal erosion locally by scour of the beach due to the high volume and velocity of water during high flows. A ponded area forms along the back beach in a trough created by erosion by the outfall water. This ponding compromises access to the beach and a temporary boardwalk is often constructed to allow crossing. This outfall has also presented water quality problems, as the urban runoff that flows to the ocean is not filtered, and can be contaminated.

Sand Dunes Drive

Sand Dunes Drive is located along the landward side of the Monterey Beach Resort. The road dead ends to vehicle traffic at the southwest extremity of the hotel where it joins a paved bike path/recreation trail. This section of road is used for access to the hotel and beach and is protected on the seaward side by the hotel. Sand Dunes Drive continues northeast running parallel to Highway 1, between the highway and the dunes, until it ends at Tioga Avenue. Immediately northeast of the Monterey Beach Resort the road is less than 250 feet from the edge of the dunes. Further to the north, the distance between the road and the shoreline becomes progressively greater. Given long-term future erosion rates of approximately 1.5 ft/year, the road would be compromised in 170 years, and is therefore at low risk of erosion.

Monterey Pump Station

Monterey Pump Station is located landward of a set of concrete structures that formed part of the former City of Monterey wastewater treatment plant decommissioned in 1990. The land surrounding the pump station is owned by the Navy, although MRWPCA continues to retain some of the underground tanks for possible emergency storage of peak flows that could occur during heavy rainfall. To date use of these tanks has not been necessary. Monterey Pump Station is set back about 350 feet from the present shoreline and at least part of the facility is protected on the seaward side by the concrete tanks. The facility is set back adequately to have a low risk of erosion over the next 50 years.

Del Monte Lake outfall

The Del Monte Lake outfall, located on the grounds of the Navy, provides drainage for Del Monte Lake overflow. The outfall is located at the dune-beach interface with water flows across the beach. A lateral access path was built over the outfall, which is protected to either side by riprap. The riprap also serves to protect the Monterey Interceptor, which is located halfway

between the headwall and the abandoned sewage treatment plant. Damage to the riprap occurred following storms in December 2002, after which it was repaired and increased through an emergency permit. Currently, the riprap extends approximately 65 feet in each direction from the outfall. Concentrated flow from this outfall can exacerbate beach erosion in the immediate vicinity, and cut off lateral access along the beach. The outfall is directly on the beach and under imminent threat of erosion and so the facility is considered to be at high risk of erosion or being damaged. However, it is a low consequence facility because the cost of repair is small, there is adequate room to rebuild and move the outfall landward, and at high tide or during storms it is possible to bypass the outfall by walking along the back of the beach.

Lake El Estero Pump Station and outfall

Lake El Estero Pump Station and outfall was likely constructed during the early 1960s. Since its construction, there have not been any issues with coastal erosion. Indeed, the City of Monterey often has problems with the outfall pipe getting buried in the sand over the summer, probably due to local accretion of beach sand in the lee of Wharf II. The Lake El Estero Pump Station and outfall are categorized as facilities at low risk of erosion.

Catellus East property near Wharf II

The Catellus East property is located near Wharf II on the seaward side of the recreation trail in Monterey. The building was constructed between 1949 and 1958, originally as a headquarters for the Sea Scouts. It served as a Boy Scout lodge and has been leased by Adventures-by-the-Sea, a local company that uses the building to host catered parties and corporate team building activities. The property is not under any immediate or long-term threat from erosion since it is well protected by local build-up of sand adjacent to Wharf II. Run-up does reach the building during the winter when the City of Monterey builds a sand berm extending from Wharf II to the Catellus building to protect Del Monte Avenue from being flooded during high tides and large waves. Future plans for the Catellus East property by the City of Monterey is to have it removed within a ten year time frame to complete the ‘windows on the bay project’.

APPENDIX C - ECONOMIC ANALYSIS USING CSBAT

Introduction

This Appendix sets out details of the input data used in the economic analysis, along with full reporting of the results that are summarized in Section 7 of the Plan.

The analysis of costs for the various beach nourishment alternatives and the recreational benefit analysis were performed using the Coastal Sediment Benefits Analysis Tool (CSBAT) developed by the California Sediment Management Workgroup (CSMW). There is no attempt to reproduce the background documents and guidance for this tool as a number of reports already exist that explain the tool and its analyses:

- The Coastal Sediment Benefits Analysis Tool (CSBAT – San Diego): *Technical Report*. Prepared by Everest, for U.S. Army Corps of Engineers (2008)
- Coastal Sediment Benefits Analysis Tool (CSBAT – San Diego): *How-To Users Guide*. Prepared by Everest, for U.S. Army Corps of Engineers (2007)
- The Coastal Sediment Benefits Analysis Tool (CSBAT – San Diego): *Technical Manual*. Prepared by Everest, for U.S. Army Corps of Engineers (2008)

These reports describe the analytical processes (e.g. cost and economic benefit functions) of the tool, together with guidance on its application. Details of the tool are also available from the CSMW website: <http://dbw.ca.gov/csmw/default.aspx>

Details of the input data and assumptions used in the CSBAT application are presented below. The data and methodology used to determine the ‘property protection benefits’ of the beach nourishment alternatives are also presented. The ‘Scenario’ and ‘Alternative’ reports produced by the tool are reproduced in full at the end of this appendix.

CSBAT assumptions and methodology

Table C.1 presents the input data used to run the CSBAT application for southern Monterey Bay. The values in white cells are inputs that were developed specifically to represent the local conditions in southern Monterey Bay. The grey cells represent those variables where no locally specific data was available so inputs were derived from review of the data used in previous (San Diego) applications of CSBAT.

Table C-1. Input Data for Southern Monterey Bay CSBAT Application

Parameter	Description	Southern Bight
s_d50	Particle diameter where there are 50 % finer [mm]	0.4 mm
s_fines	Clay and silts passing the #200 sieve (0.074 mm)	0%
existing_width	Existing width (ft) of the receiver beach before sediment application	150 ft
beach_length	Length (ft) of the beach that the source sediment could have been placed	15,000 ft (3 miles)
berm_height	Existing berm height (ft) of receiver beach	16 ft above MLLW
fill_length	Length (ft) of beach deposition of sediment from source site	15000 ft
depth_of_closure	Offshore depth (ft) beyond which there is little vertical change in the seabed with time	20 ft below MLLW
kelp	Whether kelp are present at the receiver site	yes
surfgrs	Whether surf grass beds are present at the receiver site	eel grass: yes; surf grass: unknown
grunion	Whether grunion are present at the receiver site	yes
gulltern	Whether gulls or terns are present at the receiver site	yes
divbirds	Whether diving birds are present at the receiver site	yes
shorebirds	Whether shorebirds are present at the receiver site	yes
fish	Whether fish of special status are present at the receiver site	yes
mammal	Whether reefs are present at the receiver site	yes
yearly_attendance	Number of yearly attendees	644,677
longshore_diffusivity	Coefficient corresponding to the tendency for wave action to spread out shoreline perturbation	0.261
state_spending	Amount of money spent in the state per year by visitors to the beach (\$)	11,236,720
local_spending	Amount of money spent locally per year by visitors to the beach (\$)	10,973,091
weather_value	The decimal percentage equivalent of the quality of weather at the beach	0.85
water_quality_value	The decimal percentage equivalent of the quality of water at the beach	0.84
beach_quality_value	The decimal percentage equivalent of the quality of beach at the beach	0.45
overcrowding value	The decimal percentage equivalent of the amount of space available at the beach	0.51

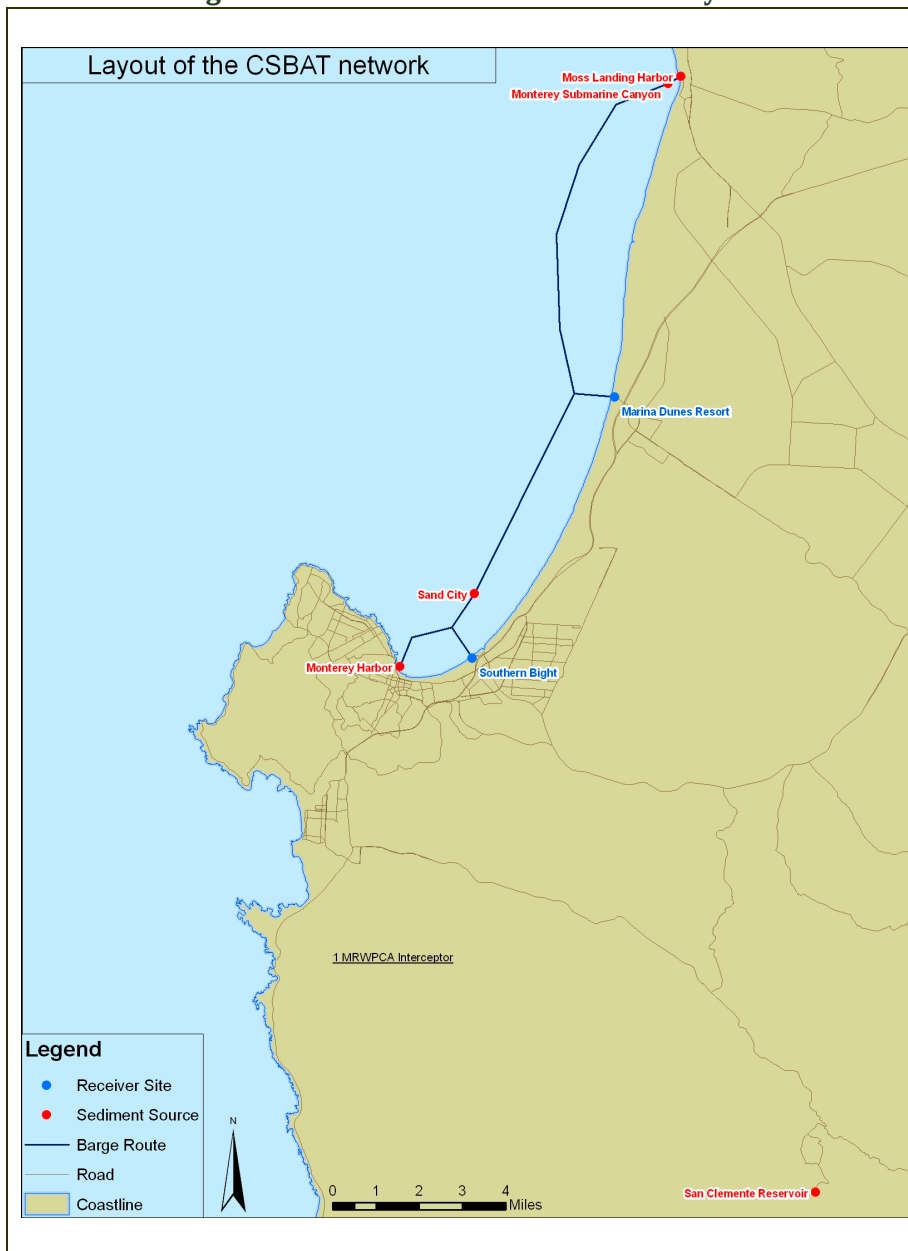
COASTAL REGIONAL SEDIMENT MANAGEMENT PLAN FOR SOUTHERN MONTEREY BAY

Parameter	Description	Southern Bight
facilities_value	The decimal percentage equivalent of the availability of facilities available at the beach	0.48
substitutes_value	The decimal percentage equivalent of the lack of available substitutes near the beach	0.44
weather_weight	Weight assigned to weather quality amenity value	0.2
water_quality_weight	Weight assigned to water quality amenity value	0.2
overcrowding_weight	Weight assigned to overcrowding amenity value	0.15
facilities_weight	Weight assigned to facilities amenity value	0.15
substitutes_weight	Weight assigned to substitutes amenity value	0.15
state_tax_rate	State tax rate	11.5
local_tax_rate	Local tax rate	2.5
discount_rate	The interest rate used in discounting future cash flows	0.05
attendance_increase_doubled	Increase in attendance when the beach width is doubled	0.025
max_daily_use_value	Maximum daily value derived per person attending the beach—\$14 for all beaches	14
day_use_value	Current value of attendance per person per day at receiver beach	8.02
overnight_factor_state	% of non-California residents who spend the night	0.36
overnight_spending_state	Dollar amount/day spent by non-California residents who spend the night	20
daytripper_factor_state	% of non-California residents who do not spend the night	0.64
daytripper_spending_state	Dollar amount/day spent by non-California residents who do not spend the night	16
overnight_factor_local	% of California residents who spend the night	0.38
overnight_spending_local	Dollar amount/day spent by California residents who spend the night	16
daytripper_factor_local	% of California residents who do not spend the night	0.62

The state and local spending totals were specific to Monterey Bay; in so much as they were calculated based on the local visitor numbers. However, the ‘spend per person’ data used to build the dollar value was derived from the figures from the San Diego application (annual spend was divided by annual attendance for each San Diego beach and the mean of these values was used for Monterey). The San Diego mean was \$17.43 and this value was multiplied by the Monterey visitor numbers to give the State and Local spending values.

The CSBAT tool uses a ‘geometric network’ within the project GIS to calculate transport routes, distances, etc in the cost calculations. Figure C.1 illustrates the network developed for southern Monterey Bay.

Figure C-1. Network Used in CSBAT Analysis



Outputs from CSBAT

The full ‘Scenario’ report outputs are at the end of this appendix. These scenarios provide a summary of the input data for each combination of source and receiver site, together with mapping to illustrate the location and environmental factors. The final page of each report presents the cost estimate, beach width increase and recreational benefit build-up.

The tool presents details for each individual scenario and then allows the user to combine a number of scenarios to create an ‘Alternative’. This allows multiple source/receiver site combinations to be considered as a single alternative, in order to rationalize mobilization/demobilization costs etc. Note that no combinations of scenarios were considered for this study, hence the alternative outputs each relate to an individual scenario. Table C.2 presents the full set of all ‘alternative’ outputs from the CSBAT application.

Discounting Process

Discounting is the procedure used to sum economic benefits over the lifetime of the project using a discount rate to scale down future benefits and costs. The effect of using a discount rate is to reduce the value of projected future benefits to their values as seen from the present day. This process effectively reduces the present day value of benefits accrued in the future in order to give them an appropriate level of influence on present day decision making. Consequently, the sooner a benefit is realized the greater its relative value will be. In the context of this study, protection of assets at risk in the early years of the analysis has the greatest relative benefit.

For this study a discount rate of 5% has been used. This is consistent with the Federal Discount Rate for FY 2008 used by the U.S. Army Corps of Engineers. To illustrate this process; if a property worth \$100,000 were anticipated to be lost this year the value of that loss would be \$100,000. However, if the loss were to occur next year the present value would be approximately \$95,000 (with the 5% reduction). With cumulative reductions over time, the later the loss, the lower its present value. Consequently the ‘benefit’ of delaying erosion is the reduction in the value of loss that is achieved through the delay.

COASTAL REGIONAL SEDIMENT MANAGEMENT PLAN FOR SOUTHERN MONTEREY BAY

Table C-2. 'Alternative' Outputs from the CSBAT Application

Option		Total Costs	Sub Total Costs	Mob/Demob Costs	Fill Volume	Increased Recreation	Benefit/Cost Ratio	Cost/Yard	Number of Environmental Factors
1a	75k from Monterey Harbor to Southern Bight via hopper beach	\$1,031,560	\$431,560	\$600,000	75,000	\$54,955	0.1	\$14	9
1b	75k from Monterey Harbor to Southern Bight via hopper nearshore	\$693,503	\$193,503	\$500,000	75,000	\$36,264	0.1	\$9	9
2a	2M from Sand City to Southern Bight via hopper beach	\$11,644,907	\$11,044,907	\$600,000	2,000,000	\$8,067,127	0.7	\$6	9
2b	2M from Sand City to Southern Bight via hopper nearshore	\$5,332,452	\$4,832,452	\$500,000	2,000,000	\$1,479,160	0.3	\$3	9
2c	2M from Monterey Sub to Southern Bight via hopper beach	\$20,347,048	\$19,747,048	\$600,000	2,000,000	\$8,067,127	0.4	\$10	9
2d	2M from Monterey Sub to Southern Bight via hopper nearshore	\$11,373,016	\$10,873,016	\$500,000	2,000,000	\$1,479,160	0.1	\$6	9

Scenario ID: 75000 Cy from Monterey Harbor to Southern Bight via hopper beach

Nearshore Placement of Sediment

Source Location

Source Site: Monterey Harbor
County: Monterey
Littoral Cell: Monterey

Receiver Location

Receiver Beach: Southern Bight
County: Monterey
Littoral Cell: Monterey

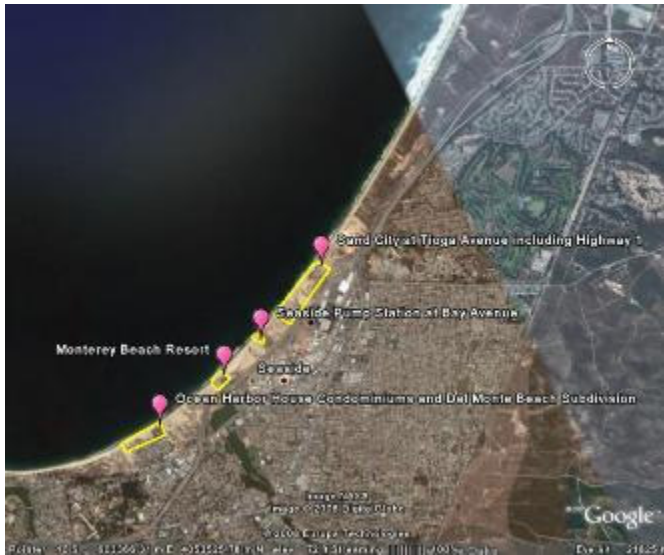
Receiver Beach Information

Existing Beach Width*(ft): 150
Beach Fill Length(ft): 15,000
Berm Fill Volume(cy): 75,000
Increased Beach Width, Yr-0(ft): 3.75

*Based on site observation in

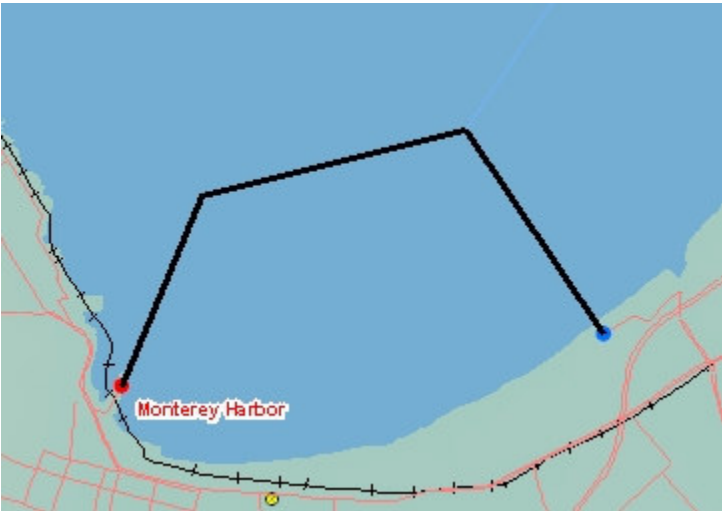
Sediment Characteristics

Receiver D50 (mm): 0.4
Source D50 (mm): 0.3
Receiver % Fines: 0
Source % Fines: 5



Receiver Beach or Sediment Source: Environmental Considerations

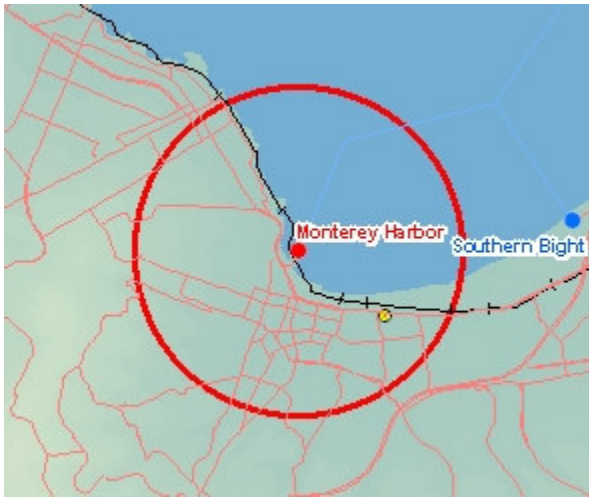
Reefs: No	Kelp Beds: Yes 	Eelgrass/ Surfgrass: Yes 	Grunion: Yes 
Fish: Yes 	Gulls/ Terns: Yes 	Shorebirds: Yes 	Diving Birds: Yes 
Shellfish: No	Wading Birds: Yes 	Marine Mammals: Yes 	Transit Trips: 28



Sediment Source: Environmental Considerations

Reefs: No	Kelp Beds: No	Eelgrass/ Surfgrass: No	Grunion: No
Fish: No	Gulls/ Terns: No	Shorebirds: No	Diving Birds: No
Shellfish: No	Wading Birds: No	Marine Mammals: No	

Kelp Persistence (1967-1999)



Oceanfloor Substrate



Receiver Beach: Environmental Considerations

Reefs: No	Kelp Beds: Yes	Eelgrass/ Surfgrass: Yes	Grunion: Yes
Fish: Yes	Gulls/ Terns: Yes	Shorebirds: Yes	Diving Birds: Yes
Shellfish: No	Wading Birds: Yes	Marine Mammals: Yes	

Kelp Persistence (1967-1999)



Oceanfloor Substrate



Receiver Beach Characteristics

Beach Width (ft):	150	Beach Fill Location:	
Beach Length (ft):	15,000	Beach Fill Length (ft):	15,000
Berm Height(ft):	16	Berm Volume (cy):	75,000
Historical Erosion Rate (ft/yr):	3.45	Depth of Closure (ft):	20
Longshore Diffusivity (sqft/sec):	0.261		

Increased Beach Width (ft) from Fill Placement:

Year-0:	Year-1:	Year-2:	Year-3:	Year-4:	Year-5:	Year-6:	Year-7:	Year-8:	Year-9:	Year-10:
3.75	0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Scenario Costs

Miles Source to Receiver

Hopper Distance (mi):	2.53
Speed of Vessel (mph):	7
Hopper Capacity (cy):	2,700

Economic Variables

Amenity Weighted Value (%)

Weather:	0.85
Water Quality:	0.84
Beach Width/Quality:	0.45

Hopper Down Time Percentage: 20%
Hopper Trips Per Day 4.6
Total Hopper Trips: 28
Construction Period (days) 6
Hopper Total Transport Cost 431,560

Overcrowding: 0.51
Facilities/Services: 0.48
Availability of Alternatives: 0.44
Total Index Value: 0.59
Day Use Value : \$5,358,353.30
Annual Attendance: 644,677
Existing Spending in CA : \$11,243,166.88
Existing Local Spending : \$9,035,792.83
Existing Taxes in CA : \$1,292,964.19
Existing Local Taxes : \$225,894.82
Existing Recreational Benefit : \$5,170,310

Beach Nourishment Cost* : \$431,560

Scenario Benefits

	Increased	S/L Spending	S/L Taxes	Rec Value
*Costs do not include mobilization and demobilization of equipment. These costs are added in once a Scenario is added to an Alternative.	Year-0	\$11,243.17	\$1,292.96	\$38,328.96
	Year-1	\$899.45	\$103.44	\$2,940.10
	Year-2	\$0.00	\$0.00	\$0.00
	Year-3	\$0.00	\$0.00	\$0.00
	Year-4	\$0.00	\$0.00	\$0.00
	Year-5	\$0.00	\$0.00	\$0.00
	Year-6	\$0.00	\$0.00	\$0.00
	Year-7	\$0.00	\$0.00	\$0.00
	Year-8	\$0.00	\$0.00	\$0.00
	Year-9	\$0.00	\$0.00	\$0.00
	Year-10	\$0.00	\$0.00	\$0.00
	Total			\$54,955
	Increase in Recreational Benefit :			\$54,955

Scenario ID: 75000 Cy from Monterey Harbor to Southern Bight via hopper nearshore

Nearshore Placement of Sediment

Source Location

Source Site: Monterey Harbor
County: Monterey
Littoral Cell: Monterey

Receiver Location

Receiver Beach: Southern Bight
County: Monterey
Littoral Cell: Monterey

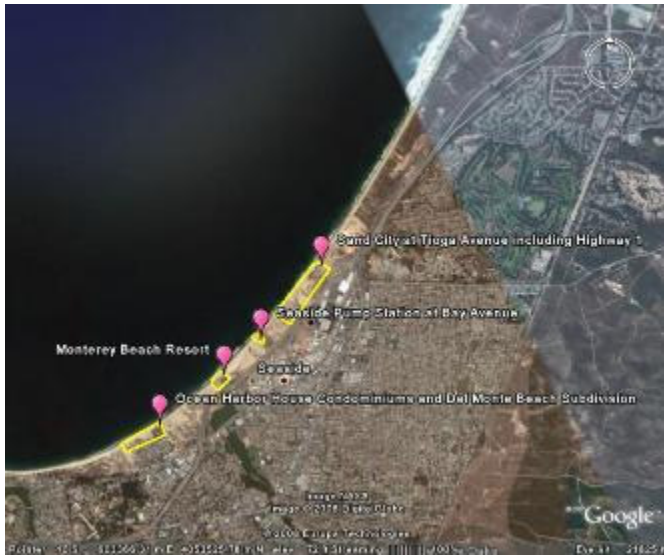
Receiver Beach Information

Existing Beach Width*(ft): 150
Beach Fill Length(ft): 15,000
Berm Fill Volume(cy): 75,000
Increased Beach Width, Yr-0(ft): 0.00

*Based on site observation in

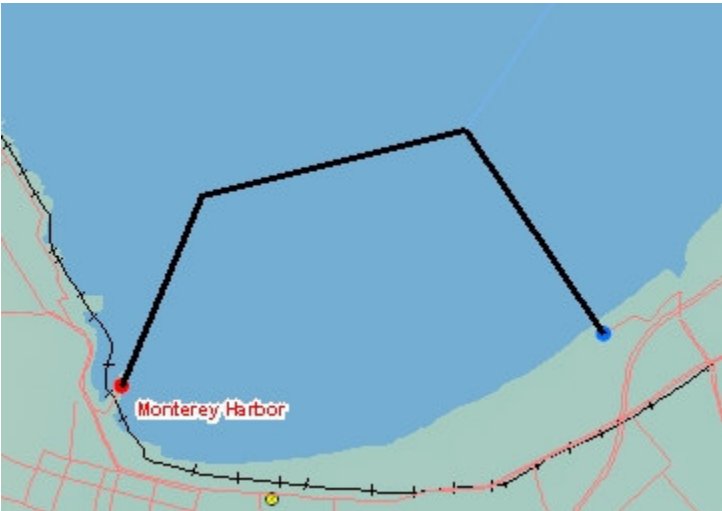
Sediment Characteristics

Receiver D50 (mm): 0.4
Source D50 (mm): 0.3
Receiver % Fines: 0
Source % Fines: 5



Receiver Beach or Sediment Source: Environmental Considerations

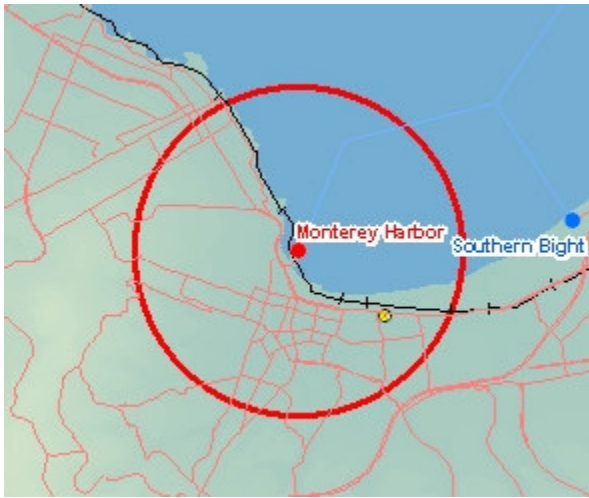
Reefs: No	Kelp Beds: Yes 	Eelgrass/ Surfgrass: Yes 	Grunion: Yes 
Fish: Yes 	Gulls/ Terns: Yes 	Shorebirds: Yes 	Diving Birds: Yes 
Shellfish: No	Wading Birds: Yes 	Marine Mammals: Yes 	Transit Trips: 28



Sediment Source: Environmental Considerations

Reefs: No	Kelp Beds: No	Eelgrass/ Surfgrass: No	Grunion: No
Fish: No	Gulls/ Terns: No	Shorebirds: No	Diving Birds: No
Shellfish: No	Wading Birds: No	Marine Mammals: No	

Kelp Persistence (1967-1999)



Oceanfloor Substrate



Receiver Beach: Environmental Considerations

Reefs: No	Kelp Beds: Yes	Eelgrass/ Surfgrass: Yes	Grunion: Yes
Fish: Yes	Gulls/ Terns: Yes	Shorebirds: Yes	Diving Birds: Yes
Shellfish: No	Wading Birds: Yes	Marine Mammals: Yes	

Kelp Persistence (1967-1999)



Oceanfloor Substrate



Receiver Beach Characteristics

Beach Width (ft):	150	Beach Fill Location:	
Beach Length (ft):	15,000	Beach Fill Length (ft):	15,000
Berm Height(ft):	16	Berm Volume (cy):	75,000
Historical Erosion Rate (ft/yr):	3.45	Depth of Closure (ft):	20
Longshore Diffusivity (sqft/sec):	0.261		

Increased Beach Width (ft) from Fill Placement:

Year-0:	Year-1:	Year-2:	Year-3:	Year-4:	Year-5:	Year-6:	Year-7:	Year-8:	Year-9:	Year-10:
0.00	0.60	0.98	1.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Scenario Costs

Miles Source to Receiver

Hopper Distance (mi):	2.53
Speed of Vessel (mph):	7
Hopper Capacity (cy):	2,700

Economic Variables

Amenity Weighted Value (%)

Weather:	0.85
Water Quality:	0.84
Beach Width/Quality:	0.45

Hopper Cost (day): \$41,100
Hopper Down Time Percentage: 20%
Hopper Trips Per Day 5.9
Total Hopper Trips: 28
Construction Period (days) 5
Hopper Total Transport Cost 193,503

Overcrowding: 0.51
Facilities/Services: 0.48
Availability of Alternatives: 0.44
Total Index Value: 0.59
Day Use Value : \$5,358,353.30
Annual Attendance: 644,677
Existing Spending in CA : \$11,243,166.88
Existing Local Spending : \$9,035,792.83
Existing Taxes in CA : \$1,292,964.19
Existing Local Taxes : \$225,894.82
Existing Recreational Benefit : \$5,170,310

Beach Nourishment Cost* : \$193,503

Scenario Benefits

	Increased	S/L Spending	S/L Taxes	Rec Value
*Costs do not include mobilization and demobilization of equipment. These costs are added in once a Scenario is added to an Alternative.	Year-0	\$0.00	\$0.00	\$0.00
	Year-1	\$1,798.91	\$206.87	\$5,876.71
	Year-2	\$2,923.22	\$336.17	\$9,088.18
	Year-3	\$3,260.52	\$374.96	\$9,651.97
	Year-4	\$0.00	\$0.00	\$0.00
	Year-5	\$0.00	\$0.00	\$0.00
	Year-6	\$0.00	\$0.00	\$0.00
	Year-7	\$0.00	\$0.00	\$0.00
	Year-8	\$0.00	\$0.00	\$0.00
	Year-9	\$0.00	\$0.00	\$0.00
	Year-10	\$0.00	\$0.00	\$0.00
	Total			\$36,264
	Increase in Recreational Benefit :			\$36,264

Scenario ID: 2000000 Cy from Sand City to Southern Bight via hopper beach

Nearshore Placement of Sediment

Source Location

Source Site: Sand City
County: Monterey
Littoral Cell: Monterey

Receiver Location

Receiver Beach: Southern Bight
County: Monterey
Littoral Cell: Monterey

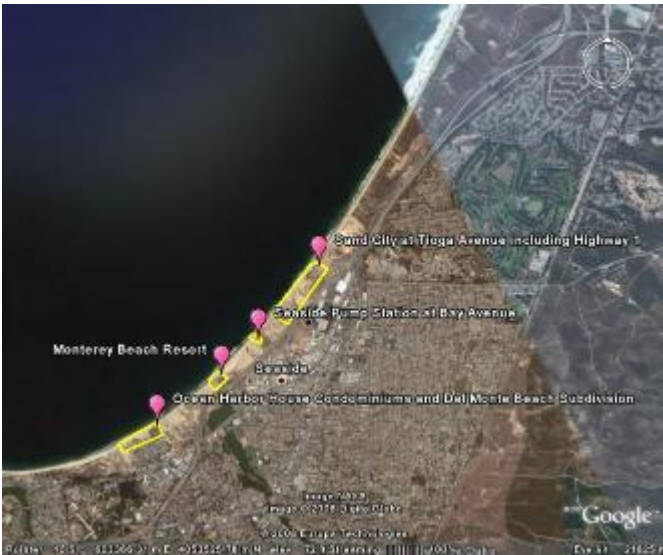
Receiver Beach Information

Existing Beach Width*(ft): 150
Beach Fill Length(ft): 15,000
Berm Fill Volume(cy): 2,000,000
Increased Beach Width, Yr-0(ft): 100.00

*Based on site observation in

Sediment Characteristics

Receiver D50 (mm): 0.4
Source D50 (mm): 0.6
Receiver % Fines: 0
Source % Fines: 20



Receiver Beach or Sediment Source: Environmental Considerations

Reefs: No	Kelp Beds: Yes 	Eelgrass/ Surfgrass: Yes 	Grunion: Yes 
Fish: Yes 	Gulls/ Terns: Yes 	Shorebirds: Yes 	Diving Birds: Yes 
Shellfish: No	Wading Birds: Yes 	Marine Mammals: Yes 	Transit Trips: 741



Sediment Source: Environmental Considerations

Reefs: No	Kelp Beds: No	Eelgrass/ Surfgrass: No	Grunion: No
Fish: No	Gulls/ Terns: No	Shorebirds: No	Diving Birds: No
Shellfish: No	Wading Birds: No	Marine Mammals: No	

Kelp Persistence (1967-1999)



Oceanfloor Substrate



Receiver Beach: Environmental Considerations

Reefs: No	Kelp Beds: Yes	Eelgrass/ Surfgrass: Yes	Grunion: Yes
Fish: Yes	Gulls/ Terns: Yes	Shorebirds: Yes	Diving Birds: Yes
Shellfish: No	Wading Birds: Yes	Marine Mammals: Yes	

Kelp Persistence (1967-1999)



Oceanfloor Substrate



Receiver Beach Characteristics

Beach Width (ft):	150	Beach Fill Location:	
Beach Length (ft):	15,000	Beach Fill Length (ft):	15,000
Berm Height(ft):	16	Berm Volume (cy):	2,000,000
Historical Erosion Rate (ft/yr):	3.45	Depth of Closure (ft):	20
Longshore Diffusivity (sqft/sec):	0.261		

Increased Beach Width (ft) from Fill Placement:

Year-0:	Year-1:	Year-2:	Year-3:	Year-4:	Year-5:	Year-6:	Year-7:	Year-8:	Year-9:	Year-10:
100.00	77.76	69.15	62.84	57.94	54.01	50.56	47.11	43.66	40.21	36.76

Scenario Costs

Miles Source to Receiver	
Hopper Distance (mi):	1.81
Speed of Vessel (mph):	7
Hopper Capacity (cy):	2,700

Economic Variables

Amenity	Weighted Value (%)
Weather:	0.85
Water Quality:	0.84
Beach Width/Quality:	0.45

Hopper Down Time Percentage:	20%
Hopper Trips Per Day	4.9
Total Hopper Trips:	741
Construction Period (days)	151
Hopper Total Transport Cost	11,044,907

Overcrowding:	0.51
Facilities/Services:	0.48
Availability of Alternatives:	0.44
Total Index Value:	0.59
Day Use Value :	\$5,358,353.30
Annual Attendance:	644,677
Existing Spending in CA :	\$11,243,166.88
Existing Local Spending :	\$9,035,792.83
Existing Taxes in CA :	\$1,292,964.19
Existing Local Taxes :	\$225,894.82

Beach Nourishment Cost* : \$11,044,907

Existing Recreational Benefit : \$5,170,310

Scenario Benefits

	Increased	S/L Spending	S/L Taxes	Rec Value
Year-0	\$299,817.78	\$34,479.05	\$880,494.95	
Year-1	\$233,135.65	\$26,810.60	\$671,329.55	
Year-2	\$207,325.31	\$23,842.41	\$575,432.49	
Year-3	\$188,413.20	\$21,667.52	\$502,571.24	
Year-4	\$173,727.76	\$19,978.69	\$444,523.33	
Year-5	\$161,928.24	\$18,621.75	\$396,936.40	
Year-6	\$151,584.52	\$17,432.22	\$355,751.75	
Year-7	\$141,240.81	\$16,242.69	\$317,381.66	
Year-8	\$130,897.10	\$15,053.17	\$281,655.19	
Year-9	\$120,553.38	\$13,863.64	\$248,411.14	
Year-10	\$110,209.67	\$12,674.11	\$217,497.50	
Total			\$8,067,127	
Increase in Recreational Benefit :			\$8,067,127	

*Costs do not include mobilization and demobilization of equipment. These costs are added in once a Scenario is added to an Alternative.

Scenario ID: 2000000 Cy from Sand City to Southern Bight via hopper nearshore

Nearshore Placement of Sediment

Source Location

Source Site: Sand City
County: Monterey
Littoral Cell: Monterey

Receiver Location

Receiver Beach: Southern Bight
County: Monterey
Littoral Cell: Monterey

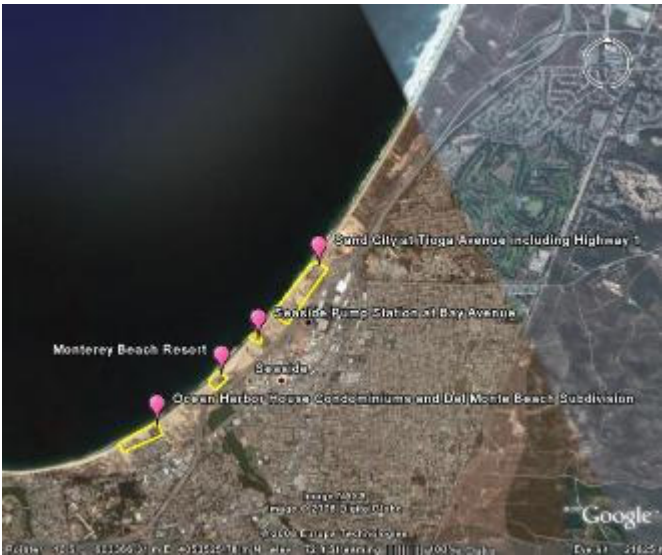
Receiver Beach Information

Existing Beach Width*(ft): 150
Beach Fill Length(ft): 15,000
Berm Fill Volume(cy): 2,000,000
Increased Beach Width, Yr-0(ft): 0.00

*Based on site observation in

Sediment Characteristics

Receiver D50 (mm): 0.4
Source D50 (mm): 0.6
Receiver % Fines: 0
Source % Fines: 20



Receiver Beach or Sediment Source: Environmental Considerations

Reefs: No	Kelp Beds: Yes 	Eelgrass/ Surfgrass: Yes 	Grunion: Yes 
Fish: Yes 	Gulls/ Terns: Yes 	Shorebirds: Yes 	Diving Birds: Yes 
Shellfish: No	Wading Birds: Yes 	Marine Mammals: Yes 	Transit Trips: 741



Sediment Source: Environmental Considerations

Reefs: No	Kelp Beds: No	Eelgrass/ Surfgrass: No	Grunion: No
Fish: No	Gulls/ Terns: No	Shorebirds: No	Diving Birds: No
Shellfish: No	Wading Birds: No	Marine Mammals: No	

Kelp Persistence (1967-1999)



Oceanfloor Substrate



Receiver Beach: Environmental Considerations

Reefs: No	Kelp Beds: Yes	Eelgrass/ Surfgrass: Yes	Grunion: Yes
Fish: Yes	Gulls/ Terns: Yes	Shorebirds: Yes	Diving Birds: Yes
Shellfish: No	Wading Birds: Yes	Marine Mammals: Yes	

Kelp Persistence (1967-1999)



Oceanfloor Substrate



Receiver Beach Characteristics

Beach Width (ft):	150	Beach Fill Location:	
Beach Length (ft):	15,000	Beach Fill Length (ft):	15,000
Berm Height(ft):	16	Berm Volume (cy):	2,000,000
Historical Erosion Rate (ft/yr):	3.45	Depth of Closure (ft):	20
Longshore Diffusivity (sqft/sec):	0.261		

Increased Beach Width (ft) from Fill Placement:

Year-0:	Year-1:	Year-2:	Year-3:	Year-4:	Year-5:	Year-6:	Year-7:	Year-8:	Year-9:	Year-10:
0.00	16.00	26.00	29.00	15.00	11.55	8.10	4.65	1.20	0.00	0.00

Scenario Costs

Miles Source to Receiver

Hopper Distance (mi):	1.81
Speed of Vessel (mph):	7
Hopper Capacity (cy):	2,700

Economic Variables

Amenity Weighted Value (%)

Weather:	0.85
Water Quality:	0.84
Beach Width/Quality:	0.45

Hopper Cost (day):	\$41,100	Overcrowding:	0.51
Hopper Down Time Percentage:	20%	Facilities/Services:	0.48
Hopper Trips Per Day	6.3	Availability of Alternatives:	0.44
Total Hopper Trips:	741	Total Index Value:	0.59
Construction Period (days)	118	Day Use Value :	\$5,358,353.30
Hopper Total Transport Cost	4,832,451	Annual Attendance:	644,677
		Existing Spending in CA :	\$11,243,166.88
		Existing Local Spending :	\$9,035,792.83
		Existing Taxes in CA :	\$1,292,964.19
		Existing Local Taxes :	\$225,894.82
Beach Nourishment Cost* : \$4,832,451		Existing Recreational Benefit :	\$5,170,310

Scenario Benefits

	Increased	S/L Spending	S/L Taxes	Rec Value
*Costs do not include mobilization and demobilization of equipment. These costs are added in once a Scenario is added to an Alternative.	Year-0	\$0.00	\$0.00	\$0.00
	Year-1	\$47,970.85	\$5,516.65	\$152,211.50
	Year-2	\$77,952.62	\$8,964.55	\$231,434.84
	Year-3	\$86,947.16	\$9,998.92	\$244,587.26
	Year-4	\$44,972.67	\$5,171.86	\$123,492.66
	Year-5	\$34,628.95	\$3,982.33	\$91,138.40
	Year-6	\$24,285.24	\$2,792.80	\$61,266.82
	Year-7	\$13,941.53	\$1,603.28	\$33,718.45
	Year-8	\$3,597.81	\$413.75	\$8,343.06
	Year-9	\$0.00	\$0.00	\$0.00
	Year-10	\$0.00	\$0.00	\$0.00
	Total			\$1,479,160
	Increase in Recreational Benefit :			\$1,479,160

Scenario ID: 2000000 Cy from Monterey Submarine Canyon to Southern Bight via hopper beach

Nearshore Placement of Sediment

Source Location

Source Site: Monterey Submarine Canyon
County: Monterey
Littoral Cell: Monterey

Receiver Location

Receiver Beach: Southern Bight
County: Monterey
Littoral Cell: Monterey

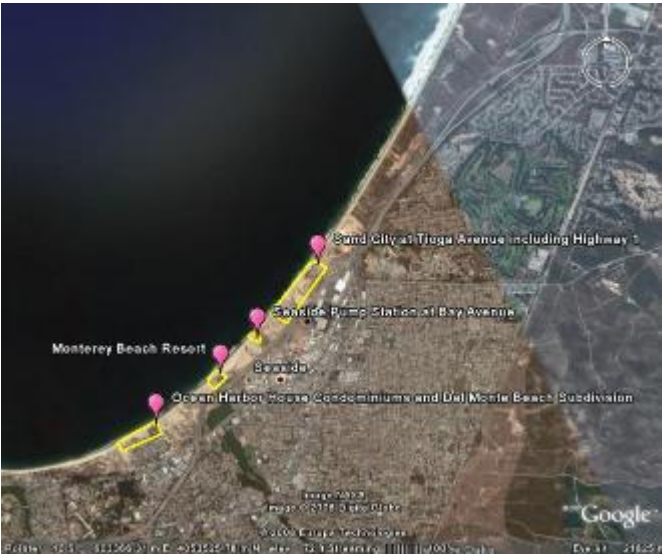
Receiver Beach Information

Existing Beach Width*(ft): 150
Beach Fill Length(ft): 15,000
Berm Fill Volume(cy): 2,000,000
Increased Beach Width, Yr-0(ft): 100.00

*Based on site observation in

Sediment Characteristics

Receiver D50 (mm): 0.4
Source D50 (mm): 0.4
Receiver % Fines: 0
Source % Fines: 5



Receiver Beach or Sediment Source: Environmental Considerations

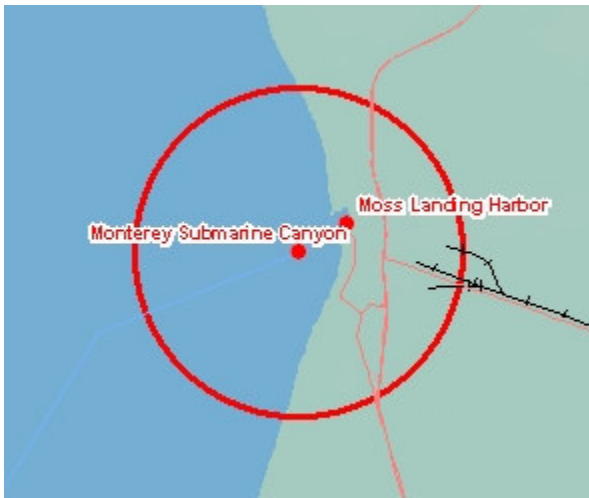
Reefs: No	Kelp Beds: Yes	Eelgrass/ Surfgrass: Yes	Grunion: Yes
Fish: Yes	Gulls/ Terns: Yes	Shorebirds: Yes	Diving Birds: Yes
Shellfish: No	Wading Birds: Yes	Marine Mammals: Yes	Transit Trips: 741



Sediment Source: Environmental Considerations

Reefs: No	Kelp Beds: No	Eelgrass/ Surfgrass: No	Grunion: No
Fish: No	Gulls/ Terns: No	Shorebirds: No	Diving Birds: No
Shellfish: No	Wading Birds: No	Marine Mammals: No	

Kelp Persistence (1967-1999)



Oceanfloor Substrate



Receiver Beach: Environmental Considerations

Reefs: No	Kelp Beds: Yes	Eelgrass/ Surfgrass: Yes	Grunion: Yes
Fish: Yes	Gulls/ Terns: Yes	Shorebirds: Yes	Diving Birds: Yes
Shellfish: No	Wading Birds: Yes	Marine Mammals: Yes	

Kelp Persistence (1967-1999)



Oceanfloor Substrate



Receiver Beach Characteristics

Beach Width (ft):	150	Beach Fill Location:	
Beach Length (ft):	15,000	Beach Fill Length (ft):	15,000
Berm Height(ft):	16	Berm Volume (cy):	2,000,000
Historical Erosion Rate (ft/yr):	3.45	Depth of Closure (ft):	20
Longshore Diffusivity (sqft/sec):	0.261		

Increased Beach Width (ft) from Fill Placement:

Year-0:	Year-1:	Year-2:	Year-3:	Year-4:	Year-5:	Year-6:	Year-7:	Year-8:	Year-9:	Year-10:
100.00	77.76	69.15	62.84	57.94	54.01	50.56	47.11	43.66	40.21	36.76

Scenario Costs

Miles Source to Receiver

Hopper Distance (mi): 15.33

Economic Variables

Amenity

Weather:

Weighted Value (%)

0.85

Speed of Vessel (mph): 7
Hopper Capacity (cy): 2,700
Hopper Down Time Percentage: 20%
Hopper Trips Per Day 2.4
Total Hopper Trips: 741
Construction Period (days) 309
Hopper Total Transport Cost 19,747,047

Water Quality: 0.84
Beach Width/Quality: 0.45
Overcrowding: 0.51
Facilities/Services: 0.48
Availability of Alternatives: 0.44
Total Index Value: 0.59
Day Use Value : \$5,358,353.30
Annual Attendance: 644,677
Existing Spending in CA : \$11,243,166.88
Existing Local Spending : \$9,035,792.83
Existing Taxes in CA : \$1,292,964.19
Existing Local Taxes : \$225,894.82

Beach Nourishment Cost* : \$19,747,047

Existing Recreational Benefit : \$5,170,310

Scenario Benefits

	Increased	S/L Spending	S/L Taxes	Rec Value
*Costs do not include mobilization and demobilization of equipment. These costs are added in once a Scenario is added to an Alternative.	Year-0	\$299,817.78	\$34,479.05	\$880,494.95
	Year-1	\$233,135.65	\$26,810.60	\$671,329.55
	Year-2	\$207,325.31	\$23,842.41	\$575,432.49
	Year-3	\$188,413.20	\$21,667.52	\$502,571.24
	Year-4	\$173,727.76	\$19,978.69	\$444,523.33
	Year-5	\$161,928.24	\$18,621.75	\$396,936.40
	Year-6	\$151,584.52	\$17,432.22	\$355,751.75
	Year-7	\$141,240.81	\$16,242.69	\$317,381.66
	Year-8	\$130,897.10	\$15,053.17	\$281,655.19
	Year-9	\$120,553.38	\$13,863.64	\$248,411.14
	Year-10	\$110,209.67	\$12,674.11	\$217,497.50
	Total			\$8,067,127
	Increase in Recreational Benefit :			\$8,067,127

Scenario ID: 2000000 Cy from Monterey Submarine Canyon to Southern Bight via hopper nearshore

Nearshore Placement of Sediment

Source Location

Source Site: Monterey Submarine Canyon
County: Monterey
Littoral Cell: Monterey

Receiver Location

Receiver Beach: Southern Bight
County: Monterey
Littoral Cell: Monterey

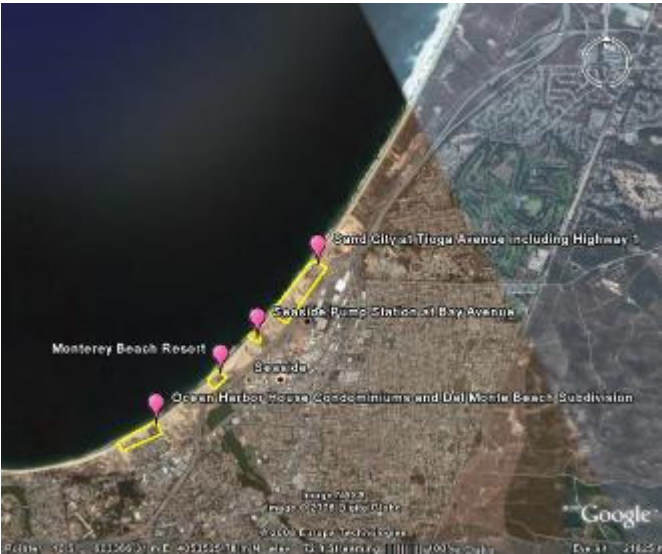
Receiver Beach Information

Existing Beach Width*(ft): 150
Beach Fill Length(ft): 15,000
Berm Fill Volume(cy): 2,000,000
Increased Beach Width, Yr-0(ft): 0.00

*Based on site observation in

Sediment Characteristics

Receiver D50 (mm): 0.4
Source D50 (mm): 0.4
Receiver % Fines: 0
Source % Fines: 5



Receiver Beach or Sediment Source: Environmental Considerations

Reefs: No	Kelp Beds: Yes	Eelgrass/ Surfgrass: Yes	Grunion: Yes
Fish: Yes	Gulls/ Terns: Yes	Shorebirds: Yes	Diving Birds: Yes
Shellfish: No	Wading Birds: Yes	Marine Mammals: Yes	Transit Trips: 741



Sediment Source: Environmental Considerations

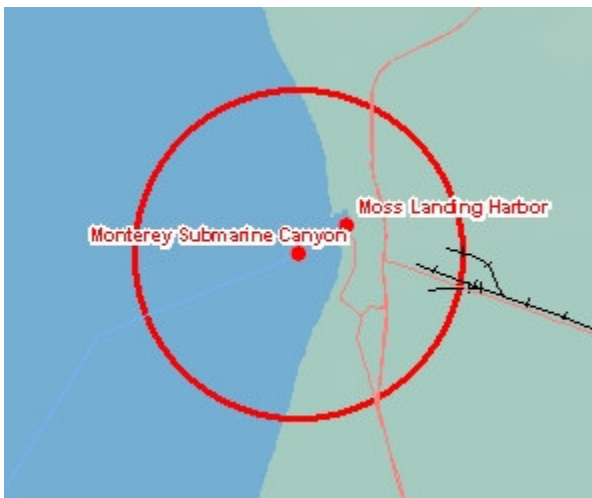
Reefs: No	Kelp Beds: No	Eelgrass/ Surfgrass: No	Grunion: No
Fish: No	Gulls/ Terns: No	Shorebirds: No	Diving Birds: No

Shellfish: No

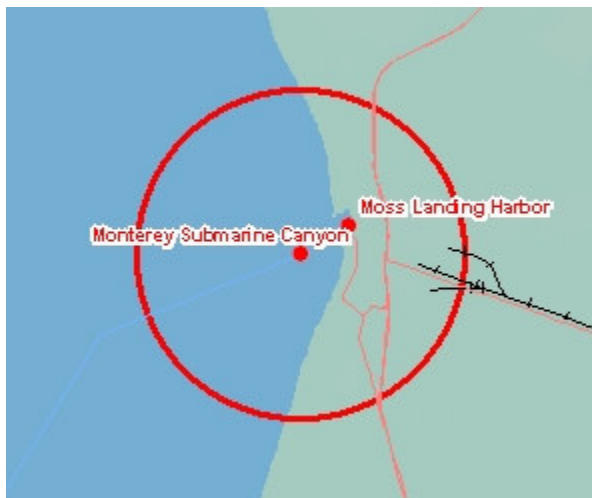
Wading Birds: No

Marine Mammals: No

Kelp Persistence (1967-1999)



Oceanfloor Substrate



Receiver Beach: Environmental Considerations

Reefs: No

Kelp Beds: Yes



Eelgrass/ Surfgrass: Yes



Grunion: Yes



Fish: Yes



Gulls/ Terns: Yes



Shorebirds: Yes



Diving Birds: Yes



Shellfish: No

Wading Birds: Yes



Marine Mammals: Yes



Kelp Persistence (1967-1999)



Oceanfloor Substrate



Receiver Beach Characteristics

Beach Width (ft): 150
Beach Length (ft): 15,000
Berm Height(ft): 16
Historical Erosion Rate (ft/yr): 3.45
Longshore Diffusivity (sqft/sec): 0.261

Beach Fill Location:
Beach Fill Length (ft): 15,000
Berm Volume (cy): 2,000,000
Depth of Closure (ft): 20

Increased Beach Width (ft) from Fill Placement:

Year-0:	Year-1:	Year-2:	Year-3:	Year-4:	Year-5:	Year-6:	Year-7:	Year-8:	Year-9:	Year-10:
0.00	16.00	26.00	29.00	15.00	11.55	8.10	4.65	1.20	0.00	0.00

Scenario Costs

Miles Source to Receiver

Hopper Distance (mi): 15.33

Economic Variables

Amenity

Weather:

Weighted Value (%)

0.85

Speed of Vessel (mph):	7	Water Quality:	0.84
Hopper Capacity (cy):	2,700	Beach Width/Quality:	0.45
Hopper Cost (day):	\$41,100	Overcrowding:	0.51
Hopper Down Time Percentage:	20%	Facilities/Services:	0.48
Hopper Trips Per Day	2.8	Availability of Alternatives:	0.44
Total Hopper Trips:	741	Total Index Value:	0.59
Construction Period (days)	265	Day Use Value :	\$5,358,353.30
Hopper Total Transport Cost	10,873,016	Annual Attendance:	644,677
		Existing Spending in CA :	\$11,243,166.88
		Existing Local Spending :	\$9,035,792.83
		Existing Taxes in CA :	\$1,292,964.19
		Existing Local Taxes :	\$225,894.82

Beach Nourishment Cost* : \$10,873,016

Existing Recreational Benefit : \$5,170,310

Scenario Benefits

	Increased	S/L Spending	S/L Taxes	Rec Value
*Costs do not include mobilization and demobilization of equipment. These costs are added in once a Scenario is added to an Alternative.	Year-0	\$0.00	\$0.00	\$0.00
	Year-1	\$47,970.85	\$5,516.65	\$152,211.50
	Year-2	\$77,952.62	\$8,964.55	\$231,434.84
	Year-3	\$86,947.16	\$9,998.92	\$244,587.26
	Year-4	\$44,972.67	\$5,171.86	\$123,492.66
	Year-5	\$34,628.95	\$3,982.33	\$91,138.40
	Year-6	\$24,285.24	\$2,792.80	\$61,266.82
	Year-7	\$13,941.53	\$1,603.28	\$33,718.45
	Year-8	\$3,597.81	\$413.75	\$8,343.06
	Year-9	\$0.00	\$0.00	\$0.00
	Year-10	\$0.00	\$0.00	\$0.00
	Total			\$1,479,160
	Increase in Recreational Benefit :			\$1,479,160

APPENDIX D - LETTERS OF SUPPORT FOR THE COASTAL RSM PLAN



Division of Science & Environmental Policy
California State University Monterey Bay

100 Campus Center, Seaside CA 93955-8001

(831)582-4110; FAX:(831)582-4122

August 4, 2008

Mr. Nicholas Papadakis
AMBAG
445 Reservation Road, Suite G
P.O. Box 809
Marina, California 93933

Dear Nick,

As you know, continual coastal retreat in southern Monterey Bay is a fact that impacts the regional economies, natural resources, and aesthetics. When coastal retreat involves private or public infrastructure, there is typically an emergency response to armor the coastline. Coastal armoring is now well-recognized as a blight that benefits a few, but impacts the entire region. The Southern Monterey Bay Coastal Erosion Workgroup (SMBCEW) was conceived to address this issue several years ago at the urging of Sam Farr. Brad Damitz led the workgroup toward the goal of developing a broader vision of proactive, sustainable coastal management. Phillips Williams and Associates (PWA) has now developed a comprehensive guide to coastal management in southern Monterey Bay based upon the combination of the SMBCEW groundwork and the scientific work of Ed Thornton, Gary Griggs, and other local scientists.

I have read the scientific and technical parts of the report. While there is always room for more data to help improve our environmental decisions, the conclusions in this report are soundly based upon the best available data. **I encourage the AMBAG board to accept and endorse results of the PWA report.**

Many management options are considered, within the context of the specific regional sand budget and current dynamics of southern Monterey Bay. At the heart of the report are two conclusions.

- 1) Industrial sand extraction from the littoral zone is likely responsible for the sand deficit that fosters regional coastal erosion.
- 2) A combination of reduced sand extraction and well-orchestrated beach nourishment will reduce coastal retreat rates at several key places where infrastructure is now threatened.

While these conclusions are bound to be unpopular in some circles, they are, in my opinion, scientifically defensible.

Sincerely,

Douglas Smith

Associate Professor
Science & Environmental Policy, CSUMB



UNITED STATES DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
NATIONAL OCEAN SERVICE

Monterey Bay National Marine Sanctuary
299 Foam Street
Monterey, California 93940

August 13, 2008

Association of Monterey Bay Area Governments, Board of Directors
Attn: Nick Papadakis, Executive Director
445 Reservation Road, Suite G
P.O. Box 809
Marina, California

RE: Southern Monterey Bay Regional Sediment Management Plan

Dear President Potelho and Board Members,

I am writing to express the Monterey Bay National Marine Sanctuary's (MBNMS) support of the recently completed *Draft Final Coastal Regional Sediment Management Plan for the Southern Monterey Bay* (Coastal RSM Plan), and to encourage the AMBAG Board of Directors' endorsement of this plan. As you know, the Southern Monterey Bay shoreline experiences the highest rates of coastal erosion in the State of California. Coastal erosion presents a significant set of policy issues that require the informed consideration of elected officials and resource managers in this region. The Coastal RSM Plan provides our region with a valuable technical resource and useful policy tool for addressing the multiple issues associated with coastal erosion in southern Monterey Bay.

The MBNMS has been involved in the issues of coastal erosion and armoring as part of the congressionally mandated update of the Sanctuary's Management Plan, as well as through our regular review and authorization process for permits that involve disturbance of the seabed. The updated management plan for MBNMS includes an Action Plan for addressing coastal erosion and armoring issues. This Action Plan emphasizes the intent of the Sanctuary to work closely with its partners in developing a more proactive and comprehensive regional approach that will help reduce the need for, and minimize the negative impacts of, coastal armoring throughout the Sanctuary.

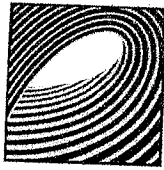
Consistent with this collaborative regional approach and at the urging of Congressman Sam Farr, the Southern Monterey Bay Coastal Erosion Workgroup (SMBCEW) was jointly established in 2005 by the Monterey Bay National Marine Sanctuary and the city of Monterey. The Workgroup's membership includes scientists, federal and state agencies, and local government representatives, conservation interests and other local experts. The Workgroup's purpose is to develop a regional planning approach for addressing the issues of coastal erosion and armoring in the southern Monterey Bay region between Moss Landing and Wharf II in Monterey. In support of the SMBCEW's efforts, MBNMS has recently funded a comprehensive analysis of other potentially promising alternatives methods for addressing coastal. The SMBCEW project and the Coastal RSM Plan will be used together to inform the development of a proactive and comprehensive regional shoreline preservation, restoration, and management plan, with selected site-specific recommendations, as well as more general guidance for responding to coastal erosion issues in southern Monterey Bay.

Thank you for AMBAG's leadership in addressing this important issue for the Sanctuary and for southern Monterey Bay communities. If you have any questions or comments please contact Brad Damitz of my staff at (831) 647-4252.

Sincerely,

Paul Michel
Superintendent, MBNMS





**Surfrider
Foundation**

August 13, 2008

Association of Monterey Bay Area Governments, Board of Directors
Attn: Nick Papadakis, Executive Director
445 Reservation Road, Suite G
P.O. Box 809
Marina, California 9393345 Fremont Street, Suite 2000

Cc: Brad Damitz and Bob Battalio

RE: Southern Monterey Bay Regional Sediment Management Plan

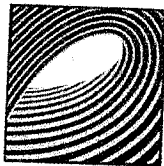
Via electronic mail

Dear President Potelho and Board Members,

I am writing on behalf of Surfrider Foundation in regards to the Regional Sediment Management Plan (RSMP) that has been drafted for the southern portion of Monterey Bay. The Surfrider Foundation is an environmental organization dedicated to the protection and enjoyment of the world's oceans, waves and beach, for all people, through conservation, activism, research and education.

Coastal erosion is a natural process affecting the shoreline of Monterey Bay; unfortunately, many important man-made structures are being threatened by the receding shoreline and many beaches are being threatened by the hardened armoring of our coast. In an effort to protect the Monterey Bay and our communities, as well as promote economic vitality in the area, it is evident that a plan is needed to guide implementation of a regional coastal erosion response that will protect structures and preserve beaches. As opposed to piecemeal responses to coastal erosion on a case-by-case basis, a regional plan is advantageous in that it can take into consideration the disproportionate affects that coastal processes have on various sections of coast within the region—understanding that there are areas where erosion is having little effect and areas where erosion is occurring rapidly—and use this knowledge to develop a method of sediment management that efficiently and effectively manages sediment resources to protect both structures and beaches.

As a work product of the Southern Monterey Bay Coastal Erosion Workgroup—the membership of which includes representatives from local, state and federal agencies, local government staff, non-governmental organizations and members of the public—the RSMP is a result of many months of data analysis and workgroup meetings. With the professional analysis provided by Bob Battalio, David Brew and their team at PWA, the RSMP has taken shape to provide decision-makers with a scientifically sound policy tool that should guide decisions related to erosion response and future coastal development plans.



Surfrider Foundation.

In our capacity as an environmental organization working to preserve beaches and protect waves for the enjoyment of all people, Surfrider Foundation has been an active participant in the Southern Monterey Bay Coastal Erosion Workgroup and a strong advocate within the group for coastal erosion responses that act to safeguard beaches. Surfrider is writing to the AMBAG Board of Directors to convey our support of the findings contained within the RSMP and to respectfully request that the Board adopt this plan based on its scientific merits and policy recommendations.

Sincerely,

Sarah Corbin
Central California Regional Manager
Surfrider Foundation



Lapis Sand Dollars

*An Economic Analysis of Non-Market
Impacts of Lapis Sand Mine in Southern
Monterey Bay*

Prepared by Alyssum Pohl and Lisa Johnston
August 2012

Executive Summary

The unique dunes and beaches of southern Monterey Bay, California are threatened by an intensified rate of coastal erosion caused by the Lapis Lustre sand mine in the city of Marina. This mine excavates high quality sand sold by the largest international cement and aggregate corporation, Cemex. Like many extractive industries, Lapis' sand production results in negative externalities for the environment. This study quantifies some of these externalities by examining non-market costs including seawall construction and lost recreational value of beach due to Lapis.

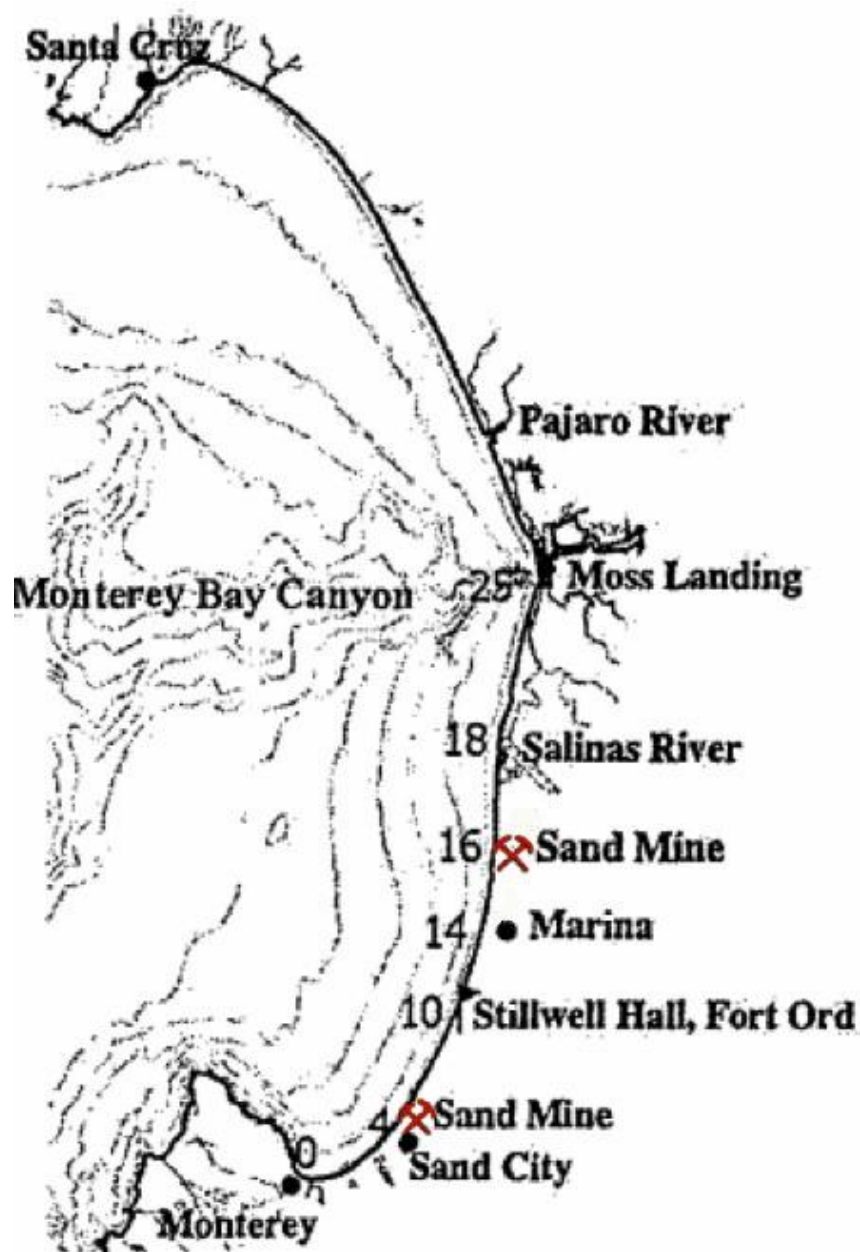
The annual cost of maintaining the existing seawalls at Ocean Harbor House and Monterey Beach Resort is \$133,975. Any additional seawalls could increase this number to more than \$256,562 annually. In addition, the cost of the recreational value of the beach area lost due to sand mining is currently \$1,104,804 annually, and may rise to \$1,122,970 annually in the future. These findings suggest that the non-market costs of the mine are significant, and would be even greater if a more diverse range of non-market costs were considered. This analysis fills a gap in information that should be considered in current and future decision-making regarding coastal resource use in Monterey County.

Introduction

The dune-covered coastline of Monterey Bay is a well-known landmark of the central California coast. The bay is characterized as a sandy, erosive shoreline backed by extensive dunes rising up to 46 meters (Thornton et al, 2006). The dunes and beaches provide numerous benefits to the local economy, attracting visitors and recreation seekers, supporting a wide range of biodiversity, and protecting coastal developments from storm surges.

The dunes also have a long history of supporting a sand mining industry stretching from the mouth of the Salinas River near Moss Landing to Municipal Wharf II in Monterey (see Figure 1). Sand from the Monterey Bay coast is especially well suited for use in cement, asphalt, mortar, plaster, stucco, road construction, backfill, sand-blasting, filtration, glass and ceramics, foundry and engine sands, roofing, landscaping, and aquariums. Not all local sand, however, is of commercial interest due to variety of size and composition near Elkhorn Slough and Pajaro River where medium and fine grained sands are more prevalent. Commercially relevant coarse beach sands extend from Seaside northward to 2 miles south of Elkhorn Slough, centering in and around Fort Ord (Hart, 1966).

Figure 1: Monterey Bay shoreline with number of kilometers from Monterey Wharf II and offshore bathymetry indicated. Mining operations marked with crossed pick-axes.



Source: Thornton et al, 2006

The southern coast of Monterey Bay was mined for sand intensively from 1906 to 1990. Six commercial sites operated in Marina and Sand City, primarily extracting sand directly from the surf zone using draglines to capture the high-value coarse sand deposits (Thornton et al, 2006).

During the 1990's, all shoreline mines were closed due to concern that they were contributing to significant shoreline erosion. However, one mine that extracts from the back beach and dunes

instead of directly from the shoreline is still in operation today: the Lapis Lustre sand mine located in Marina, CA.

Lapis was originally opened by E.B. and A.L. Stone in 1906 in response to demands for construction materials needed to rebuild San Francisco after the great earthquake (Hart, 1966). The mine has been held by several different owners and is currently owned and operated by Cemex, the largest cement, aggregates, and concrete company in the world. Today, the extracted sand is sorted by size, dried, blended, and predominantly sold for plaster and sandblasting.

Since shoreline dredging at Lapis ceased in 1959, the mine has been using a suction dredging process to extract sand from a man-made pond located between the shoreline and dunes (Hart, 1966) (See Figure 2). This mining process acts as a sand sink, drawing in sand during annual storm events and high tides. This results in less sand available in the southern Monterey Bay littoral cell sand budget¹ and significantly impacts the erosion rate (PWA, 2008). The southern Monterey Bay littoral cell is bound by the Salinas River to the north and Municipal Wharf II in Monterey to the south and comprises the geographical scope of this study. Waves refracting over the submarine canyon offshore from the Salinas River delta cause the mean alongshore sediment transport south of the Salinas River to be directed South, and the mean alongshore sediment transport north of the Salinas River to be directed North (Thornton et al, 2006).

Figure 2: The Lapis mine site and dredge pond. Note how waves from the bay (foreground) wash over the beach (right side of photo), depositing water and sand into the Lapis mine pond.



Source: Thornton, 2007

¹ A littoral cell is a geographically limited region along the coast with sand inputs such as rivers and beaches. The sand budget refers to the amount of sand available for transportation up and down the coast within the littoral cell.

A study by Thornton et al quantified the impact on shoreline erosion in southern Monterey Bay by comparing rates of erosion during the period of intensive mining (1940-1990), to rates of erosion after most of the mines ceased operation (1990-2004). The study found that of the 18 km stretch of shoreline studied, erosion rates ranged from 0.5 m/yr near Monterey to 1.5 m/yr near Fort Ord. Erosion events are highly episodic and depend on multiple factors including concentration of wave energy, variations in sea level, changes in rainfall, as well as the amount of sand mining. The study estimates that from 1940-1984, approximately 139,983 yd³/yr of sand was excavated, equivalent to 50% of the yearly averaged dune volume loss during this period. Since the sand mining operations stopped, erosion rates significantly dropped south of Sand City, where the former mines existed, but there has been no significant change in erosion rate in Marina, the location of Lapis (Thornton et al, 2006).

Currently, Lapis extracts approximately 200,000 yd³/yr of sand. Using the table below, PWA estimates that this mining is directly responsible for beach sand loss of approximately 2 ft/yr between the Salinas River and Wharf II. This erosion rate of 2 ft/yr accounts for 50-75% of the ongoing erosion along the Southern Monterey Bay (PWA, 2008). Table 1 describes the historical dune erosion rates alongside extraction rates at Marina State Beach from the 1940s to 2000s.

Table 1: Beach sand extraction and dune erosion rates in Marina

Decade	Sand Mined from Beach (yd ³ /year x 1000)	Average Erosion Rate at Marina State Beach (ft/year)
1940s	20	1.0
1950s	40	
1960s	84	
1970s	129	
1980s	143	
1990s	200	4.7
2000s	200	

Source: PWA, 2008

Table 1 shows that extraction and erosion rates have not changed since the 1990s, despite the closure of all sand mines except Lapis. This provides significant evidence that Lapis is directly responsible for the increased rate of shoreline erosion in southern Monterey Bay.

The legal context of coastal resource use in California has also had a large impact on the history of sand mining in southern Monterey Bay. Sand mining was first regulated in 1968 by the State Lands Commission, which began licensing shoreline sand mining operations through leases. The Army Corps of Engineers also asserted jurisdiction over mining in 1974, requiring leases under the Rivers and Harbors Act of 1899. However, the mining leases of both the State

Lands and Corps of Engineers in southern Monterey Bay expired in 1988 (Thornton et al, 2006). After that time the Corps concluded that the mining of beach sand caused coastal erosion and did not renew the permits for the five shoreline mining operations in southern Monterey Bay (PWA, 2008).

In addition, the California Coastal Commission is the primary state agency responsible for regulating any land and water use within California's coastal zone. Under the jurisdiction of the Coastal Commission, local governments run Local Coastal Programs (LCPs) to develop ground rules for future coastal developments as well as conservation of coastal resources. The Monterey County LCP was certified in 1988. Within the county LCP, city LCPs provide additional jurisdiction within city limits. The City of Marina's LCP has specific policy related to sand mining operations within the Marina City limits, which are relevant to Lapis (PWA, 2008).² While the legal considerations surrounding Lapis are highly relevant, they require a lengthy discussion which is beyond the scope of this report. The California Coastal Commission Enforcement Program is currently investigating whether Lapis is in compliance with the LCP.

Purpose and Objectives

Extractive industries generally fail to recognize the full array of negative externalities for which they are responsible. Instead, the public bears the burden. This case study typifies just such a situation, as the high rate of coastal erosion will continue to threaten the economic and ecological well-being along the southern coast of Monterey Bay, and will most likely be further exacerbated by increasingly unpredictable effects of climate change and sea level rise. Without taking action to minimize the causes of coastal erosion in southern Monterey Bay, the future economic implications for Monterey County could be great, as the beach from Moss Landing to Monterey could be gone or highly fragmented within 50 years.³

According to a study by PWA, the main factor exacerbating shoreline erosion in southern Monterey Bay is hydraulic sand mining from the beach at the Lapis mine in Marina. The study indicates that the mining operations account for a reduction of approximately 200,000 yd³ of sand per year from the littoral cell, which would otherwise replenish the beaches up and down the coast. This volume of sand loss accounts for 2 ft of beach loss each year, which is approximately 50-75% of the ongoing erosion that occurs in southern Monterey Bay (PWA, 2008). The economic cost of the additional beach erosion that results from sand mining has not been accounted for in previous studies.

²Relevant policies from Marina's LCP include: "1) existing surf zone sand mining operations, as established coastal dependent uses, shall be permitted to continue at their existing locations in substantially the same manner as they are currently being conducted, and have been conducted in the past. All provisions of the LCP (including the Implementation Plan) relating to mining shall be construed and applied in a manner that supports such continuation of existing surf zone sand mining operations, so long as such existing surf zone sand mining operations are in accordance with the LCP. 2) the City shall not approve or renew a Mining Permit and/or Coastal Development Permit for new surf zone or beach sand mining, if it finds that such new sand mining, either individually or cumulatively, will have significant adverse impacts on shoreline erosion." (PWA, 2008)

³ Average width of beach = 200 ft/average erosion rate 4 ft/year = 50 years (PWA, 2008).

This report aims to provide an analysis of the economic costs incurred by private sectors and the public as a result of the increased erosion caused by the mine. This information may support current and future decisions regarding coastal planning and regulation.

The following analysis attempts to quantify a portion of the non-market values of the beaches that are impacted by Lapis by utilizing the two methodologies; 1) recreational value of beach loss, and 2) cost of seawall maintenance and sand loss mitigation.

Location of Study

This study focuses on the southern half of Monterey Bay because the Lapis mine primarily affects the southern littoral cell of Monterey Bay, which is bound by the Salinas River to the north and Municipal Wharf II in Monterey to the south and comprises the geographical scope of this study. Figure 3 identifies the location of areas critically affected by erosion in southern Monterey Bay. PWA identified ten specific locations within the highlighted areas in Figure 3. Numbers 1-7 below are labeled specifically in Figure 3, while numbers 8-10 lie within the highlighted areas in Figure 3:

1. Sanctuary Beach Resort near Reservation Road
2. Marina Coast Water District buildings near Reservation Road
3. Sand City and Tioga Avenue west of Highway I (relocate)
4. Seaside Pump Station at Bay Avenue (relocate)
5. Monterey Beach Resort
6. Ocean Harbor House condominiums
7. Monterey La Playa town homes at La Playa Street
8. Monterey Interceptor between Seaside Pump Station and Monterey Beach Resort (relocate)
9. Del Monte Beach Subdivision
10. Monterey Interceptor between Monterey Pump Station and Wharf II (relocate)

Figure 3: Locations of critical areas of erosion

Source: PWA, 2008

Of these locations, this report provides an analysis of the costs incurred where seawalls have been or potentially could be installed as a means of protecting existing buildings. Seawall construction, while preventing near term damage to shore front structures, also causes additional shoreline erosion in the vicinity of the project, which requires sand loss mitigation. This has already occurred at locations where seawalls have been installed such as the Monterey Beach Resort and the Ocean Harbor House (OHHS, 2004). The areas marked with “relocate” in the list above indicate that a seawall will not have to be installed, but that the area or fixture will have to be entirely relocated. These relocations will incur additional costs, the calculations of which are beyond the scope of this study.

Methodology 1: Recreational value of beach loss

Tourism is the second largest industry in Monterey County. Because the beach from Moss Landing to Wharf II in Monterey is publicly accessible and frequently visited, this is one of the main losses that the public incurs due to erosion from Lapis. In this section, we place a recreational value on the land tied directly to the lost public access to these beaches due to erosion from sand extraction by Lapis.

The beaches of southern Monterey Bay offer an estimated \$13 per person in this area in consumer surplus (OHHS, 2004). This equates to a recreational value of beach of \$253,001/acre (OHHS, 2004) in front of Ocean Harbor House Condominiums. This small area of beach is literally continuous with the rest of southern Monterey Bay beach, both to the north and to the south, so we extrapolate these numbers in the following calculations (benefit transfer). Thus, the annual recreational value of Monterey Bay beaches affected by erosion due to Lapis is \$1,099,762.⁴

In addition to the lost beach area, erosion has caused the need for seawalls in front of coastal structures. The seawalls themselves cause additional erosion, half of which can be attributed to Lapis, and this must be accounted for in the annual recreational value of beach loss (OHHS, 2004). Currently two seawalls exist: one at Ocean Harbor House Condominiums, and one at the Monterey Bay Beach Resort (Best Western) both in Seaside. The combined annual recreational value of beach lost in front of these seawalls is \$4,745.61 (see appendix A). When added to the recreational value of beach lost above, the total annual recreational value of beach lost due to Lapis in southern Monterey Bay is \$1,104,804 (see appendix A).

Additional seawalls will potentially need to be built to protect existing structures from the effects of the rising sea levels and surf zone encroachment, including Sanctuary Beach Resort near Reservation Road, Marina Coast Water District buildings near Reservation Road, and Monterey La Playa Town Homes on La Playa Street. If these areas were protected by seawalls, the additional erosion could add an additional \$18,166.24 (see appendix A) annually in lost recreational value of beach due to Lapis.

Methodology 2: Cost of seawall maintenance and sand loss mitigation

Sea level rise and climate change events cause the shoreline of Monterey Bay to retreat, but the urgency of building these seawalls increases with the additional erosion caused by Lapis. In this section, we examine the cost of building the seawalls and the sand mitigation to maintain these seawalls, appropriated to Lapis. While Methodology 1 is a true non-market valuation, this methodology reflects a hybrid market/non-market valuation. The cost of sand per cubic yard is a market value, but this cost is not normally considered when discussing the impact of mining. Although the seawalls are built once and sand mitigation is not maintained on a yearly basis, we break these numbers down into annual amounts so that they are comparable with the annual costs we have already discussed.

⁴ 18 miles total beach affected by sand loss from Lapis x 5280 ft/mile (conversion) = 95040 ft length of beach affected. 95040 ft x 4 ft average projected erosion rate of Mty Bay = 380160 sq ft/yr area beach in Mty Bay affected by erosion. 380160 sq ft x 0.5 (50% erosion due to Lapis) = 190080 sq ft/yr total area beach in Mty Bay affected by erosion due to Lapis. 190080 sq ft/yr x 43560 sq ft/acre (conversion) = 4.36 acre/yr total area of beach in Mty Bay affected by erosion due to Lapis. 4.36 acre/yr x 207714 \$2004/acre annual recreational value of Mty beach = 905633.04 \$2004/yr = \$1099762 in 2012 dollars.

Extrapolating from information from Ocean Harbor House Seawall (OHHS), we calculate that the cost to replace sand due to erosion per foot of seawall is \$61.11/ft annually.⁵ To use this value in other calculations, the seawall must have similar erosion rates to OHHS (~1.25ft/yr), which was the case for the Monterey Beach Resort where the erosion rate is ~1.5ft/yr.

The annual cost to mitigate sand loss at the current seawalls (Ocean Harbor House Seawall and Monterey Beach Resort) is estimated at \$72,415.35. Yearly maintenance costs for seawalls are estimated to be 1%-4% of total cost of the seawall, annually (Heberger et al, 2009). Average cost of seawalls in northern California is \$5194.88/ft.⁶ Thus, the estimated yearly cost of maintenance for these existing seawalls is \$61,559.33 for a total of \$133,975/year in mitigation and maintenance costs for existing seawalls.⁷

If the other three seawalls were to be built, the annual cost to mitigate sand loss in southern Monterey Bay from these seawalls would increase by \$122,586.66.⁸ Table 2 shows the additional costs related to building these potential seawalls. The sum of maintenance and sand loss mitigation costs for these potential seawalls is \$226,797.

⁵ 54350 yd³ sand needed to mitigate OHHS x 50 yrs (length of project) = 1087 yd³/yr sand loss mitigation at OHHS. 1087 yd³/yr x \$32.89/yd³ cost to mitigate sand loss = \$35,751.43 annual cost to mitigate OHHS sand loss. \$35,751.43/yr / 585 ft length of OHHS = \$61.11 annual cost to mitigate sand loss per 1 ft of seawall.

⁶ Average cost of seawalls per foot in northern California \$2646-\$6173 in 2005 dollars = \$4409.5 average cost in 2005 dollars = \$5194.88 2012 dollars (Heberger et al, 2009)

⁷ 585 ft length of OHHS + 600 ft length of Monterey Beach Resort seawall = 1185 ft existing seawalls in S. Mty Bay. 1185 ft x \$61.11/yr sand loss mitigation per 1 ft of seawall = \$72,415.35 annual cost to mitigate sand loss at OHHS and Monterey Beach Resort. 1185 ft x \$5194.88/ft cost of seawalls x 1% estimated annual maintenance cost for seawalls = \$61,559.33/yr estimated cost of maintenance for existing seawalls.

⁸ 1056 ft length of potential seawall at Monterey La Playa town homes (measured) + 550 ft length of potential seawall at Sanctuary Beach Resort + 400 ft length of potential seawall at Marina Coast Water District buildings = 2006 ft additional length of seawall in southern Monterey Bay. 2006 ft x \$61.11/yr = \$122,586.66 additional annual cost to mitigate sand loss in southern Monterey Bay.

Table 2: Additional Costs Related to Potential Seawalls⁹

Potential Seawall Location	Estimated cost of Seawall (\$)	Estimated maintenance cost for seawalls/yr (\$)
Sanctuary Beach Resort (SBR)	2,857,184	28,572
Marina Coast Water District (MCWD)	2,077,952	20,780
Monterey La Playa Town Homes (MLPTH)	5,485,793	54,858

The seawalls would be built regardless of the erosion due to Lapis, so the cost of the seawalls themselves is not a relevant cost in relation to the mine. However, the seawalls will need to be installed earlier if erosion continues due to Lapis than if the mine ceased sand excavation. Therefore, we can calculate the cost of capital due to having to invest in seawalls earlier versus keeping that money and earning interest on it during the same amount of time (See Table 3).

Table 3: Estimated interest lost by building seawall earlier due to erosion¹⁰

Potential Seawall Location	Estimated Interest Lost by Building Seawall Earlier Due to Erosion (\$)
Sanctuary Beach Resort (SBR)	5,714,368
Marina Coast Water District (MCWD)	457,149
Monterey La Playa Town Homes (MLPTH)	(no estimated timeframe provided, as erosion rates are low at this location)

The total interest lost for these two potential seawalls is over \$6 million. Note that because the Monterey La Playa Town Homes have a slower erosion rate¹¹, no estimated time frame has been given for building a seawall in that location. However, if or when a seawall is built at this location, it would be approximately twice the length as other existing seawalls and accordingly

⁹ 550 ft SBR potential seawall x \$5194.88 cost of seawall per foot = \$2,857,184 cost of potential SBR seawall. 400 ft MCWD potential seawall x \$5194.88 = \$2,077,952 cost of potential MCWD seawall. 1056 ft MLPTH potential seawall x \$5194.88 = \$5,485,793 cost of potential MLPTH seawall.

¹⁰ Private equity rate of 10% (assumed) x 20 yrs (building estimated to be affected by erosion necessitating a seawall, from 2008) x \$2,857,184 cost of potential SBR seawall = \$5,714,368 interest that could have been earned. Government bond interest rate of 2.2% (because the MCWD is publicly owned) x 10 yrs (buildings estimated to be affected by erosion in this timeframe) x \$2,077,952 cost of potential MCWD seawall = \$457,149 interest that could have been earned.

¹¹ 1 ft/yr erosion rate at Monterey La Playa Town Homes. (PWA, 2008)

more expensive. Interest lost to building that seawall is not calculated here since the building of a seawall would be significantly in the future¹², but this potential cost should be factored into decision making processes.

Conclusion

Extensive geotechnical and engineering evidence supports the conclusion that Lapis is directly responsible for the rapid erosion of the beach and dune ecosystem of southern Monterey Bay. In an effort to quantify the economic impact and environmental costs of the mine, this study conducted non-market analysis and found (Methodology 1) that the annual recreational value of Monterey Bay beaches affected by erosion due to Lapis is \$1,104,804. An alternative valuation method (Methodology 2) shows that the annual cost of seawall maintenance and mitigation of sand loss at existing seawall sites is \$133,975. If the other seawalls were to be built, this number would increase by at least \$226,797 per year, and estimated interest lost by building seawalls earlier due to erosion could be between approximately \$450,000 to more than \$6 million.

A third possible methodology would be to evaluate the real estate value of the beaches that will be lost due to erosion caused by the mine. Because the 18 km of beach between Moss Landing and Wharf II in Monterey are primarily public, state-owned beaches, this area is not expected to incur significant development in the future. Although this stretch of beach is public, if it were private land, southern Monterey Bay would experience approximately \$5,294,596 worth of annual beach loss due to Lapis sand mining operations.

Including additional methods of non-market valuation could greatly strengthen the findings of this study. However, due to limitations in time and resources, additional methodologies were beyond the scope of this report. This study provides a starting point for additional non-market valuation studies to build upon in the future.

It is important to remember that the calculations of cost are conservative and do not comprehensively reflect the entire non-market values of the beaches and dunes of southern Monterey Bay. In addition, this study does not take into account the full range of ecosystem services provided by the beaches and dunes, such as the value of habitat for endangered species and unique biodiversity, the existence value that community and visitors have for beaches and dunes, or the value of hydrologic functions they provide. It is worth pointing out that Lapis produces 19 jobs and ~\$202,000/yr in property tax revenue to Monterey County community (appendix B). These are important factors to consider for coastal management planning. However, the intention of this study was to put a value on the externalities of the Lapis Lustre sand mine, which had previously not been attempted. In short, the estimates provided herein do not consider the full range of non-market costs that the public bears in order to support the private extraction of a public good. We hope that local decision makers will consider the findings herein during current and future discussions of the Lapis mine. Considering the non-market implications of any natural resource use can lead to better-informed policy and regulations that benefit both the environment and the economy.

¹² Average width of beach = 200 ft (PWA, 2008). Average erosion rate at MLP_{TH} = 1 ft/yr. 200 ft / (1 ft/yr) = 200 yrs before surf reaches MLP_{TH}.

Appendix A

Calculations for non-market recreational value of beach loss due to Lapis.

Ocean Harbor House Condominiums

435 ft shoreline affected x 1.7 ft/yr erosion rate at this location = 739.5 sq ft/yr area affected annually at OHHC

739.5 sq ft/yr x 0.5 (50% erosion due to Lapis) = 369.75 sq ft/yr area beach by OHHC affected by erosion due to Lapis

369.75 sq ft/yr / 43560 sq ft/acre (conversion) = 0.0085 acre/yr area beach by OHHC affected by erosion due to Lapis

0.0085 acre/yr x 207714 \$/acre annual recreational value of s Mty beach = \$1763.14/yr (2004 years) = **\$2147.55** (2012 years) annual recreational value of beach by OHHC affected by erosion due to Lapis

Monterey Bay Beach Resort

600 ft shoreline affected x 1.5 ft/yr erosion rate at this location = 900 sq ft/yr area affected annually at MBBR

900 sq ft/yr x 0.5 (50% erosion due to Lapis) = 450 sq ft/yr area beach by MBBR affected by erosion due to Lapis

450 sq ft/yr / 43560 sq ft/acre (conversion) = 0.0103 acre/yr area beach by MBBR affected by erosion due to Lapis

0.0103 acre/yr x 207714 \$/acre annual recreational value of s Mty beach = \$2139.45/yr (2004 years) = **\$2598.06** (2012 years) annual recreational value of beach by MBBR affected by erosion due to Lapis

Sanctuary Beach Resort

550 ft shoreline affected x 5.5 ft/yr erosion rate at this location = 3025 sq ft/yr area affected annually at SBR

3025 sq ft/yr x 0.5 (50% erosion due to Lapis) = 1512.5 sq ft/yr area beach by SBR affected by erosion due to Lapis

1512.5 sq ft/yr / 43560 sq ft/acre (conversion) = 0.03472 acre/yr area beach by SBR affected by erosion due to Lapis

0.03472 acre/yr x 207714 \$/acre annual recreational value of s Mty beach = \$7211.83/yr (2004 years) = **\$8757.73** (2012 years) annual recreational value of beach by SBR affected by erosion due to Lapis

Marina Coast Water District

400 ft shoreline affected x 5.5 ft/yr erosion rate at this location = 2200 sq ft/yr area affected annually at MCWD

2200 sq ft/yr x 0.5 (50% erosion due to Lapis) = 1100 sq ft/yr area beach by MCWD affected by erosion due to Lapis

1100 sq ft/yr / 43560 sq ft/acre (conversion) = 0.0253 acre/yr area beach by MCWD affected by erosion due to Lapis

0.0253 acre/yr x 207714 \$/acre annual recreational value of s Mty beach = \$5255.17/yr (2004 years) = **\$6381.64** (2012 years) annual recreational value of beach by MCWD affected by erosion due to Lapis

Monterey La Playa Town Homes

1056 ft shoreline affected x 1 ft/yr erosion rate at this location = 1056 sq ft/yr area affected annually at MLPTH

$1056 \text{ sq ft/yr} \times 0.5$ (50% erosion due to Lapis) = 528 sq ft/yr area beach by MLPPTH affected by erosion due to Lapis
 $528 \text{ sq ft/yr} / 43560 \text{ sq ft/acre}$ (conversion) = 0.012 acre/yr area beach by MLPPTH affected by erosion due to Lapis
 $0.012 \text{ acre/yr} \times 207714 \text{ \$/acre}$ annual recreational value of s Mty beach = \$2492.57/yr (2004 years) = **\$3026.87** (2012 years) annual recreational value of beach by MLPPTH affected by erosion due to Lapis

Appendix B

Partial Market Analysis of Lapis

The data in Appendix B utilize input-output analysis provided by IMPLAN economic impact assessment software. The input-output method used by IMPLAN is based on the idea that the production of any output requires inputs in the form of goods and services (Armstrong & Taylor, 2000). Modeling these economic transactions is extremely complex. IMPLAN software allows users to easily construct economic impact models that suit their research needs. IMPLAN also provides individual region or nation-wide data sets for purchase. This study utilized the California data set.

The input-output model is used as a framework for economic impact analysis. Economic impact analysis measures economy-wide changes in output, employment, and income due to outside triggers from the final demand sector (Wang & Vam Hofe, 2007). Economic impact can be broken down into its direct, indirect, and induced effects. Direct effects measure the immediate effects on a single industry's output, employment, or income following an outside change. Indirect effects measure the changes in output, employment and income that follow a direct effect. Induced effects result from the fact that household spending may increase or decrease due to the direct and indirect effects of a change. Induced effects represent a generic expansion or contraction of the local economy due to direct and indirect effects within a sector.

Using IMPLAN to model Sector 26 for Monterey County, we determined an estimate of the direct, indirect, and induced effects for employment. The results are displayed in Table 4.

Table 4: Employment Impacts for Sector 26, Monterey County

	Direct Effects	Indirect Effects	Induced Effects	Total
Employment (number of employees)	16.36	2.17	0.94	19.46

Source: IMPLAN 2012

The total employment impact of Lapis, summing direct, indirect and induced effects, is 19.46 jobs.

In addition to employment contributions, the Lapis mine also contributed \$191,778.32 in Monterey County property tax revenue in 2010, equivalent to \$202,357.72 in 2012 dollars (Soria, 2012).

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Using Vessel-Based LIDAR to Quantify Coastal Erosion during El Niño and Inter-El Niño Periods in Monterey Bay, CA

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ABSTRACT

Quan, S.; Kvitek, R.; Smith, D., and Griggs, G. 0000, Using vessel-based LIDAR to quantify coastal erosion during El Niño and inter-El Niño periods in Monterey Bay, CA. *Journal of Coastal Research*, 00(0), 000–000. Coconut Creek (Florida), ISSN 0749-0208.

Vessel-based light detection and ranging (LIDAR) was employed to collect coastal topography data and to quantify the rates of erosion and spatial distribution of coastal retreat around Monterey Bay, California during the 2008–09 (non-El Niño) and 2009–10 El Niño. These data were compared with pre/post-El Niño LIDAR data from 1997–98 to assess shoreline change and to test the following hypotheses: (1) that broad-scale (km) spatial distribution of erosion rates is positively correlated with wave energy, and (2) that fine-scale erosion hot spots (segments of the coastline exhibiting considerably higher rates of erosion than adjacent areas) shift at predictable alongshore wavelengths between consecutive El Niño and inter-El Niño periods. Broad-scale erosion was found to be significantly higher during the 2009–10 El Niño *vs.* the 2008–09 non-El Niño period in both the south (1.8 m *vs.* 0.1 m average) and north bays (0.5 m *vs.* 0.0 m average). The broad-scale distribution of erosion rates during the 2009–10 El Niño was positively correlated with wave energy. In southern Monterey Bay, erosion rates increased along a wave energy gradient from south to north, whereas erosion and wave energy were both focused and highest at a single location in the northern bay. Fine-scale erosion hot spots were found to occur during the 1997–98 and 2009–10 El Niño and the 1998–08 inter-El Niño period. These hot spots were found to be significantly correlated at ~160 m during the 1997–98 El Niño to 1998–2009 inter-El Niño periods and 100 m during the 1998–2009 inter-El Niño to 2009–10 El Niño periods in southern Monterey Bay. Hot spots that occurred during one El Niño or inter-El Niño period shifted spatially alongshore during the subsequent El Niño or inter-El Niño period. Vessel-based LIDAR proved to be effective for detecting coastal change at high spatial resolutions and revealing fine-scale patterns of shoreline retreat.

ADDITIONAL INDEX WORDS: *Shoreline change, erosion rates, seacliff retreat, bluff retreat, coastal geomorphology, remote sensing, coastal processes, El Niño, LIDAR.*

INTRODUCTION

Holocene sea-level rise has produced coastal retreat on a global scale. Erosion is expected to worsen with global warming-induced climate change and accelerated sea-level rise (Church and White, 2006; Varekamp, Thomas, and Van de Plassche, 1992; Zhang, Douglas, and Leatherman, 2004) and an increased intensity of storm events predicted for the 21st century (Meehl *et al.*, 2007).

The primary forcing parameters for coastal erosion along the U.S. west coast (elevated sea levels, increased wave height, and higher precipitation) are associated with moderate to high intensity El Niño Southern Oscillation (ENSO) events (Allan

and Komar, 2006; Storlazzi and Griggs, 2000). Recent documentation of wave height increases along the west coast suggests that one effect of global climate change may be high intensity storms, similar to those experienced during significant ENSO events (Ruggiero, Komar, and Allan, 2010; Seymour, 2011; Storlazzi and Wingfield, 2005). These ENSO events may therefore serve as proxies for anticipated 21st century weather patterns and an opportunity to explore the potential effects of sea-level rise and high intensity storms on shoreline erosion. With an estimated \$184 million in losses, including the destruction of 33 ocean front houses and damage to 3900 homes and business along the U.S. west coast during the 1982–83 El Niño period (Griggs and Johnson, 1983; Griggs and Patsch, 2005), new monitoring and forecasting tools to aid in proactive coastal management are needed to minimize societal impacts of impending climate change.

The ability to more accurately predict where, and at what rates, coastal erosion is likely to occur will be important to

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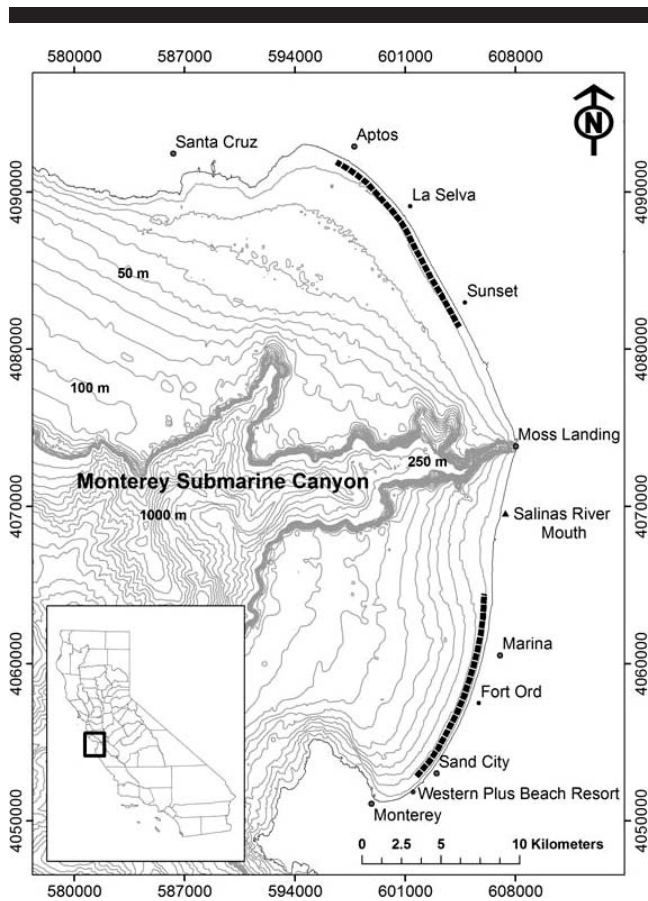


Figure 1. Central California map showing the Monterey Bay coastline and geographical location of the north and south analysis regions (represented with bold dashed lines). Bathymetry contours (10 m) are represented in grey. Coordinate system: UTM zone 10N NAD83.

these planning efforts. Here we use vessel-based mobile topographic light detection and ranging (LIDAR) for shoreline mapping in Monterey Bay, California (Figure 1) to test for predictable differences in spatial and temporal patterns of coastal erosion occurring at different scales during El Niño and inter-El Niño periods.

Monterey Bay

The arcuate shoreline of Monterey Bay along the central California coastline (Figure 1) presents a location uniquely suited to studying spatial variations in coastal retreat. The hooked shape of the headlands at both ends of the bay is in an equilibrium configuration controlled by the interaction of geology and a dominant wave approach from the NW (Griggs and Jones, 1985). This interplay creates large gradients in wave exposure, with the central bay shoreline fully exposed and the north and south extremes partially shielded by their headlands under certain wave conditions. Additionally, the head of Monterey Submarine Canyon in the center of the bay refracts and focuses wave energy to the north and south shores on either side of Moss Landing (Thornton, MacMahan, and

Sallenger, 2007). These steep spatial gradients in wave exposure make the bay an ideal laboratory for testing hypotheses on the relationship between wave energy and patterns of coastal erosion.

Monterey Bay is rimmed by wide sandy beaches that are backed by Flandrian dunes (Cooper, 1967) in the southern section and Tertiary sedimentary rock cliffs and weaker bluffs in the northern section. The north and south headlands consist of more resistant marine sedimentary rocks and granodiorite, respectively (Griggs and Patsch, 2005; Wagner, Greene, and Saucedo, 2002). The strength of the coastal rocks and sediments determines the erodability of the coastline, with softer sediment types having higher susceptibility to erosion *vs.* hard sediment types (Benumof *et al.*, 2000). For this study, sites were restricted to sections of the coastline backed by coastal dunes and bluffs to control for geologic variation in shoreline recession rate analyses (Figure 1).

Long-term erosion (>25 y) rates around Monterey Bay can be traced back to the 1940s and have been found to be persistent and relatively uniform (~ 0.3 – 2 m/y) over long time frames (Hapke *et al.*, 2006; Thornton *et al.*, 2006). These studies, based on analysis of historic aerial photographs (Sklavidis and Lima-Blanco, 1985), were focused on broad-scale, long-term assessments of the coastline.

Short-term erosion (<25 y), however, does not occur uniformly in space or time around Monterey Bay but rather in spatially variable “hot spots”; segments of the coastline exhibiting considerably higher rates of erosion than adjacent areas and occur alongshore at scales of 100s of m. This small-scale erosion pattern has been well documented for the 1997–98 El Niño period, with the most extreme rates located in the exposed central section of the bay and decreasing in magnitude toward the more protected southern and northern ends (Egley, 2002; Hapke and Richmond, 2002; Moore and Griggs, 2002; Thornton *et al.*, 2006; Thornton, MacMahan, and Sallenger, 2007). Bluff erosion during the 1997–98 El Niño winter (Oct 1997–April 1998) ranged from 0 to 4 m at Monterey. Rates at Sand City ranged from 0 to 2 m and at Fort Ord from 0.5 to 13 m with net volume loss calculated to be nearly seven times the historic annual average (Thornton *et al.*, 2006).

Direct links were found between hot spot erosion and the formation and location of rip channels and large megacusps (Thornton, MacMahan, and Sallenger, 2007), with the relationship hypothesized to be attributable to narrowing of beach width at mega-cusp embayments, allowing wave run-up to easily reach and erode coastal bluffs (Revell, Komar, and Sallenger, 2002; Shih and Komar, 1994; Thornton, MacMahan, and Sallenger, 2007). The location and formation of rip channels, mega-cusps, and hot spots are hypothesized to migrate and regenerate along the coastline but are not expected to return to their same location the following year because southern Monterey Bay exhibits nearly uniform long-term erosion along sections of the coastline subject to uniform wave exposure (Thornton, MacMahan, and Sallenger, 2007). Given the framework of past studies, we can predict where erosion will occur on long time scales and broad spatial scales, but few researchers have been successful at accurately predicting the location and rate of erosion on short time scales within

local areas due to the spatially variable characteristic of hot spot erosion and the episodic nature of intense storms that appear to control these hot spots (Hapke and Plant, 2010). Considering the impacts to the coastline that occurred during previous El Niño periods, the study and prediction of fine-scale spatial erosion patterns is a crucial step in planning for anticipated increases in shoreline retreat rates.

The quantitative detection of fine-scale hot spot erosion in recent studies was only achievable through the use of high-resolution digital surface models produced from aerial LIDAR data. LIDAR is optical remote sensing using the measurement of time delay between transmittance and return of laser pulses, providing the ability to rapidly and efficiently measure surface geomorphology in three dimensions at high resolution over broad areas. In 1997 and 1998, NASA, USGS, and NOAA collaborated to conduct pre- and post-El Niño airborne LIDAR surveys of the California coastline, providing researchers with digital surface models of the coastline. This data set provided the first clear assessment of El Niño erosion rates in Monterey Bay (Hapke and Reid, 2007; Hapke *et al.*, 2006; Thornton *et al.*, 2006; Thornton, MacMahan, and Sallenger, 2007). Prior to this study there had been only one additional airborne LIDAR survey, which was completed in 2004 by NOAA and USGS, leaving the measurement of erosion rates to be derived by less precise means. While airborne LIDAR has been an effective and groundbreaking method for collecting topographic data by providing high resolution, precision, and broad coverage, the technique has its limitations. Availability, cost, the ability to respond on short notice to significant environmental events, and atmospheric conditions (*e.g.*, low cloud ceilings) that either preclude the use of aircraft or effectiveness of the sensor can limit the use of airborne LIDAR.

Our study employed a vessel-based LIDAR system as an alternative to airborne LIDAR to collect topographic data. This approach combines the high resolution characteristics of LIDAR data with an efficient and effective platform for collecting topographic data. Our expectations were that the high resolution datasets produced using this system would provide insight into the short-term and fine-scale patterns of change that have occurred since the 1998 LIDAR survey and the impacts of the most recent 2009–10 El Niño winter, relative to the 2008–09 normal (non-El Niño) winter, as well as providing a basis for comparing patterns of erosion from two different El Niño periods (1997–98 *vs.* 2009–10).

The project had four objectives: (1) to evaluate the utility of a vessel-based topographic LIDAR system as a rapid-response alternative to airborne LIDAR for collecting coastal topography data and quantifying the spatial distribution of coastal retreat; (2) to use the vessel-based system to quantify and compare the rates and spatial distribution of coastal erosion during the 2008–09 normal (non-El Niño) year and 2009–10 El Niño year and to compare these findings with the results from pre- and post-El Niño airborne LIDAR surveys in 1997 and 1998 (Egley, 2002); (3) to test the assumption that broad-scale erosion is correlated with the spatial distribution of the highest wave energy; and (4) to test the hypothesis that the spatial locations of fine-scale erosion hot spots shift at predictable

alongshore wavelengths between consecutive El Niño and inter-El Niño periods.

METHODS

Vessel-Based LIDAR

We used a Riegl LMS-Z420i terrestrial laser scanner mounted atop a hydrographic survey vessel with its sensor positioned shoreline-normal to produce high resolution topographic datasets at a relatively low cost compared to conventional airborne LIDAR. The Riegl LMS-Z420i (hereafter 420i), originally designed for use as a stationary terrestrial laser scanner, was mounted on the 10 m research vessel *R.V. VenTresca*. The 420i has a range of 1 km, a positional accuracy of 10 mm, and a scan swath angle of 135°. While the 420i was designed to rotate through 360°, in our mobile application the scanner head is fixed in one position and set to line scan mode. This allows for adjacent measurement of coastal relief while the vessel travels parallel to the coast. The scan and acquisition rates for the 420i in a fixed line-scan position are 20 Hz and 8000 points per second, respectively.

Vessel trajectory data were collected to correct the 420i data for platform position and attitude during postprocessing. An Applanix POS/MV 320 was used to collect sensor position and attitude data at 200 Hz. These data were then postprocessed and corrected in Applanix POSpac software with global positioning system (GPS) ephemeris from a network of continuously operating GPS reference stations to yield a tightly coupled inertial-GPS Smoothed Best Estimated Trajectory (SBET) of the 420i's position and attitude (pitch, roll, yaw) referenced to the NAD83 (CORS96 epoch 2002) UTM coordinate system and NAVD88 (Geoid 2003) datum.

The accuracy and precision of this coupled mobile system (Riegl LMS-Z420i and Applanix POS/MV 320) was quantified by scanning six separate target locations on different dates both before and after the shoreline surveys at which a Trimble NetR5 GPS receiver was set up collecting static L1/L2 GPS fixes. The static GPS data were postprocessed using the National Geodetic Survey Online Positioning User Service (OPUS). All six targets were scanned at ranges between 50 and 100 m. The LIDAR-derived solutions for repeat scans of each target varied by <0.04 m horizontally and vertically, and the mean horizontal and vertical LIDAR solutions for each target were all within 0.10 m of the corresponding static GPS solutions.

Vessel-based LIDAR data were collected along the shoreline of Monterey Bay on December 9 and 10, 2008; November 4, 2009; and on July 15, 16, and 17, 2010, during low tide and relatively calm seas (Figure 1). These conditions are optimal for vessel-based LIDAR measurements as collection during low tide provides the fullest coverage of the shoreline relief. Rough seas increase boat motion and can therefore reduce data density as the laser sensor's swath covers relatively more sky and water and less shoreline when rolling heavily.

The raw vessel-based LIDAR data contained time, range, bearing, and intensity information all relative to the scanner's geometrical center. Riegl RiScanPro software was used to apply SBET solutions to the raw LIDAR data, yielding correctly georeferenced XYZ data in NAD83 (CORS96 epoch 2002) UTM

coordinate system and NAVD88 (Geoid 2003) vertical datum. The XYZ data densities were generally five points per m^2 .

Postsurvey ground-truthing was completed to verify the accuracy and precision of these georeferenced vessel-based LIDAR datasets. The positions of three clearly identifiable objects visible in the LIDAR point clouds from three sections of the Monterey Bay coastline (south, central, and north) were independently measured with a Trimble NetR5 GPS receiver and postprocessed in OPUS. The postprocessed static GPS positions were then compared on a point-by-point basis to those of their respective targets visible in all three vessel-based LIDAR survey datasets.

Fledermaus (IVS3D) software was used for editing and 3D visualization of vessel-based LIDAR data. This process involved the manual rejection of outliers on a point-by-point basis based on visual interpretation of the colinearity between points. Digital elevation models (DEM) in ArcGrid format were generated in Fledermaus at 1 m resolution using the mean squares algorithm. These DEMs were subsequently used in ArcGIS (ESRI) for analysis.

Pre-existing data from the collaborative USGS, NASA, and NOAA airborne LIDAR surveys conducted on October 12 and 13, 1997, and April 15, 17, and 18, 1998, via NASA's Airborne Topographic Mapper (ATM) were also used in conjunction with the vessel-based LIDAR from this study for shoreline change analyses. These earlier LIDAR data sets were downloaded as georeferenced XYZ point cloud data and processed using the same editing and gridding techniques used with the 420i data, but with an output resolution of 2 m because of their lower point densities. Unfortunately, the 2004 NOAA and USGS LIDAR results could not be included in this analysis because of coverage gaps in those data for the north and south bay study areas used here.

GIS Analyses

Previous researchers have employed a variety of geomorphic reference features to measure shoreline recession including the intersection of the back beach and dune apron (Thornton *et al.*, 2006), top of the seacliff face (Hapke and Reid, 2007; Hapke, Reid, and Richmond, 2009) and the "high tide line" (Hapke *et al.*, 2006). Each of these approaches has its advantages and limitations, and the decision of which method and reference feature to use may depend on the type of data available, the nature of the coastal topography, accessibility of the site, or personal preference. The intersection of the back beach and dune can oscillate back and forth seasonally, so it may not be an optimal feature to monitor depending on the time scale of the study. The seacliff top captures bedrock erosion but can be difficult to delineate in DEMs where the break in slope or change in aspect is not as pronounced for some gently sloping coastal bluffs. Because "bedrock" represents the local geologic material that best resists erosion, its landward retreat can be used as the basis for monitoring long-term coastal erosion. In the Monterey Bay study area, bedrock locally includes weak marine sandstone, poorly lithified Quaternary dunes, and modern dunes, all of which are subject to relatively rapid erosion.

The use of high density LIDAR data provides significant flexibility in selecting the geomorphic feature to monitor. For

this study our chief criteria in selecting a reference feature included the following factors. (1) It must be the most resistant material present in order to capture monotonic, parallel retreat of the eroding coastline; (2) it must foster reproducibility for future vessel-based and airborne LIDAR studies; and (3) it must have a high density of LIDAR strikes to ensure high precision.

For the purposes of this study we chose to measure coastal position and change on the seacliff face along the 10-meter elevation contour (NAVD88). This reference contour was selected based on field inspections throughout the study area that revealed this elevation to be the one most representative of the local bedrock face because it was generally well above the seacliff sand apron but below the often low seacliff tops (Figure 2).

The Digital Shoreline Analysis System (DSAS; Thielert *et al.*, 2009) was used to calculate shoreline recession along the coastline at the 10 m contour (NAVD88) derived in ArcGIS for each dataset. Transects were spaced at 20 m intervals and oriented normal to the coastline to accommodate any crenulated cliffs and to facilitate comparison with previous USGS (Hapke and Reid, 2007; Hapke *et al.*, 2006; Morton and Miller, 2005) and DSAS (Hapke, Reid, and Richmond, 2009) cliff-change analyses. The analysis was broken up into southern and northern Monterey Bay sections approximately 10 km and 11 km in length, respectively (Figure 1). Net erosion based on reference feature movement was calculated for each transect using the horizontal shift in the 10 m contour line position. In order to achieve the most accurate measure of net shoreline change at the location of each transect, the otherwise shoreline-normal orientation of individual transects was edited to be normal to the seacliff face in deeply crenulated cliffs according to the methods of Hapke *et al.* (2006). One Way Analysis of Variance (ANOVA) and Welch's Two Sample *t*-test were used to test for significant differences between the 1997–98 El Niño, 1998–2009 inter- El Niño, 2008–09 non- El Niño, and 2009–10 El Niño periods for southern Monterey Bay and northern Monterey Bay, respectively.

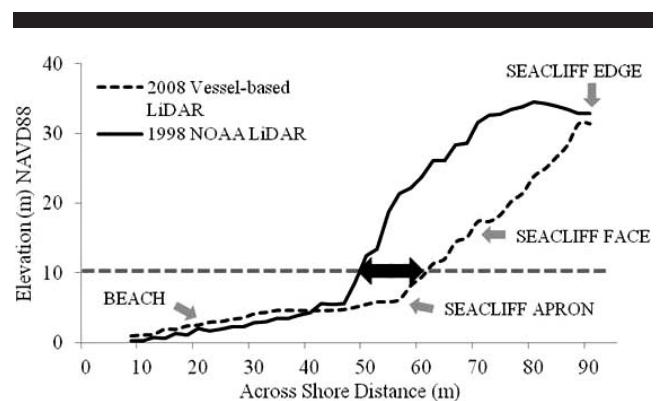


Figure 2. Shore-normal profiles of 1998 and 2008 LIDAR digital elevation models showing an example of shoreline recession measurement with the erosion reference feature being the position of the seacliff face at 10 m elevation NAVD88 (grey dashed line).

Total positional uncertainty for the net shoreline movement calculations were derived using methods from Hapke *et al.* (2006) and Stockdon *et al.* (2002). Net erosion reference feature movement uncertainty was calculated as the quadrature summation of LIDAR data uncertainty and contour derivation uncertainty. The independently measured GPS positions of three objects along the Monterey Bay coastline initially used for ground-truthing were compared with their respective positions in the vessel-based LIDAR point clouds. The root mean square (RMS) was calculated for each x , y , and z for each dataset (RMS_x , RMS_y , and RMS_z), comparing the position of coastal structures in all vessel-based LIDAR datasets to their respective static GPS positions. The root sum of squares (RSS) or combined RMS for each x , y , and z position was used for an estimate of vessel-based LIDAR uncertainty. Due to the lower data densities of the 1997 and 1998 LIDAR, point-to-point comparisons with independently measured GPS positions were not possible. Therefore, airborne LIDAR uncertainty estimate was derived from existing airborne LIDAR studies on NASA's ATM (Sallenger *et al.*, 2003) at 0.15 m.

Contour derivation uncertainty was estimated by extracting horizontal positions in all datasets at a structurally sound vertical feature at a fixed vertical elevation. We used the Best Western Plus Beach Resort Monterey seawall for that purpose (Figures 1 and 3). Contours from each data set were generated across the sea wall at 5 m elevation (NAVD 88). Two shore-normal transects were generated randomly along the seawall and were used to intersect the generated contours to extract horizontal positions at each intersection. RMS was calculated for each UTM easting (RMS_x) and (RMS_y), comparing the mean x and y positions. RSS for both RMS_x and RMS_y were used as an estimate for contour derivation uncertainty.

Running averages were conducted on the results of the DSAS net shoreline movement analysis to minimize noise and reveal the spatial periodicity of erosion hot spots. A shoreline segment length of 100 m for the running average was used to give a clear signal because that value is less than the spatial scales of the estimated 200–300 m mega-cusp-length hot spots located in Monterey Bay (Thornton, MacMahan, and Sallenger, 2007).

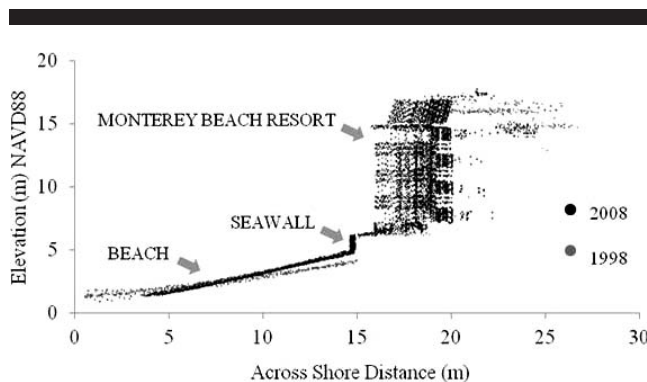


Figure 3. Shore-normal profiles of 2008 vessel-based LIDAR and 1998 aerial LIDAR to assess intersurvey precision. Location: Monterey Bay Beach Resort.

Cross-correlation analysis was used to test the hypothesis that erosion hot spots exhibit a predictable alternating spatial pattern alongshore between consecutive El Niño and inter-El Niño periods. Digital Shoreline Analysis System results for consecutive El Niño and inter-El Niño periods from 1997–2010 were cross-correlated in sequence (1997–98 El Niño then 1998–2009 inter- El Niño, 1998–2009 inter-El Niño then 2009–2010 El Niño) to identify the displacement of maximum correlation or the mean shift between hot spot shorelines relative to each other.

Coastal Data Information Program (CDIP) swell-height distribution NOWcast models (250 m resolution) were used to generate a mean composite for the 2009–10 El Niño period to compare swell-height distribution with seacliff erosion rate values in Monterey Bay. The five strongest El Niño storms were selected using a compilation of National Buoy Data Center significant wave height and tidal height data. The greatest combination of high significant wave height and high tidal height at any given period was used to determine the five strongest El Niño winter storms (October 15, 2009; November 28, 2009; January 19, 2010; February 13, 2010; and February 28, 2010). Coastal Data Information Program swell-height distribution NOWcast models for each of the five selected El Niño winter storms were downloaded as 8-bit bitmap images, reclassified, and merged in ArcGIS to create a mean composite of wave height distribution of the five strongest storms for the 2009–10 El Niño year at 250 m spatial resolution. Digital Shoreline Analysis System results were binned to closely match the 250 m resolution of the mean composite swell-height distribution model and statistically compared with regression analyses.

RESULTS

Ground truth surveys of three coastal structures along the Monterey Bay coastline compared to all of the vessel-based LIDAR datasets yielded differences ranging from -0.36 to 0.20 m in easting, from -0.04 to 0.17 m in northing, and from -0.11 to 0.14 m vertically. Total vessel-based LIDAR RMS_x , RMS_y , and RMS_z were 0.25 m, 0.28 m, and 0.16 m, respectively. The RSS of RMS_x , RMS_y , and RMS_z for vessel-based LIDAR was 0.41 m. Because of the point-to-point comparisons, error may be attributable to sparse data density particularly at the coastal structures that were independently surveyed. Other sources of error include LIDAR system accuracy, which Riegl estimates is 0.10 m.

Easting and northing position comparisons of the 1998, 2008, 2009, and 2010 LIDAR datasets at the Best Western Plus Beach Resort Monterey seawall at 5 m (NAVD88) yielded differences ranging from -1.0 to 0.7 m easting and from -0.7 to 0.1 m northing. Unfortunately, the 1997 data set did not cover the seawall site. Total RMS_x and RMS_y were 0.9 m and 0.9 m, respectively. The RSS of RMS_x and RMS_y was 1.3 m. The total positional uncertainty, composed of the RSS of vessel-based LIDAR, airborne LIDAR, and contour derivation uncertainty, was 1.4 m, which is consistent with previous LIDAR positional uncertainty estimates (Stockdon *et al.*, 2002). Sources of error are attributable to grid generation using the mean squares algorithm and the generation of contour lines from these grids.

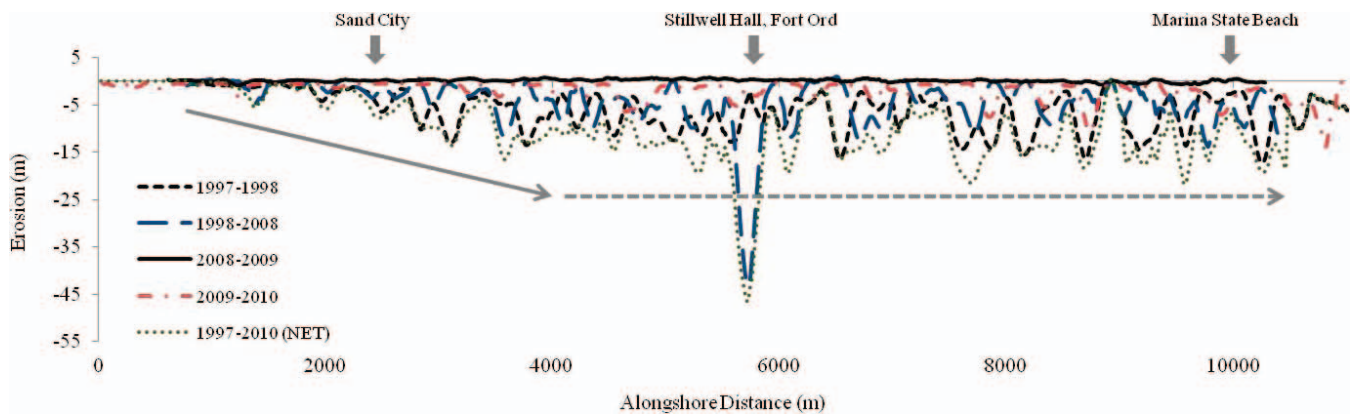


Figure 4. Southern study area plot of shoreline recession with a 100 m running average at 10 m elevation (NAVD88). X axis represents alongshore distance (m) starting in Sand City and ending at Marina Sate Beach. Y axis represents shoreline recession (m). The solid line depicts a trend of increasing erosion magnitude alongshore, whereas the dashed line depicts signs of shoreline averaging found along this stretch of coastline found in this stretch of coastline.

Erosion results for this study are reported raw (*i.e.*, without account for uncertainty estimates) and on a per period basis (*i.e.*, survey date to survey date). Annualizing these rates can yield misleading results because coastal erosion is highly seasonal along the U.S. west coast, with most erosion occurring in winter months. In keeping with previous work, results show numerous spatially variable erosion hot spots that increase in occurrence and magnitude along a gradient from south to north

along southern Monterey Bay during the 2009–10 El Niño period (Figure 4). Although moderate in severity compared to the 1997–98 El Niño period, substantial erosion occurred during the 2009–10 El Niño. The highest rates of shoreline recession were detected between Fort Ord Dunes State Beach at the old Stillwell hall site (~14 m) and at Marina Beach (~8 m) during the 2009–10 El Niño (Figures 4 and 5) with an average of 1.8 m (Table 1). Although erosion during the 2008–09 non-El Niño period was minor and fell below our estimated level of uncertainty, considerably higher rates of erosion were found during the 2009–10 El Niño period (1.8 m average) than the 2008–09 non-El Niño period (0.1 m average) (Table 1). Significant differences were found between erosion during the 1997–98 El Niño, 1998–2009 inter- El Niño, 2008–09 non- El Niño, and 2009–10 El Niño periods for southern Monterey Bay (Table 1).

Spatially variable erosion hot spots were also detected in southern Monterey Bay during the inter-El Niño period (1998–2009) with an erosion average of 3.7 m (Table 1). Multi-El Niño cycle (1997–2010) analyses revealed a stronger south to north gradient signal, which was only slightly apparent in the 2009–10 El Niño for the same region (Figure 4). During the multi-El



Figure 5. Aerial photographs of the Marina launch ramp at Marina State Beach captured in 2008 and 2010. Shoreline recession was measured at up to 8 m in this area. [Photos copyright (c) 2010, Adelman and Adelman (2010), Kenneth and Gabrielle Adelman, California Coastal Records Project, www.californiacoastline.org.] Resistant horizontal band in seaciff is a paleosol within the Quaternary Aromas Red Sandstone depicted with the horizontal black arrows.

Table 1. Summary of average shoreline change rates for Monterey Bay derived from DSAS results. Asterisks denote *p* values (0.01*, 0.001**, <0.001***) for ANOVA (Southern Monterey Bay 1997–98, 1998–2009, 2008–2009, and 2009–2010 periods) and Welch Two Sample *t*-test (Northern Monterey Bay 2008–09 and 2009–10 periods) tests.

	Average Erosion (m)	±95% Ci (m)	SD (m)	N
Southern Monterey Bay				
2009–10 El Niño period	–1.8***	0.15	1.7	484
2008–09 Inter-El Niño year	–0.1***	0.03	0.3	484
1998–2009 Inter-El Niño period	–3.7***	0.30	3.4	484
1997–98 El Niño period	–6.4***	0.37	4.1	484
Northern Monterey Bay				
2009–10 El Niño period	–0.5***	0.04	0.44	408
2008–09 Inter-El Niño year	–0.0***	0.01	0.14	408

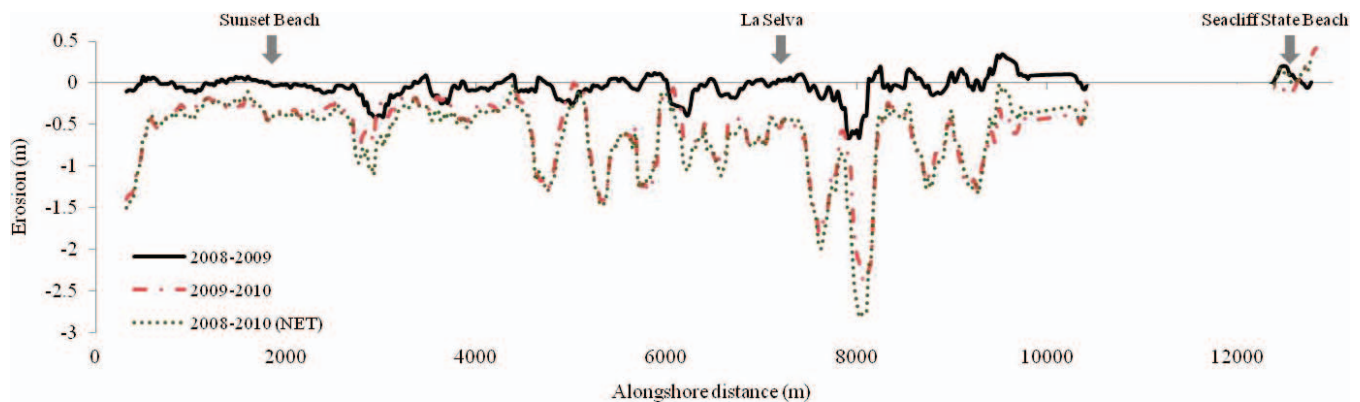


Figure 6. Northern study area plot of shoreline recession with a 100 m running average at 10 m elevation (NAVD88). X axis represents alongshore distance (m) starting from Sunset Beach and ending at Seaciff State Beach. Y axis represents shoreline recession (m).

Niño cycle (1997–2010), erosion magnitude increased at an approximate rate of 5 m of retreat per km alongshore for the first 0 to 4 km of coastline starting 2 km SW of Sand City (Figure 4). The 8 km of coastline between Sand City and Marina exhibited signs of shoreline averaging, where erosion is persistent and relatively uniform over long timeframes, as there were no obvious alongshore trends in erosion magnitude over large spatial and temporal scales.

In northern Monterey Bay, erosion during the 2009–10 El Niño period was minimal compared to the southern bay, with an overall mean of 0.5 m (Table 1). Erosion reached a maximum of 2.5 m at erosion hot spots near La Selva (Figure 6). Mean erosion during the 2008–09 normal year was 0.0 m for northern Monterey Bay (Table 1). Significant differences were also found between erosion during the 2008–09 non-El Niño and 2009–10 El Niño periods for northern Monterey Bay (Table 1), but the overall results fall below our level of estimated total positional uncertainty.

A comparison of the spatial locations of El Niño and inter-El Niño hot spots in southern Monterey suggests the occurrence of a hot spot migration process during consecutive 1997–98 El Niño to 1998–2009 inter-El Niño periods and 1998–2009 inter-El Niño to 2009–10 El Niño periods (Figure 7). For the majority of the coastline, hot spots that occurred during one period tend to have little or no activity in the consecutive period.

Cross correlations of El Niño and inter-El Niño erosion hot spot variations were found to be significantly correlated at 95% confidence at –160 m during the 1997–98 El Niño to 1998–2009 inter-El Niño periods and 100 m during the 1998–2009 inter-El Niño to 2009–10 El Niño periods in southern Monterey Bay (Figure 8). Erosion hot spots that occurred during one El Niño or inter-El Niño period shifted spatially alongshore during subsequent El Niño or inter-El Niño period.

The composite swell-height distribution model for the 2009–10 El Niño period revealed gradients and variations of wave height in Monterey Bay (Figure 9). In northern Monterey Bay high wave energy was found at La Selva Beach with the remainder of the northern coastline, exhibiting relatively uniform wave-energy exposure. In southern Monterey Bay a

strong gradient of increasing swell height from south to north was found centered on Sand City. The shoreline adjacent to this gradient from north of Sand City to the Salinas river mouth is characterized by uniform wave-energy exposure. The highest wave energy occurred at the muted delta of the Salinas River, indicated by seaward deflected isobaths near the Salinas River mouth (Figure 1). As expected, results from both El Niño and inter-El Niño analyses indicate that locations with the highest rates of erosion coincided with the locations of highest wave energy. In the southern Monterey Sand City region the wave-energy gradient coincided with the erosion gradient, and in northern Monterey Bay the area of highest wave energy coincided with the erosion hot spot at La Selva (Figures 4, 6, and 9).

The DSAS results are plotted with wave height data for both southern and northern Monterey Bay (Figure 10). Wave height values were selected at 100 m offshore relative to the shoreline to omit erroneous breaking wave zone data. Exponential (southern Monterey Bay) and linear (northern Monterey Bay) regression results indicate significant relationships between shoreline recession and wave height ($p < 0.05$, northern Monterey Bay adjusted $R^2 = 0.1621$).

DISCUSSION

Consistent with previous pre/post-El Niño shoreline assessments (Hapke and Richmond, 2002; Moore and Griggs, 2002; Thornton *et al.*, 2006), spatially variable erosion hot spots occurred during the 2009–10 El Niño period and at significantly higher rates of change than during the 2008–09 normal year. The southern Monterey Bay coastline changed considerably from 1997 to 2010, with both El Niño and inter-El Niño periods playing important roles in coastal erosion. Erosion during the two El Niño periods (1997–98, 2009–10) produced the greatest change over short time frames, but erosion during the 11-year inter-El Niño period (1998–2009) contributed to substantial net change at a lower rate. Hot spot erosion was previously found to occur only during El Niño or extreme storm events (Thornton *et al.*, 2006, Thornton, MacMahan, and Sallenger, 2007), but in

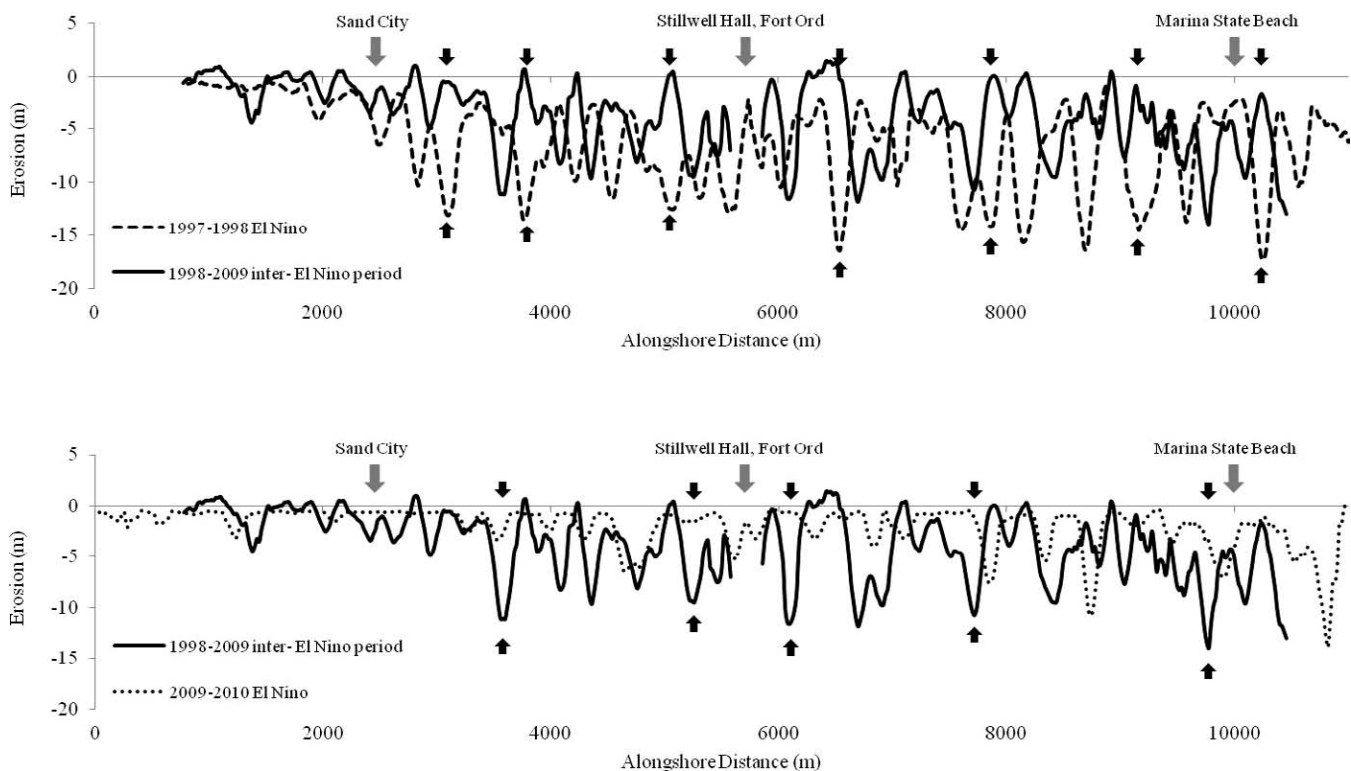


Figure 7. Plots of shoreline recession after consecutive El Niño to inter-El Niño periods (top) and inter-El Niño to El Niño periods (bottom) with a 100 m running average at 10 m elevation (NAVD88) for Southern Monterey Bay. X axis represents alongshore distance (m) starting in Sand City and ending at Marina State Beach. Y axis represents shoreline recession (m). Black arrows indicate some erosion hot spot shift locations. Anomalous high shoreline recession values at Stillwell hall were omitted.

this study hot spot erosion was shown to occur during both El Niño and inter-El Niño periods.

Net alongshore erosion at the decadal time scale spanning two El Niños and the inter-El Niño period from 1997 to 2010 in southern Monterey Bay was found to exhibit signs of shoreline averaging over the 8 km of shoreline north of the identified wave energy gradient at Sand City (Figure 4). One anomaly in this trend of uniform long-term retreat occurred at Stillwell Hall in Fort Ord. Coastal armoring at that site created a local promontory, relative to the adjacent coastline. When a riprap seawall was removed from the bluff toe in 2004, the promontory quickly retreated with respect to the adjacent unmodified seacliffs (Figures 4 and 11). Analysis of swell-height distribution with results from the DSAS yielded significant correlation between swell height and shoreline recession (Figure 10). Along the southern bay shoreline, where the sandy bluffs are uniformly weak and susceptible to erosion, wave distribution models may prove to be a reliable predictor for future coastal erosion on broad scales in this region.

The alongshore shifts in the locations of erosion hot spots that were found in southern Monterey Bay when comparing consecutive El Niño and inter-El Niño periods (1997–98 El Niño to 1998–2009 inter-El Niño to 2009–10 El Niño) (Figure 7) suggest the occurrence of a hot spot migration or jump process

in which the spatial location of erosion hot spots shift north or south between consecutive El Niño and inter-El Niño periods.

Cross correlations of El Niño and inter-El Niño erosion hot spot variations indicated an average hot spot shift of 160 m to the south between the 1997–98 El Niño relative to 1998–2009 inter-El Niño periods and an average hot spot shift 100 m to the north between the 1998–2009 inter-El Niño relative to 2009–10 El Niño periods in southern Monterey Bay (Figure 8). These results also indicate a net shift of 60 m south between the 1997–98 and 2009–10 El Niños. The relevant length scale (distance between peak maxima) from the two cross correlation analyses are 320 m for the 1997–98 El Niño to 1998–2009 inter-El Niño period and 200 m for the 1998–2009 inter-El Niño to 2009–10 El Niño period. These values match up well with the mean spacing of hot spots found in the DSAS results and the estimated 200–300 m mega-cusp lengths alongshore (Thornton, MacMahan, and Sallenger, 2007).

Previous work has shown that rip currents migrate with mega-cusps, and that the formation and location of mega-cusps play a significant role in the amount of wave run-up and subsequently the potential for erosion hot spots (Thornton, MacMahan, and Sallenger, 2007). Rip currents were found to migrate throughout the year during both El Niño (Thornton, MacMahan, and Sallenger, 2007) and non-El Niño years (Orzech *et al.*, 2010). Orzech *et al.*, 2010 found rip channels in

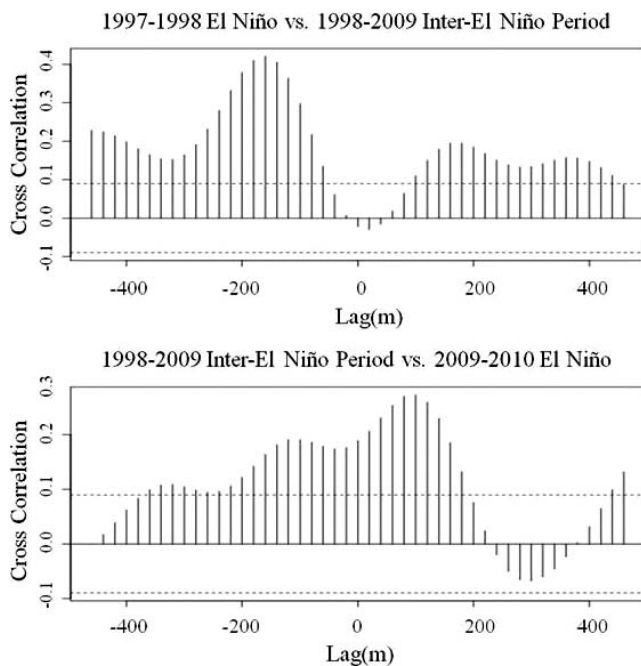


Figure 8. Cross-correlations between consecutive El Niño and inter-El Niño period hot spot erosion for Southern Monterey Bay. The most significant cross correlation values were found at a spatial lag of -160 m (top) and 100 m (bottom), indicating mean alongshore shifts in hot spot locations between periods. Horizontal dashed lines represent 95% confidence levels. Anomalous high shoreline recession values at Stillwell Hall were omitted.

the center of southern Monterey Bay to slowly migrate south during most of the year and migrate north at a faster rate during the winter with nearly no net annual migration. A complicated coastal process presents itself as mega-cusps migrate up and down annually along the southern Monterey Bay shoreline, and hot spots occur variably only during times with coincident large waves and high tides. Measurements in this study only serve as snapshots sometime during this complicated process. Therefore, we can only speculate on the processes that cause the shifts in erosion hot spot location (*i.e.*, migration or jump) found in this study.

The detection of hot spot shifts between consecutive El Niño and inter-El Niño periods aids in short-term coastal management decisions for southern Monterey Bay. Previously interpreted as primarily episodic and variable, occurring during extreme storm periods characteristic of El Niño episodes, results from this study along with previous studies (Orzech *et al.*, 2010) demonstrate that relatively rapid erosion can also occur during quiescent periods. These hot spots are not expected to grow in the same location during the following period but will migrate (or jump) so that the mean shoreline averaged over broad scales and long timeframes recesses at the same rate. This process apparently leads to the overall gently curving nature of the shoreline/bluff edge at both ends of the bay (Griggs and Jones, 1985).

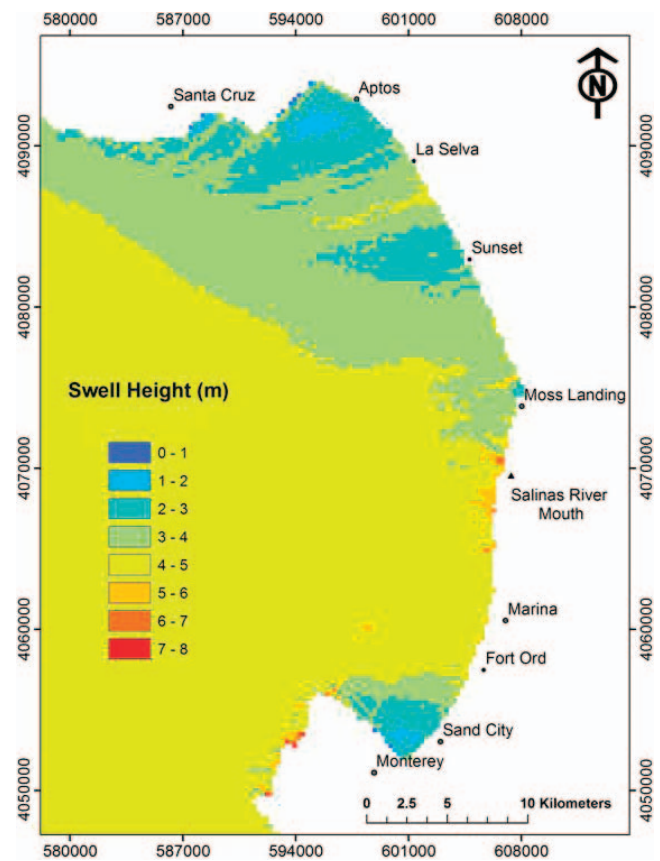


Figure 9. Coastal Data Information Program mean swell height distribution NOWcast model composite (250 m cell size) derived from the five strongest 2009–10 El Niño winter storms (October 15, 2009; November 28, 2009; January 19, 2010; February 13, 2010; and February 28, 2010). Coordinate system: UTM zone 10N NAD83.

Given the complicated fine-scale coastal processes that occur in Monterey Bay, there is great need for new, efficient, and cost-effective tools for precisely monitoring the distribution and rates of coastal erosion over shorter time frames to enable more

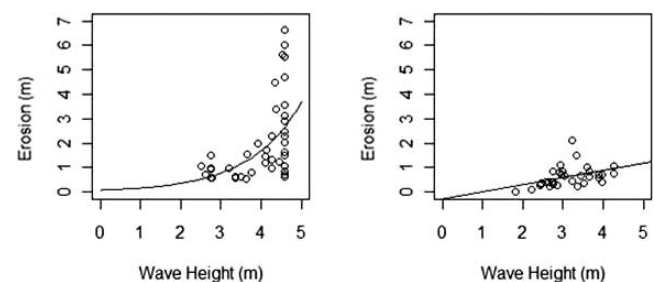


Figure 10. Bluff erosion (m) plotted against average wave height (m) for southern Monterey Bay (left, $N=46$) and northern Monterey Bay (right, $N=34$) during the 2009–10 El Niño period with their respective exponential (left) and linear (right) regression lines.



Figure 11. Aerial photographs of Stillwell Hall at Fort Ord captured in 2002 and 2010. [Photos copyright (c) 2010, Adelman and Adelman (2010), Kenneth and Gabrielle Adelman, California Coastal Records Project, www.californiacoastline.org.] This location is a good example of passive erosion fronting coastal armoring, which can be recovered with armor removal.

nimble adaptive management in response to accelerating climate change and sea-level rise. The flexible, rapidly mobilized vessel-based LIDAR system used in this study produces high resolution terrain data in a relatively cost-effective manner compared to traditional airborne LIDAR surveys, for which high cost is one of the biggest limiting factors for repeat aerial LIDAR surveys. Because of its low, horizontal viewpoint, vessel-based LIDAR, unlike airborne LIDAR, can miss flat spots above the level of the sensor and topographic lows behind berms and dunes. While this limitation precludes the ability to measure back dunes, vessel-based LIDAR is optimal for measuring shoreline recession, deposition, and topography of seaciff faces. This horizontal viewpoint is particularly effective for measuring marine terrace and steep seaciff faces: topographic features that aerial LIDAR's down-looking viewpoint can miss and/or misrepresent because of sparse data density.

CONCLUSIONS

Vessel-based LIDAR data collected in 2008, 2009, and 2010 and pre-existing USGS, NASA, and NOAA airborne topographic LIDAR data from 1997 and 1998 were analyzed using spatial analysis tools in ArcGIS to quantify alongshore erosion during the 1997–98 El Niño, 1998–2009 inter-El Niño period, and 2009–10 El Niño for the Monterey Bay shoreline.

Erosion occurred during the 1997–98 El Niño and 2009–10 El Niño in southern Monterey Bay and was found to be

significantly higher during the 2009–10 El Niño *vs.* the 2008–09 non-El Niño period (1.8 m average *vs.* 0.1 m average in the southern bay and 0.5 m average *vs.* 0.0 m average in the northern bay). Spatially variable hot spots were found post 2009–10 El Niño, and although moderate compared to 1997–98, substantial erosion occurred during the 2009–10 El Niño. El Niño and inter-El Niño erosion hot spot variations were found to be significantly correlated at the 95% confidence at –160 m during the 1997–98 El Niño to 1998–2009 inter-El Niño periods and 100 m during the 1998–2009 inter-El Niño to 2009–10 El Niño periods in southern Monterey Bay. Erosion hot spots that occurred during one El Niño or inter-El Niño period shifted spatially alongshore during the subsequent El Niño or inter-El Niño period. The DSAS shoreline recession results during the multi-El Niño cycle (1997–2010) indicate signs of shoreline averaging over large spatial and temporal scales along the southern Monterey Bay coastline with net erosion consistent with significant wave energy. This correspondence suggests that wave energy distribution models may prove valuable as reliable predictors of future coastal erosion on broad scales.

The utilization of vessel-based LIDAR proved to be an effective and efficient method for the collection of high resolution shoreline topographic data, able to support the accurate and precise quantification, analysis, and modeling of small-scale geomorphic coastal processes. With the effects of global warming and sea-level rise projected to exacerbate coastal erosion, this approach offers a cost-effective alternative for conducting the more frequent seasonal and event-driven repeat surveys required for long- and short-term change analyses.

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Concepts in Sediment Budgets

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ABSTRACT

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The sediment budget is fundamental in coastal science and engineering. Budgets allow estimates to be made of the volume or volume rate of sediment entering and exiting a defined region of the coast and the surplus or deficit remaining in that region. Sediment budgets have been regularly employed with variations in approaches to determine the sources and sinks through application of the primary conservation of mass equation. Historically, sediment budgets have been constructed and displayed on paper or maps. Challenges in constructing a sediment budget include determining the appropriate boundaries of the budget and interior cells; defining the possible range of sediment transport pathways, and the relative magnitude of each; representing the uncertainty associated with values and assumptions in the budget; and testing the sensitivity of the series of budgets to variations in the unknown and temporally-changing values. These challenges are usually addressed by representing a series of budget alternatives that are ultimately drawn on paper, maps, or graphs. Applications of the methodology include detailed local-scale sediment budgets, such as for an inlet or beach fill project, and large-scale sediment budgets for the region surrounding the study area. The local-scale budget has calculation cells representing features on the order of 10s to 100s of meters, and it must be shown separately from the regional sediment budget, with cells ranging from 100s of meters to kilometers.

This paper reviews commonly applied sediment budget concepts and introduces new considerations intended to make the sediment budget process more reliable, streamlined, and understandable. The need for both local and regional sediment budgets is discussed, and the utility of combining, or collapsing, cells is shown to be beneficial for local budgets within a regional system. Collapsing all cells within the budget creates a “macrobudget,” which can be applied to check for overall balance of values. An automated means of changing the magnitude of terms, while maintaining the same dependency on other values within the sediment budget, is presented. Finally, the need for and method of tracking uncertainty within the sediment budget, and a means for conducting sensitivity analyses, are discussed. These new concepts are demonstrated within the Sediment Budget Analysis System with an application for Long Island, New York, and Ocean City Inlet, Maryland.

ADDITIONAL INDEX WORDS: *Uncertainty, sensitivity testing, Long Island, New York, Ocean City Inlet, Maryland, regional scale, computer program, beaches.*

INTRODUCTION

Sediment budgets are regularly created in coastal engineering and science studies to develop understanding of the sediment sources, sinks, transport pathways and magnitudes for a selected region of coast and within a defined period of time. The sediment budget is a balance of volumes (or volume rates of change) for sediments entering (source) and leaving (sink) a selected region of coast, and the resulting erosion or accretion in the coastal area under consideration. The sediment budget may be constructed to represent short-term conditions, such as for a particular season of the year, to longer time periods representing a particular historical time period or existing conditions at the site. Once the sediment budget has been developed, values in the budget may be altered to explore possible erosional or accretionary aspects of a proposed engineering project, or variations in assumed terms. Sediment budgets are a fundamental tool for project man-

agement, and they often serve as a common framework for discussions with colleagues and sponsors involved in a study.

BOWEN and INMAN (1966) introduced the general sediment budget concept with an application to the southern California coast, based upon coastal geology (rocky headlands) and estimates of longshore sand transport to define five semi-contained littoral cells and sub-cells over approximately 105 km of shoreline. The authors estimated longshore sand transport rates from calculations of the longshore components of wave power, and for specified sources (river influx, sea cliff erosion) and sinks (submarine canyons and dune-building processes) for the sediment budget calculation cells (Figure 1a). They also discuss the diffusion behavior of sediment movement on the coast, implying that purely deterministic accountings might have limitations.

CALDWELL (1966) summarized a regional sediment budget developed in the 1950s by the Corps of Engineers for the north New Jersey coast (U.S. ARMY CORPS OF ENGINEERS, 1957, 1958). The budget was formulated by analyzing differences in shoreline position with the objective of examining alternatives to mitigate for erosion over a wide stretch of ur-

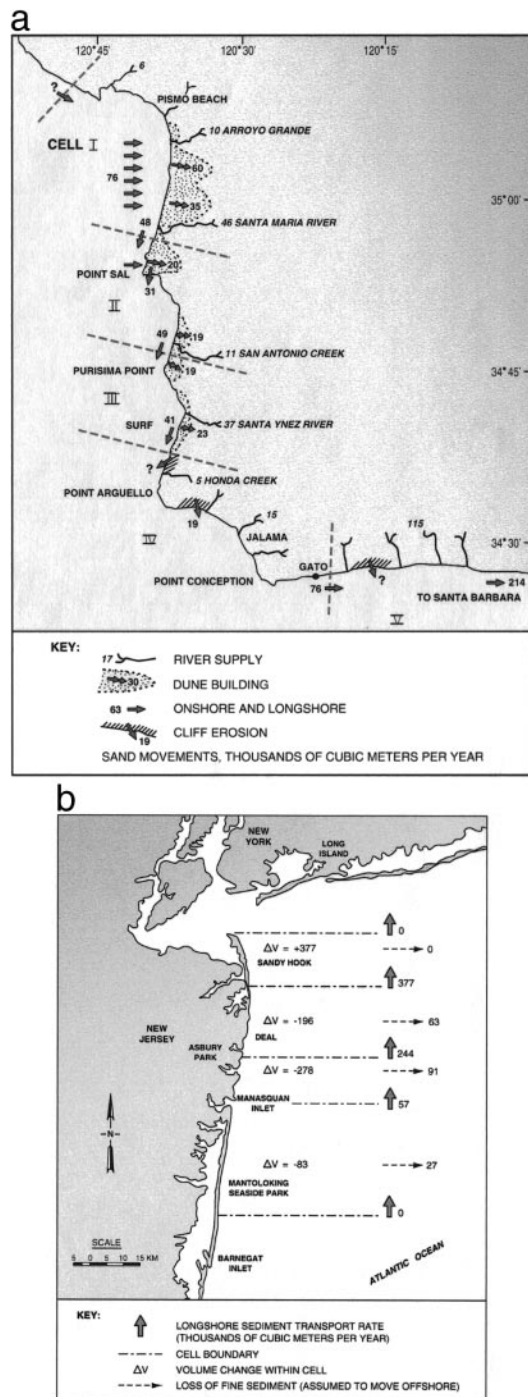


Figure 1. Early sediment budgets (a) Southern California sediment budget (adapted from Bowen and Inman 1966), (b) North New Jersey sediment budget (adapted from Caldwell 1966).

banized and semiurbanized beach. This study deduced the existence of a regional divergent nodal area in net longshore transport direction at Mantoloking, located just north of Dover Township. Net longshore transport to the north increased with distance north from Mantoloking because of the wave

sheltering by Long Island, New York. The budget covered average annual net and gross longshore sand transport rates for this 190-km reach, including ten inlets, over time intervals of 50 to 115 years. Both the magnitudes and directions of transport, including location of the nodal area, are still considered to be valid (Figure 1b).

Today, sediment budgets are a fundamental element of coastal sediment processes studies encompassing many applications (KOMAR, 1998). Budgets typically start from documented accretion and erosion to estimate other contributions with higher uncertainty. Budgets serve as a common framework to evaluate alternative project designs, develop an understanding of sediment transport pathways through time, or estimate future rates of sediment accretion or erosion. This paper reviews sediment budget concepts and introduces new considerations intended to streamline the sediment budget evaluation and presentation process. Estimation of uncertainty in sediment budgets is considered a central element of a modern treatment. The state of personal computer technology has allowed automation of many convenient, if not essential, features of the new concepts. Basic and new sediment budget methods are demonstrated with applications for Long Island, New York and Ocean City Inlet, Maryland.

REVIEW OF SEDIMENT BUDGET CONCEPTS

Theory and Definitions

A sediment budget is a tally of sediment **gains** and **losses**, or **sources** and **sinks**, within a specified control volume (or cell), or in a series of connecting calculation cells, over a given time. As with any accounting system, the algebraic difference between sediment sources and sinks in each cell, hence for the entire sediment budget, must equal the rate of change in sediment volume occurring within that region, accounting for possible engineering activities. Expressed in terms of variables consistent as volume or as volumetric rate of change, the sediment budget equation is,

$$\sum Q_{source} - \sum Q_{sink} - \Delta V + P - R = Residual \quad (1)$$

where Q_{source} and Q_{sink} are the sources and sinks to the control volume, respectively, ΔV is the net change in volume within the cell, P and R are the amounts of material placed in and removed from the cell, respectively, and *Residual* represents the degree to which the cell is balanced (KRAUS and ROSATI, 1999a, 1999b). For a balanced cell, the residual is zero. Figure 2 schematically illustrates the parameters appearing in Equation 1, in which LST denotes longshore sediment transport. For a reach of coast consisting of many contiguous cells, the budget for individual cells must balance in achieving a balanced budget for the entire reach.

As noted in Figure 2, **sources** in the sediment budget include longshore sediment transport into the cell, erosion of bluffs, transport of sediment to the coast by rivers, erosion of the beach, beach fill and dredged material placement as from navigation channel maintenance, and a relative sea level fall. Examples of sediment budget **sinks** are longshore sediment transport out of the cell, accretion of the beach, dredging and mining of the beach or nearshore, relative sea level rise, and losses to a submarine canyon.

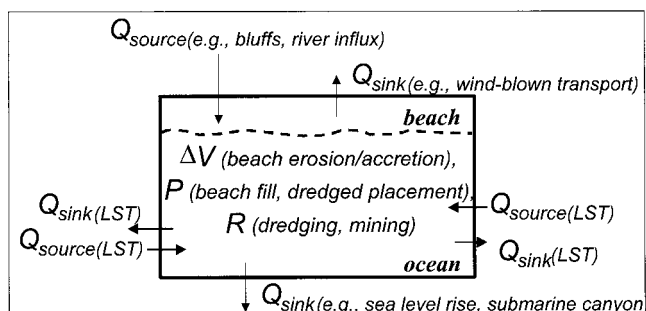


Figure 2. Sediment budget parameters as may enter Equation (1).

Longshore transport rates may be defined as left- and right-directed or as net and gross. The *net* longshore transport rate is defined as the difference between the right-directed and left-directed littoral transport over a specified time interval for a seaward-facing observer,

$$Q_{net} = Q_R - Q_L \quad (2)$$

in which both the leftward-directed transport Q_L and rightward-directed transport Q_R are taken as positive. The *gross* longshore transport rate is defined as the sum of the right-directed and left-directed transport rates over a specified time interval for a seaward-facing observer,

$$Q_{gross} = Q_R + Q_L \quad (3)$$

An inlet channel may capture much of the left- and right-directed components of the longshore transport, and the inlet system may bypass left- and right-directed longshore transport. Thus, knowledge of the net and gross transport rates, as well as pathways of sediment transport for left- and right-directed dominance (as might occur during seasons of net transport reversal), are required to accurately represent transport within the vicinity of inlets (BODGE, 1993). The net or predominant direction of longshore sediment transport at an inlet or at a groin or jetty can usually be inferred by the asymmetry in geomorphology at the site (CARR and KRAUS, 2001). The asymmetry can be related to the ratio of net to gross longshore transport Q_{net}/Q_{gross} which varies from zero (balanced left- and right-directed longshore transport, hence near-symmetrical morphology) to unity (unidirectional longshore transport).

Estimating Values in the Sediment Budget

Overview. Several approaches have been developed that apply a form of Equation (1). Generally, these methods estimate a likely range of values for the best-known quantities and solve for the lesser-known terms. Volume change data, and removal and placement records usually provide the foundation for the sediment budget. Then, a range of “accepted” longshore transport rates and a range in relative magnitude of other fluxes are applied to solve the budget. Imbalance of the equation is addressed by varying these parameters, and other terms with great uncertainty, such as offshore losses

and wind-blown transport, and uncertainty in the values of the best-known quantities.

Conceptual Budget. DOLAN *et al.* (1987) and KANA and STEVENS (1992) discuss a “conceptual sediment budget,” which they recommend developing in the planning stage prior to making detailed calculations. The conceptual sediment budget is a qualitative model giving a regional perspective of beach and inlet processes, containing the effects of offshore bathymetry (particularly shoals and, therefore, wave-driven sources and sinks), and incorporating natural morphologic indicators of net (and gross) sand transport. The conceptual model may be put together in part by adopting sediment budgets developed for other sites in similar settings, and incorporates all sediment sinks, sources, and pathways. The conceptual model is developed initially, perhaps based upon a reconnaissance study at the site as part of the initial data set. Once the conceptual sediment budget has been completed, data are assimilated to validate the conceptual model rather than to develop the model.

Delineating Sediment Budget Cells. Sediment budget calculation cells or “control volumes” define the boundaries for each sediment budget calculation and denote the existence of a complete self-contained sediment budget within its boundaries (DOLAN *et al.*, 1987). Cells are defined by geologic controls, available data resolution, coastal structures, knowledge of the site, and to isolate known quantities or the quantity of interest. From one to a nearly unlimited number of cells may be defined using one or more of these means to characterize the sediment transport regime of a region. BOWEN and INMAN (1966) introduced the concept of littoral cells (INMAN and FRAUTSCHY, 1966) within a sediment budget. The southern California coast lends itself to this concept, with evident sources (river influx, sea cliff erosion), sinks (submarine canyons), and coastal geology (rocky headlands) defining semi-contained littoral cells and subcells (KOMAR, 1996, 1998). A littoral cell can also be defined to represent a region bounded by assumed or better known transport conditions, or by engineered or natural features such as by a long jetty or by the average location of a nodal region (zone in which $Q_{net} \sim 0$) in net longshore transport direction.

Defining Sediment Budget Pathways. Sediment budget pathways specify the significant transport transfers between cells within a sediment budget. Pathways can be estimated through knowledge of the site, by examining aerial photographs, field observation of drogue or dye movement, through interpretation of engineering activities such as channel dredging and evolution of beach fill, and mapping of bedforms on the sea floor using side scan sonar (e.g., BLACK and HEALY 1983). The relative magnitude and direction of each pathway can be varied to develop alternative sediment budget solutions. Figure 3 shows possible sediment transport pathways for a natural beach, an engineered beach, and a stabilized inlet. The pathways are cumulative from Figure 3a to 3b to 3c; e.g., all pathways illustrated for the natural beach (Figure 3a) also apply to the engineered beach (Figure 3b), and all those shown for both the natural and engineered beaches apply to the inlet case (Figure 3c).

Pathways of sediment movement in the vicinity of an inlet can be circuitous, as shown in Figure 3c along the downdrift

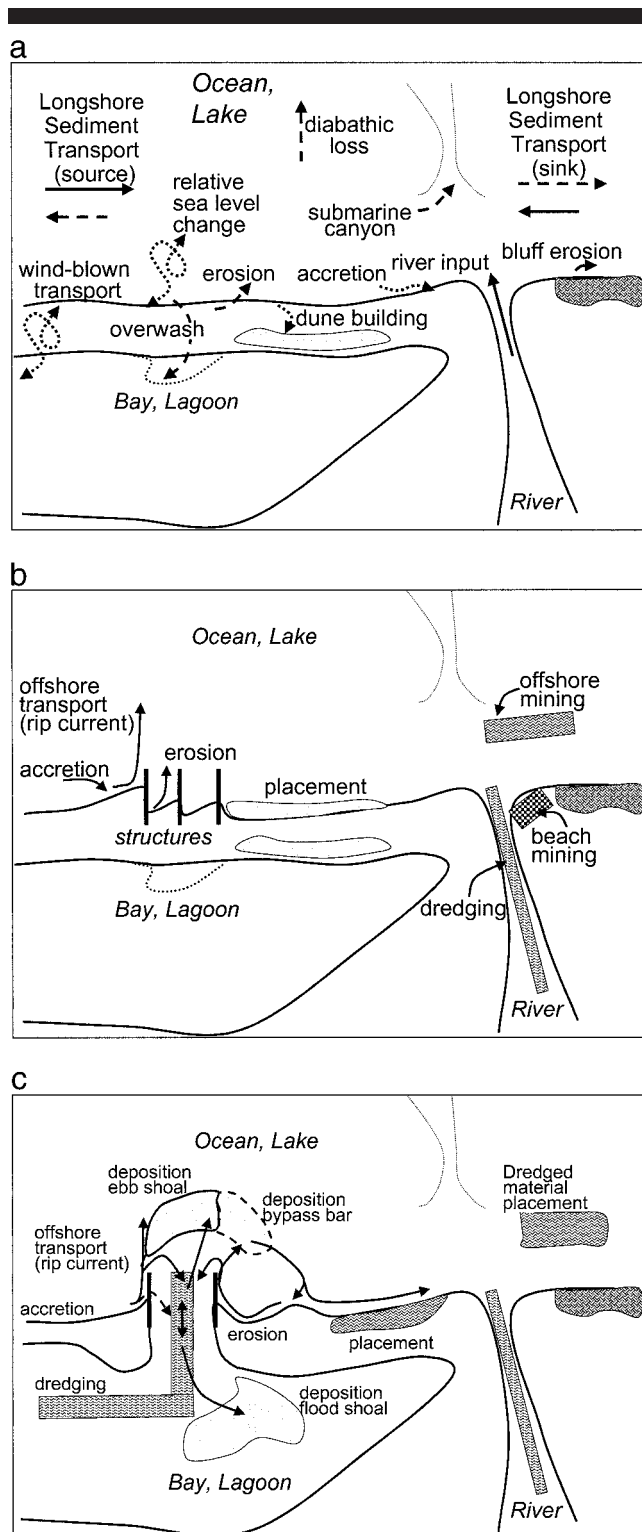


Figure 3. Possible sediment transport pathways for different types of coastal regions (a) Natural beach, (b) Engineered beach, (c) Inlet and adjacent beaches (Note: All pathways illustrated for the natural beach (a) also apply to the engineered beach (b), and all those shown for both the natural and engineered beaches apply to the inlet case (c)).

beach. Thus, equations describing the sediment budget for regions directly adjacent to the inlet are not unique (i.e., different formulations are possible). For natural and engineered beaches (Figures 3a and 3b), determining the magnitude of sediment transport may present a challenge, but the pathways are relatively simple to define. An inlet channel has the potential to capture the left- and right-directed components of the gross longshore transport of sediment, and the inlet system may bypass left- and right-directed longshore transport. Thus, knowledge of the net and gross transport rates, as well as the potential behavior of the inlet with respect to the transport pathways, may be required to correctly represent transport conditions within the vicinity of inlets, as emphasized by BODGE (1993).

BODGE (1999) presents an algebraic method with which a range of sediment budget solutions can be developed to numerically bound and describe sediment transport pathways at inlets. The method incorporates examination of the sediment budget based on a range in the following variables: net and gross longshore sediment transport rates, permeability of jetties to sediment transport, natural bypassing rate from both the updrift and downdrift beaches, and the magnitude of local inlet-induced transport on both the updrift and downdrift beaches. The method also accounts for riverine input, dredging and placement, and mechanical bypassing. Because ranges of values are involved, the final result is a family of solutions that balance the sediment budget. One or several of these solutions may be selected to represent typical sediment transport conditions at the site. Viewing the area defined by the ranges allows one to judge, at least subjectively, the reasonability of selecting various values to represent a particular budget.

Volume Change, Removal, and Placement. Volume change, removal and placement of dredged material or beach fill must be included in the sediment budget if pertinent to the time period being analyzed. Volume change magnitudes and rates may be estimated for each cell of the sediment budget using shoreline position data, beach profile data, bathymetric change data, or shoreline change rates. Alternatively, Equation (1) can be applied with estimates of longshore transport rates to solve for the net volume change within each cell. Because many sediment budgets are formulated based on historical data, the dredging and placement methods used at the time the data were collected must be known. The following is summarized from KRAUS and ROSATI (1999a, 1999b).

Estimating the actual volume dredged and subsequent placement of the material is dependent on the type of equipment used, time frame of removal and placement, and type of material. For example, a hopper dredge may have been filled to capacity while allowing overflow of fine sediments, which theoretically would be transported away from an inlet channel by tidal and other currents. In this situation, consideration should be given to the possibility that some littoral material may not have been included in the dredging estimates, or potentially that the material was rehandled if it settled within the channel. The period of the dredging cycle must also be considered. If the dredging occurred over several months, seasons, or years, a dredging quantity based on pre-dredging and post-dredging bathymetry surveys could rep-

resent additional shoaling of the channel after the initial dredging cycle. The type of material dredged and placed may alter the estimate of the true volume: fine sediments may be suspended during nearshore placement, and thereby overestimate the quantity introduced to the budget; dredging of organic material may tend to overestimate the volume dredged; and the volume of littoral sediments (e.g., sand, gravel) within a mixed material including clays and silts must account for the percentage of non-littoral material in estimations of volumes within the sediment budget.

Practical details may skew an average-annual rate of volume change associated with dredging. For example, sometimes overdredging or additional dredging is performed simply because equipment is available. Gross rates of longshore transport inferred from such dredging records will be overestimates. Similarly, if dredging equipment is damaged in the course of work or must leave a site because of weather, scheduling, or closure of environmental windows, the resultant volumes might underestimate the gross rate for that particular period.

One of the more accurate dredging estimates comes from comparison of pre-dredging and post-dredging surveys. The estimates can have significantly different degrees of reliability and can vary greatly. For example, a dredging contractor is usually paid only for the volume taken out of the design template. If a dredger digs outside the template (whether too deep or to the side of the template), then the reported pay quantity will be less than the volume removed and placed in the disposal area. In calm seas, the reported pay quantity may be only slightly greater than the pay quantity ($< +20\%$), whereas in rough seas and intermittent calm and rough seas (when material can move back into the dredging area), the reported quantity might be double the pay quantity ($\sim +100\%$).

Another method for estimating dredged quantity references the volume of the storage bin or hopper on a dredge. A typical volume is 765 cu m (1,000 cu yd). One method of determining the dredged material volume is to fill the hopper, allow the sediments within the hopper to settle (with excess water spilling over the hopper sides), and measure the vertical distance from the top of the hopper to the sediment surface. The hopper volume can then be calculated with a relatively low uncertainty, estimated at $\pm 10\%$ of the total volume.

A third method of volume calculation is to survey the placed material, whether as an offshore mound or as a beach fill. Uncertainty enters through the insitu voids ratio and whether fine sediments or any of the placed material has run off or slumped beyond the construction template. In this method, the contractor is paid based on surveys aimed to demonstrate that the construction template was filled. Typically, more material must be dredged and placed to meet the survey requirement.

Sidecasting of dredged material is occasionally performed. Typically, an average production rate for the dredge is multiplied by the slurry flow and the time the dredge has operated to obtain a volume. Occasionally, a nuclear-density meter operates on the sidecasting arm and can more accurately estimate the percentage of sediment in the dredged slurry.

The uncertainty estimate for these methods is expected to be relatively large, perhaps $\pm 30\%$.

Sometimes the only estimate of dredged volume is the permitted quantity or the design quantity specified to meet depth requirements for navigation, and this "paper" quantity may not provide a reliable estimate of the actual volume dredged. Typically, the permitted or design quantity will be exceeded, but the amount of exceedance is unknown.

In summary, dredged volume inaccuracies can enter as (a) uncertainty in the pre-dredging condition; (b) uncertainty in the volume-estimation process; (c) unquantified sediment shoaling that occurs between the pre- and post-dredging surveys; (d) failure to include nonpay volume (material removed from side slopes beyond the design channel location and unintentional overdepth dredging); and (e) changes in bulk density between the site where the volume was measured and the site or budget compartment where the volume is placed.

Fill can be placed either as an authorized shore-protection (beachfill) project or as a beneficial use of dredged material. For an authorized beachfill project, the fill is surveyed in place to ensure that the design cross-section is met along the shore. For a beneficial-uses project, the placed material will typically not be measured in place, and the volume will be estimated as that from the dredging site. In both cases, considerations as discussed above for dredged material will apply.

Fluxes. Sand fluxes within the sediment budget may represent, for example, longshore sand transport due to waves and currents; cross-shore transport, perhaps due to storm-induced transport or relative sea level change; riverine input; aeolian transport; and bluff erosion.

The rate of longshore sand transport along a particular beach is a term that is typically varied in Equation (1) to develop alternative sediment budgets. Longshore transport rates may be estimated through local knowledge of the site; history of engineering activities and the subsequent beach response, such as impoundment at a groin or jetty; and calculation of the longshore energy flux due to the site's wave climate.

Sediment-transport fluxes are difficult to define at inlets, even in a relative sense. Flood and ebb currents, combined waves and currents, wave refraction and diffraction over complex bathymetry, and engineering activities complicate transport rate directions and may increase or decrease their magnitudes.

The Longshore Energy Flux sediment budget method incorporates incident wave climatology, shoreline position and beach profile data, and bathymetry to develop estimates of breaking wave parameters (JARRETT, 1977, 1991). From these parameters, the longshore energy flux factor may be related to the longshore transport rate by solving Equation (1) at each sediment budget calculation cell. In JARRETT's (1977, 1991) applications along the South Carolina coast, a relatively consistent proportionality constant was found for each cell, and the mean value was applied to all cells in developing the final sediment budget. The proportionality constant in the calculated energy flux serves as a free parameter for which to solve.

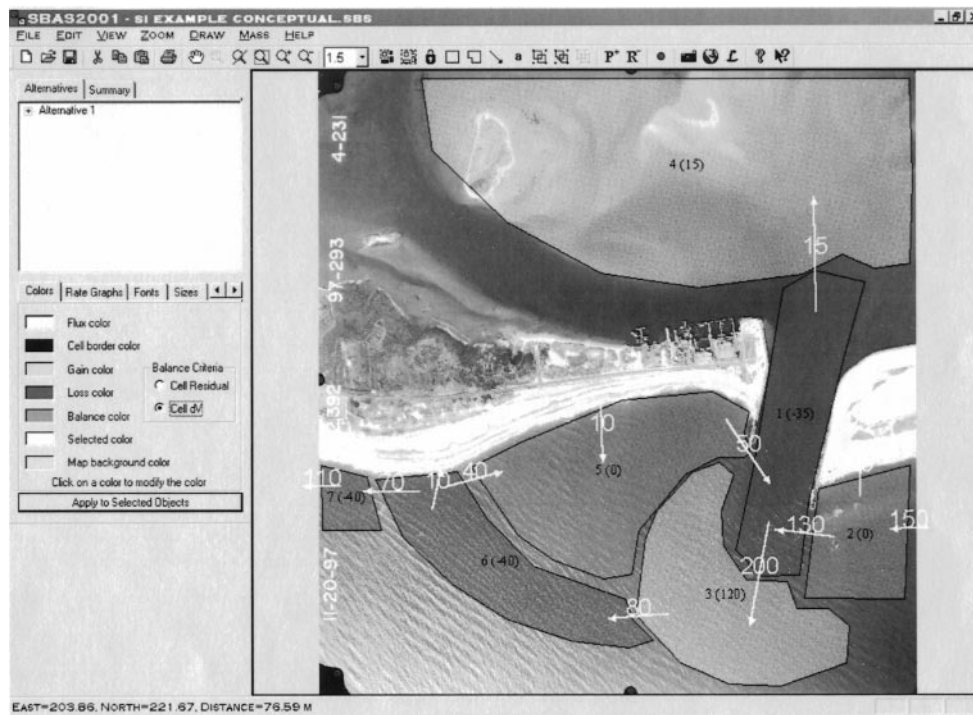


Figure 4. Example conceptual budget for Shinnecock Inlet, New York (color is specified by the user to represent either cell balance or cell erosion/accretion).

NEW SEDIMENT BUDGET CONSIDERATIONS

The following section introduces new considerations as they apply to the formulation of sediment budgets. Some of these topics are not original to this paper, but are innovative applications of existing concepts, or represent a new emphasis on a traditional method. Each of these approaches is demonstrated within the Sediment Budget Analysis System (SBAS) (KRAUS and ROSATI, 1999b; ROSATI and KRAUS 1999c, 2001), a personal computer-based program for constructing and presenting sediment budgets within a geo-referenced framework. In the next section, a short overview of SBAS¹ is given.

Overview. SBAS was developed to streamline the formulation of sediment budgets, minimize errors, and facilitate comprehension and presentations. The user visually constructs the sediment budget by drawing rectangular or polygonal cells and sediment fluxes on the right side of the screen. The user can import georeferenced (or nonreferenced) images over which the sediment budget can be drawn (Figure 4). Placement and removal also are indicated for each cell. The user then has formulated all the relevant terms in Equation (1) for each cell, and a spreadsheet can be displayed by doubleclicking on a cell (Figure 5). Values can be entered, and the cells change colors based on a user-specified criterion:

either the cell residual (positive, negative, or balanced) or cell erosion or accretion (Figure 4). In this way, the user obtains immediate visual indication as to the balance of the budget, or the erosional/accretionary trends along the coast. A preliminary conceptual budget, as well as several detailed budgets, can be formulated within the same project file. Other features of SBAS are discussed in the following sections as they apply to new concepts in sediment budgets.

Local and Regional Sediment Budgets. Sediment budgets may be formulated to aid in the design of a project, characterize sediment transport patterns and magnitudes, and to determine a project's erosion or accretionary impacts on adjacent beaches and inlets. These local-scale sediment budgets have calculation cells representing features on the order of 10s to 100s of meters. For many projects, only a local-scale sediment budget is prepared; however, a regional budget often is needed to fully understand the long-term effects of the project on adjacent beaches and inlets. Extending the local-scale sediment budget to encompass a regional setting (cells ranging from 100s of meters to kilometers) may require multiple maps to illustrate transport patterns and magnitudes within these different scales.

SBAS provides a means of displaying multiple local and regional sediment budgets. SBAS has the capability to incorporate georeferenced (and nonreferenced) maps and images as the background map, and has zoom features to show project-level as well as regional details of the sediment budget. Figure 6 illustrates a regional sediment budget for Long Is-

¹ SBAS is available free of charge from the U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, <http://cirp.wes.army.mil/cirp/cirp.html>.

Variable	Value	Uncertainty	Locked	Shared With	Notes
SOURCE FLUXES					
Q10	88.00	40.00	☐	5	
SINK FLUXES					
Q16	68.00	40.00	☐	9	
dV	20.00	2.00	☐	N/A	
Residual					
	0	56.6	46.59090909		

Figure 5. Cell Properties spreadsheet for sediment budget cell.

land, New York, with local sediment budgets at the inlets. Figure 7 is a zoomed-in screen of the local sediment budget at Shinnecock Inlet, New York.

Macrobudget and Collapsing Cells. A macrobudget is a useful check for possible discrepancies in the process of formulating a sediment budget. A macrobudget is a quantitative balance of sediment inflows, outflows, volume changes, and engineering activities for all cells within the sediment budget. Essentially, the macrobudget solves the budget with one

large cell (temporarily combining one to many interior cells) that encompass the entire longshore and cross-shore extents of interest. Balancing the macrobudget reduces the possibility of inadvertently including potential inconsistencies in a detailed or full budget. SBAS includes a feature to display the macrobudget at any time during the process of creating the budget.

Collapsing cells is a similar concept, but the user may choose any subset of cells to combine. SBAS allows the user

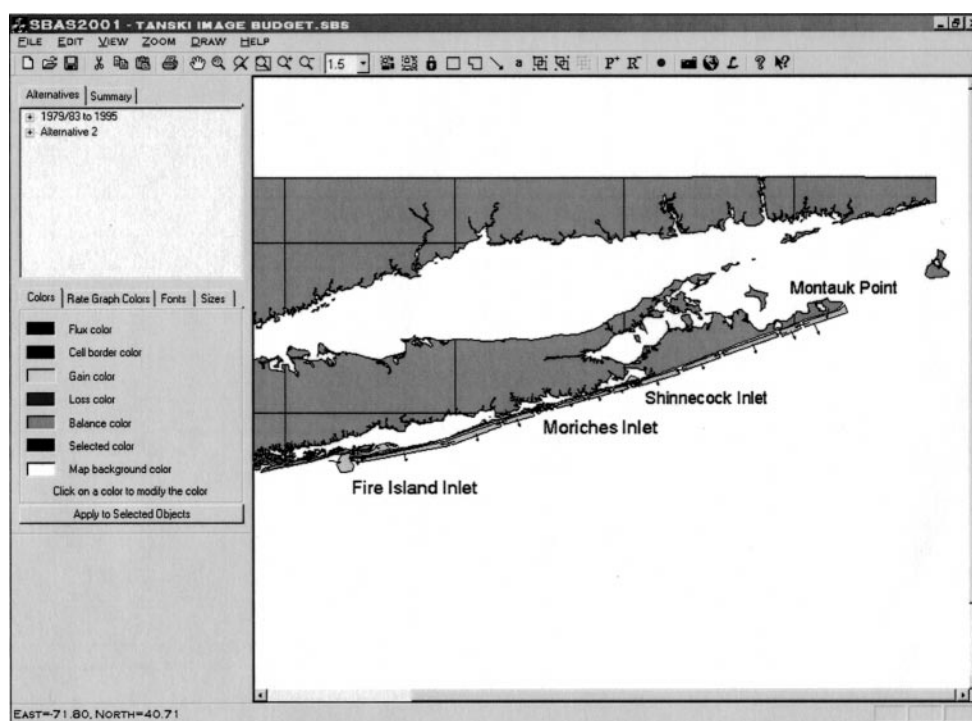


Figure 6. Regional sediment budget from Fire Island Inlet to Montauk Point.

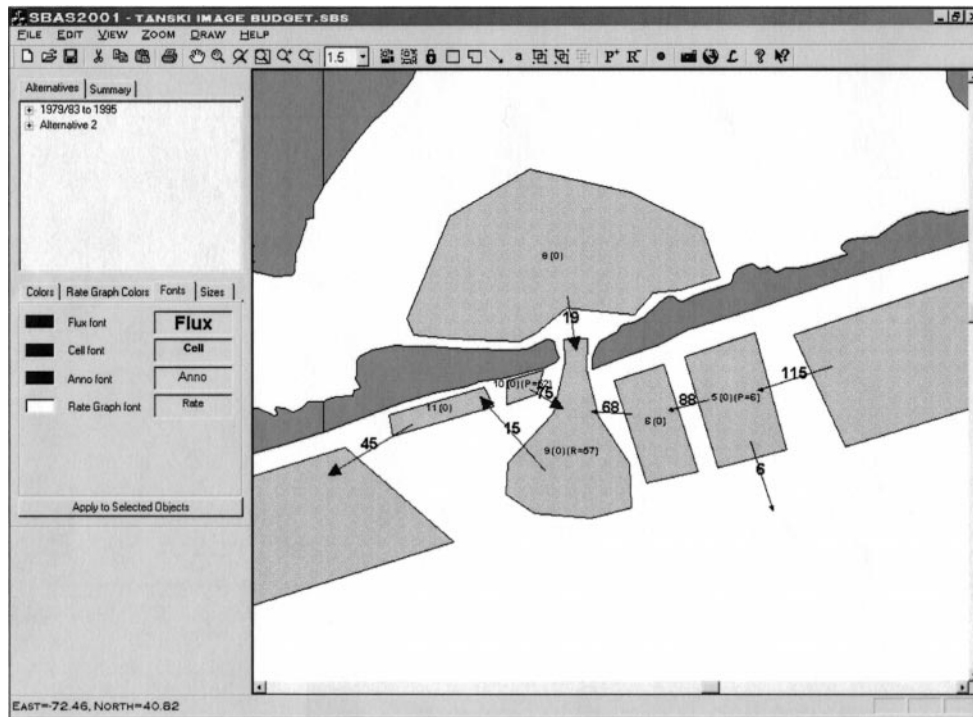


Figure 7. Local sediment budget for Shinnecock Inlet, New York.

to select cells and fluxes to combine within the area of a user-specified rectangle or polygon (Figure 8a). The selected items are then combined into one cell that is shaded to show whether it is balanced (Figure 8b). The Collapsing cells feature is useful for presenting detailed local budgets within a regional budget. For presentation of the regional budget, the local budget can be collapsed into one cell by activating a rectangular or polygonal selection tool, thereby presenting the local budget at the same spatial scale as the regional budget. When presenting the local budget, the user can zoom-in and reinstate the combined cell to the original form.

Propagating Longshore Transport Rates. In some applications, one of the more uncertain quantities in a sediment budget is the rate of longshore sediment transport. In creating the sediment budget, a range of feasible longshore sand transport rates is typically specified to create a series of "representative" budgets. However, the relationships between some of the fluxes in the budget may remain the same regardless of their magnitudes. For example, the transport through and over a jetty structure might be represented by 50% of the incoming transport. The capability to set these dependencies within the budget allows changes in the transport rate entering the sediment budget to propagate through all cells. SBAS has an option to define a linear relationship between one or more fluxes.

Uncertainty and Sensitivity Testing

Every measurement has limitations in accuracy (see KRAUS and ROSATI, 1999a). For coastal and inlet processes, typically

direct measurement of many quantities cannot be made, such as the long-term longshore sand transport rate or the amount of material bypassing a jetty. Values of such quantities are inferred from shoreline change or bathymetric change data, obtained with predictive formulas, or through estimates based on experience and judgment, which integrate over the system. Therefore, measured or estimated values entering a sediment budget consist of a best estimate and its uncertainty. Uncertainty, in turn, consists of *error* and *true uncertainty*. A general source of error is limitation in the measurement process or instrument. True uncertainty is the error contributed by unknowns that may not be directly related to the measurement process. Significant contributors to true uncertainty enter through natural variability and unknowns in the measurement process.

In coastal processes, significant contributors to true uncertainty enter through natural variability. Such variability includes (a) temporal variability (daily, seasonal, and annual beach change), (b) spatial variability (alongshore and across shore), (c) selection of definitions (e.g., shoreline orientation, direction of random seas), and (d) unknowns such as grain size and porosity of the sediment (especially true in placement of dredged material). For example, a survey of the beach profile is capable of specifying the horizontal position of the mean high-water shoreline with an error less than a few centimeters with respect to a local benchmark (measurement error). However, a measurement made days before or after the original measurement or 50 m upcoast or downcoast may record a shoreline position differing by several meters



Figure 8. Collapsing cells within SBAS. (a) Polygonal selection for collapsing cells, (b) collapsed sediment budge cells for Shinnecock Inlet.

from the original measurement (true uncertainty), creating ambiguity about the representative or true value. Error and uncertainty themselves are typically best estimates.

In inlet processes, uncertainty enters several ways. Two prominent ways are through limited knowledge of (a) changes in ebb- and flood-tidal delta sand volumes, and (b) the paths and relative magnitudes of transport, such as transport through and around jetties and to the tidal shoals.

Let X denote a coastal parameter to be estimated for a sediment budget, and suppose X is a function of several independent variables or measurements. An example is volume change for a sediment budget cell as calculated from shore-line position and profile data. Let δX denote an uncertainty in X . The uncertainty δX is considered to be an extreme plausible error, and it carries a sign, that is,

$$\delta X = \pm |\delta X| \quad (4)$$

If X is a function of the independent variables x , y , and z , by assuming the uncertainty in each variable is reasonably small, a Taylor series gives to lowest order,

$$X_{rms} + \delta X \approx X_{rms} + \frac{\partial X}{\partial x} \delta x + \frac{\partial X}{\partial y} \delta y + \frac{\partial X}{\partial z} \delta z \quad (5)$$

so that the maximum uncertainty in X is

$$\delta X_{max} \approx \frac{\partial X}{\partial x} \delta x + \frac{\partial X}{\partial y} \delta y + \frac{\partial X}{\partial z} \delta z \quad (6)$$

to lowest order. Because the δx , δy , δz , etc., each contain a sign ($\pm$), the partial derivatives in Equations 5 and 6 are interpreted as absolute (positive) values. That is, in uncertainty analysis we form extreme values by consistently applying ($\pm$) to each term to avoid cancellation between and among terms.

From Equations 5 and 6, and other assumptions (see TAYLOR, 1997), general relationships can be derived. If the variable X is a sum or difference of several independent parameters as $X = x + y - z + \dots - \dots$, then the root-mean-square (rms) uncertainty is

$$\delta X_{rms} = \sqrt{(\delta x)^2 + (\delta y)^2 + (\delta z)^2 + \dots} \quad (7)$$

The validity of this expression rests on the assumptions that the individual uncertainties are independent and random. The rms error accounts for the uncertainty in uncertainty by giving a value that is not an extreme, such as δX_{max} .

If the variable X is expressed as another variable raised to a power, $X = ax^n$, where a is a constant and has no uncertainty, then, from Equation 6,

$$\frac{\delta X}{|X|} = |n| \frac{\delta x}{|x|} \quad (8)$$

Equation 8 conveniently expresses error as a fractional uncertainty or percentage ratio of uncertainty.

Suppose the quantity entering the budget is expressed as a product or quotient of independent variables as $X = xyz$ or as xy/z . In either case, the uncertainty in X is

$$\left(\frac{\delta X}{X} \right)_{rms} = \sqrt{\left(\frac{\delta x}{x} \right)^2 + \left(\frac{\delta y}{y} \right)^2 + \left(\frac{\delta z}{z} \right)^2} \quad (9)$$

The errors are additive whether a variable enters as a prod-

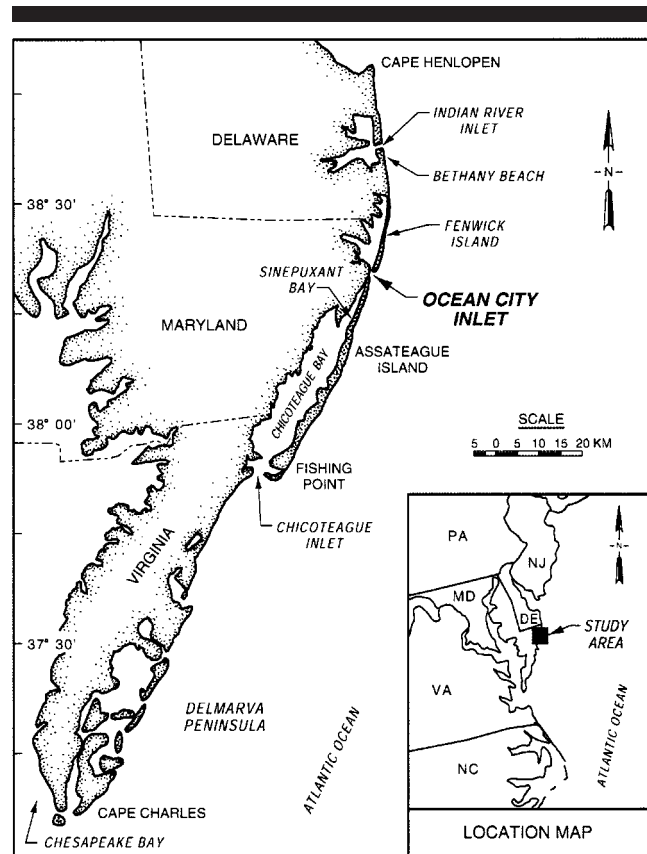


Figure 9. Location of Ocean City Inlet, Maryland.

uct or quotient. These equations state that the relative uncertainty of a product or quotient is equal to the sum of relative uncertainties of each term forming the product or quotient.

Application: Ocean City Inlet, Maryland, Sediment Budget, 1929/33–1962

To illustrate application of the concepts discussed herein, a sediment budget for Ocean City Inlet, Maryland, and its adjacent beaches is developed.

Setting and History

Ocean City Inlet, Maryland, is located on the mid-Atlantic Coast (Figure 9). This region of the coast has a semidiurnal tide with mean and spring ranges of 1 and 1.2 m, respectively. The annual mean significant wave height is approximately 1 m (at 16 m depth), and net longshore sand transport is predominantly directed from north to south at rates estimated to be from 115,000 to 215,000 m³/year (DEAN and PERLIN, 1977; DEAN *et al.*, 1978; UNDERWOOD and HILAND, 1995). The inlet was formed by a hurricane on August 23, 1933, which separated the existing barrier island into Fenwick Island to the north and Assateague Island to the south. Ebb and flood tidal shoals subsequently began to form.

The north jetty was constructed from September 1933 to

Table 1. Data for Ocean City Inlet Sediment Budget, 1929/33-1962.

Sediment Budget Cells (Distance from Inlet, km)*	Ocean Shore					Bay Shore	
	$\Delta y, \delta \Delta y^\dagger$ (m/yr)	$A_D, \delta A_D$ (m)	$P^\ddagger$ (m ³ /yr)	$R^\S$ (m ³ /yr)	Δt (years)	$\Delta V, \delta \Delta V$ (m ³ /yr)	$\Delta V, \delta \Delta V^\S$ (m ³ /yr)
-19.5 to -16.5	-1.6; 1.9	9.1; 1.4	0	0	33	-42,800; 9,400	No data
-16.5 to -15.0	-0.97; 1.3	9.1; 1.4	0	0	33	-13,300; 3,400	No data
-15.0 to -11.0	-1.4; 2.2	9.1; 1.4	0	0	33	-50,800; 12,100	No data
-11.0 to -5.0	-1.8; 2.7	9.1; 1.4	0	0	33	-98,600; 21,000	20,500; 15,200
-5.0 to -2.0	0.19; 0.05	9.1; 1.4	0	0	33	5,600; 8,600	
-2.0 to -0.2	4.0; 1.5	9.1; 1.4	0	0	33	66,000; 11,200	
Ebb Shoal**	N/a	N/a	N/a	0	33	76,800; 12,700	N/a
Bypass Bar**	N/a	N/a	N/a	N/a	25	90,400; 17,100	N/a
Channel	N/a	N/a	N/a	47,000; 23,500	33	0	N/a
Flood Shoal	N/a	N/a	N/a	N/a	33	20,000; 10,000	N/a
0.2 to 1.1	-12.9; 1.1	8.2; 1.4	41,000; 20,500	0	33	-101,900; 17,100	5,200; 3,900
1.1 to 2.3	-14.5; 0.07	8.4; 1.4	760; 380	0	33	-130,700; 21,500	
2.3 to 2.6	N/a (breach)	8.5; 1.4	0	0	29	-6,000; 1,200	
2.6 to 5.0	-8.2; 1.7	8.5; 1.4	0	0	29	-169,400; 28,100	
5.0 to 12.0	-1.6; 2.9	8.6; 1.4	0	0	29	-95,800; 22,600	No data
12.0 to 14.2	-1.3; 1.6	8.6; 1.4	0	0	29	-24,300; 6,100	No data
14.2 to 23.5	-0.7; 3.3	8.6; 1.4	0	0	29	-53,600; 23,600	No data

* Measured from the centerline of the inlet, with negative values to the north, and positive values to the south of the inlet.

† Assumed ± 5.7 m uncertainty in shoreline position.

‡ Assumed 50% uncertainty.

§ Assumed active depth and associated uncertainty for bay profiles $A_D = 2$ m, $\delta A_D = 1$ m.

** Volume change and error data courtesy Dr. Mark Byrnes, Applied Research and Engineering, Inc.

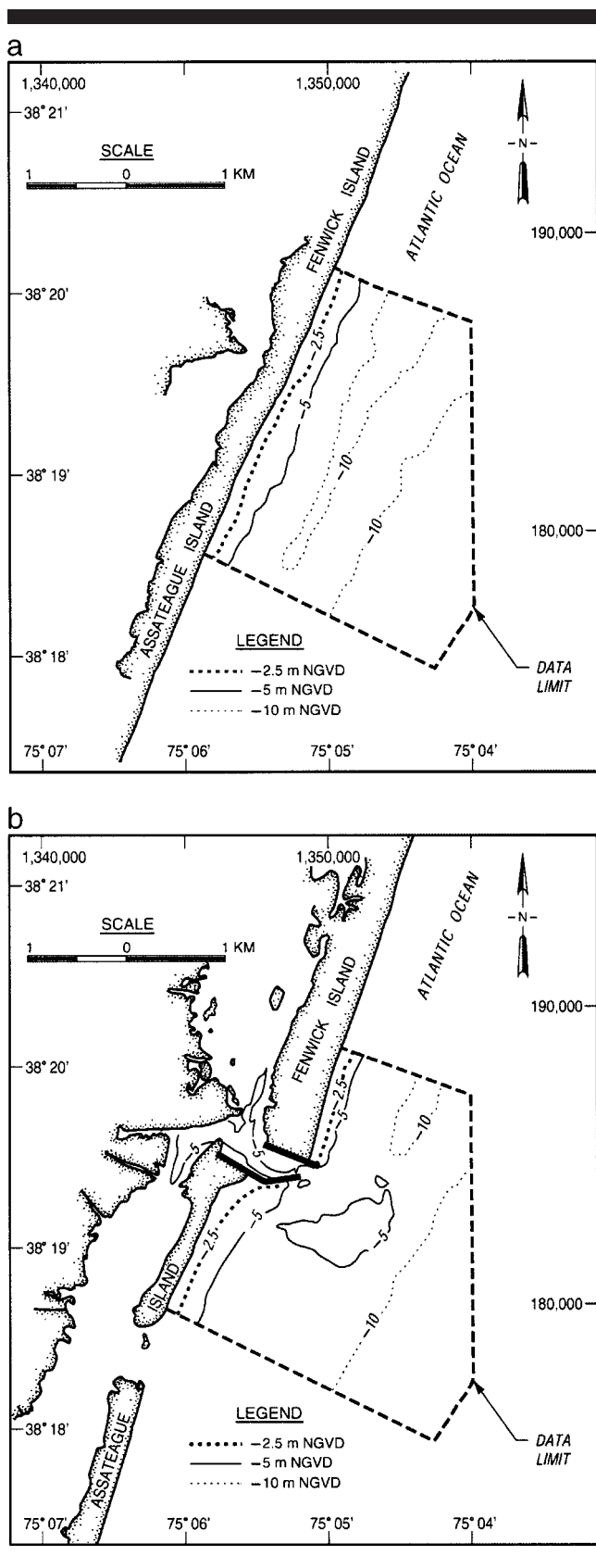
October 1934 at an initial elevation (0.8 m National Geodetic Vertical Datum (NGVD), the datum referenced in this paper), which was quickly deemed too low to prevent sediment transport over the jetty and into the inlet. From 1935 to 1956, three additional north jetty modifications increased its sand-tightness, resulting in a structure at an elevation of 2.3 m. The south jetty was constructed from October 1934 to May 1935 at an elevation of approximately 1.4 m. Soon after construction, morphological evidence indicated the tendency for sediment transport into the inlet and bay creating a shoal on the northwest corner of Assateague Island. The south jetty was entirely flanked in November 1961, prior to the March 1962 "Ash Wednesday Storm," and an additional inshore segment was added after the 1962 storm, reconnecting the structure to Assateague Island. However, the northwest shoal persisted. In 1984/85, the south jetty was elevated from 1.1 to 2.3 m, and three headland breakwaters were constructed on northern Assateague Island (BASS *et al.*, 1994). It is emphasized that the low south jetty elevation (between 1.4 m as initially constructed and 1.1 m as documented by DEAN *et al.*, 1978) and the tendency for sediment transport over, through, and around this structure appears to have existed for a majority of the post-inlet time period (52 years).

The March 1962 storm worsened the breach at the south jetty that had occurred in 1961, and it created two other breaches, one along Fenwick Island 6.7 km north of the inlet, and the other approximately 2 km south of the inlet on Assateague Island. The Fenwick Island and south jetty breaches were closed during the period April 1962 through January 1963, but the Assateague Island south breach persisted (despite closure attempts during April and May 1962) until it was closed in January 1965.

Data Sets

The data for this sediment budget include ocean and bay shoreline position, beach profiles, bathymetry, and aerial photography. Shoreline position and bathymetric data were digitized within a Geographic Information System (GIS). After the maps were digitized and corrected for errors, the data were converted to a common horizontal datum, projection, and coordinate system (Universal Transverse Mercator Zone 18, North Atlantic Datum (NAD) 83). Sediment budget cells (see Column 1 in Table 1) were specified based on common trends in beach and bathymetric change for the study area. The following sections discuss these data sets and how they were used in formulating the sediment budget.

Shoreline Position. Both ocean and bay shoreline position were derived from National Ocean Service (NOS) Topographic maps (T-sheets) (1:20,000 scale) dated 1929, 1933, and 1962. The shoreline position on these maps delineates the high-water line, which is determined from the discernable change in color, texture, or composition of the beach, reflecting the maximum runup of recent high tides (SHALOWITZ, 1964). This feature on the beach approximates the berm crest. The data were recorded with respect to a baseline that was set to zero at the centerline of the inlet and used a right-handed coordinate convention (i.e., negative values indicate baseline distances north of the inlet, and positive values indicate baseline distances south of the inlet.) Shoreline position for each time period was calculated as a distance seaward of the baseline at a 50-m alongshore spacing. Shoreline change rates, Δy , were calculated by subtracting the shoreline position data at a given baseline coordinate, and dividing by the number of years between the two measurements (Column 2 in Table 1).



After 1920, NOS T-sheets were compiled from rectified aerial photography, a procedure which has a potential error of ± 5 m due to the interpretation of the remotely-obtained shoreline position. There are also errors in digitizing the shoreline from the T-sheets associated with equipment and operation accuracy and precision. Digitizing tables used in this study have an absolute accuracy of 0.1 mm, which translates to ± 2 m for a 1:20,000 scale map. In addition, errors associated with the digitizing process itself were estimated to be ± 2 m, for a total root-mean-square (rms) uncertainty associated with the shoreline position data, $\delta\Delta y = \sqrt{5^2 + 2^2 + 2^2} = 5.7$ m. If we assume that errors associated with the digitizing process are random, i.e., they tend to cancel for a large number of data points, then this value of uncertainty represents an upper limit.

Beach Profiles. Beach profiles for Fenwick and Assateague Islands dated June 1976 (earliest data set available) were used to define the active depth of the ocean beach, A_D . These profiles were taken by a field crew using a rod and level. Erosion of the beaches, including overwash of the barriers was significant during the 1962 Ash Wednesday storm, especially on Assateague Island. However, in the absence of other data, it was assumed that the 1976 profile data were representative of the period 1933 to 1962.

Active depth represents the part of the beach profile that is eroding or accreting during the time period of consideration, and is typically defined as the absolute sum of the berm crest elevation, B , and depth of closure, D_c .

$$A_D = B + D_c \quad (11)$$

Berm crest, depth of closure, and average active depth values were calculated (oceanside) or estimated (bayside) for each sediment budget cell.

The uncertainties associated with determination of B , and D_c , include errors due to the measurement method and errors in interpreting the values. KRAUS and HEILMAN (1988) measured the accuracy in elevation measurements for distances from the survey station ranging from 10 m to 1 km. They determined that potential error in elevation measurements was between 2 and 8 mm for measurements located from 10 m to 1 km from the survey station. The Ocean City profile data analyzed herein transverse less than 1 km, and thus these error estimates are adopted for the present study. For ocean profiles, B (ocean) ranged from 2.1 to 3.0 m, with an associated variation for a given sediment budget cell ranging from 0.4 to 0.6 m. Thus, the rms uncertainty associated with the ocean berm crest elevation is estimated to be $\delta B(\text{ocean}) = \sqrt{0.008^2 + 0.4^2 \text{ to } 0.6^2} = 0.4 \text{ to } 0.6$ m. Uncertainty in horizontal position is assumed to be negligible.

Profile data for the bay shoreline were not available. Based on interviews with people familiar with the site, and those who have conducted previous field measurements at Ocean City Inlet, it was estimated that a reasonable estimate for

Figure 10. Ocean City Inlet bathymetry used in study, (a) 1929/33, (b) 1962.

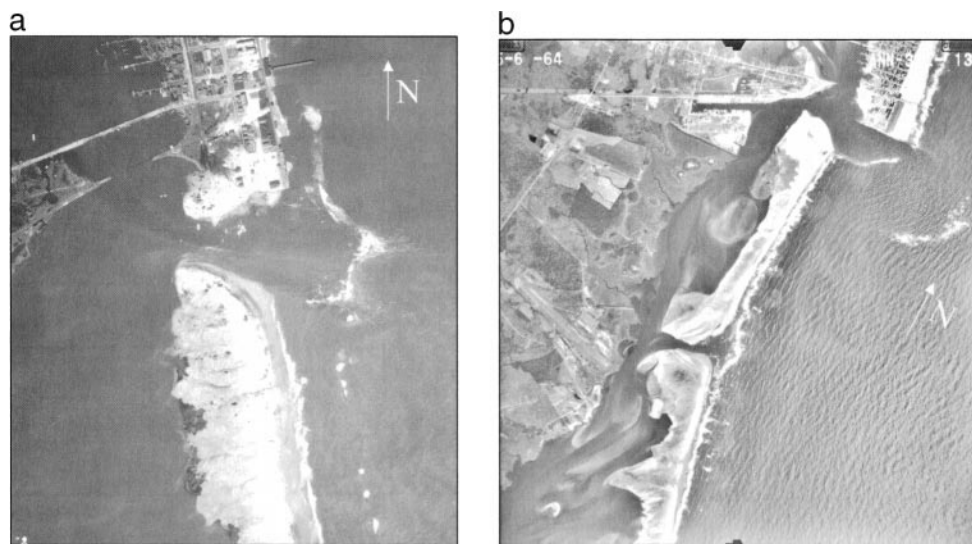


Figure 11. Aerial photographs of Ocean City Inlet, Maryland, (a) September 18, 1933, (b) May 6, 1964.

the bay berm crest elevation is $B(\text{bay}) = 1 \text{ m}$, with $\delta B(\text{bay}) = 1 \text{ m}$.

STAUBLE *et al.* (1993) estimated D_c for Fenwick Island by analysis of profiles from Spring 1988 and Winter 1992. This data set encompassed higher wave energy events as well as typical waves. Depth of closure was defined as the minimum depth at which the standard deviation in depth changes decreased to a near-constant value. As discussed previously, error in vertical measurements is estimated at 8 mm. The depth of closure was estimated to range from 4.8 to 6.7 m NGVD, with 6.1 m NGVD being a representative value (STAUBLE *et al.*, 1993). To capture this range in values, the depth of closure for the study area is estimated as $D_c(\text{ocean}) = 6.1 \text{ m}$ with an associated variation of 1.3 m. Therefore, the rms uncertainty is $\delta D_c(\text{ocean}) = \sqrt{0.008^2 + 1.3^2} = 1.3 \text{ m}$. In the absence of data and based on the interviews discussed previously, the depth of closure for the bayshore was estimated as $D_c(\text{bay}) = 1 \text{ m}$ with $\delta D_c(\text{bay}) = 1 \text{ m}$.

Values for A_D and its associated uncertainty were calculated as follows (see Column 3 in Table 1 for ocean values),

$$\begin{aligned} A_D(\text{ocean}) &= B(\text{ocean}) + D_c(\text{ocean}) \\ &= 2.1 \text{ to } 3.0 + 6.1 = 8.2 \text{ to } 9.1 \text{ m} \end{aligned} \quad (\text{Eq. 10})$$

$$\begin{aligned} \delta A_D(\text{ocean}) &= \sqrt{\delta B^2 + \delta D_c^2} \\ &= \sqrt{0.4^2 + 0.6^2 + 1.3^2} \approx 1.4 \text{ m} \end{aligned} \quad (\text{Eq. 7})$$

$$A_D(\text{bay}) = B(\text{bay}) + D_c(\text{bay}) = 1 + 1 = 2 \text{ m} \quad (\text{Eq. 10})$$

$$\delta A_D(\text{bay}) = \sqrt{\delta B^2 + \delta D_c^2} = \sqrt{1^2 + 1^2} = 1.4 \text{ m} \quad (\text{Eq. 7})$$

Bathymetry. Bathymetric data for the ocean from 1929/33 and 1962 were digitized from NOS Hydrographic Sheets (H-sheets) (Figures 10a, 10b). For surveys conducted in the mid- to late 20th century, depth differences in the offshore line were not to exceed ± 0.3 to 0.6 m (UMBACH, 1976; BYRNES *et al.*, 2002). To make estimates of volume change, a Triangulated Irregular Network (TIN) was used to represent the bathymetric surfaces. The rms error for these surfaces was taken as $\pm 0.6 \text{ m}$. Volume change was calculated for the ebb shoal (defined as the depositional region directly in the path of the ebb jet) and the bypass bar (defined as the morphologic feature that extends from the ebb shoal towards the adjacent beach(es) (reference Fig. 3c) (KRAUS, 2000). The volume change and associated uncertainty are presented in Table 1 (personal communication, Dr. Mark Byrnes, 2002).

Full bathymetric coverage of the bay that included growth of the flood shoal was not available. Instead, bathymetric data providing partial coverage of the flood tidal shoal, together with aerial photography, and a review of previous studies (DEAN and PERLIN, 1977; DEAN *et al.*, 1978) were used to estimate the flood shoal growth equal to $20,000 \text{ m}^3/\text{year}$. Because of the sparse data set, this estimate is considered to have a high uncertainty of $\pm 10,000 \text{ m}^3/\text{year}$.

Engineering Activities. A history of engineering activities at Ocean City Inlet was developed using data provided in previous studies of the inlet and adjacent beaches (e.g., WICKER, 1974; DEAN *et al.*, 1978; U.S. ARMY ENGINEER DISTRICT, BALTIMORE, 1978). Beach material placement, P , and dredging (removal), R , estimates were converted to a yearly rate based on these data (Columns 4 and 5, Table 1). Because some of these early records are vague with respect to the areas dredged and where material was placed, these data are considered to have a high level of uncertainty, set to $\pm 50\%$ of the estimated value.

Aerial Photography. Aerial photographs from September 18, 1933 and May 6, 1964 were examined to provide qualitative information about sediment transport pathways and morphologic forms at Ocean City Inlet and along adjacent beaches (Figure 11). The 1933 photograph shows the inlet just after creation, and before the jetties were constructed. Note the breaking wave pattern offshore, indicating initial formation

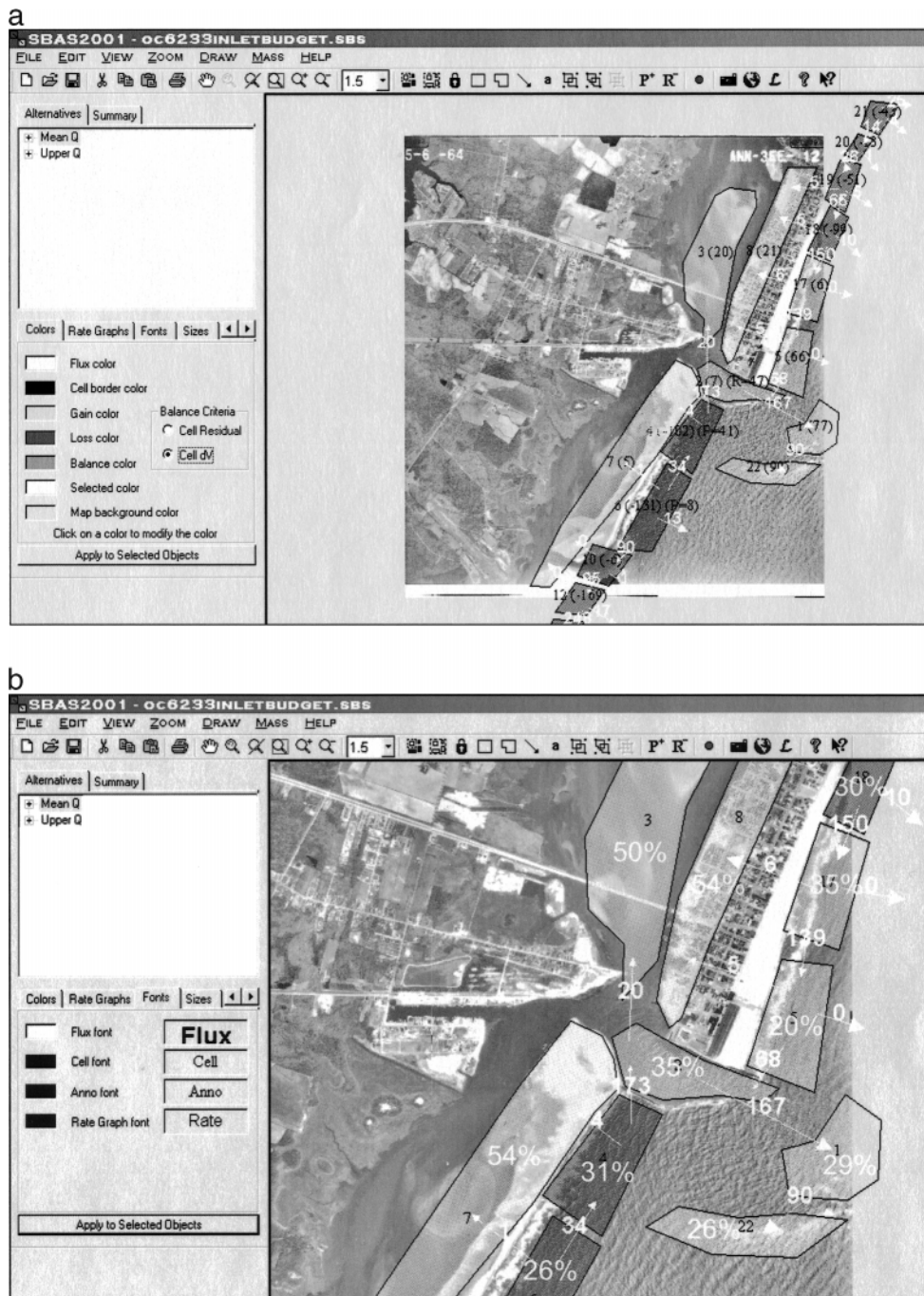


Figure 12. Ocean City Inlet and adjacent beach sediment budget, 1929/33–1962 (accretion and erosion are represented by color-coded cells), (a) Regional sediment budget, (b) Local budget showing percentage uncertainty for each cell.

of the ebb shoal. Overwash of Assateague Island was significant during the 1933 hurricane, as indicated by the lack of vegetation on the barrier and the fans of sediment extending into the bay. Notice that the barrier islands are basically in line with each other. In comparison, the 1964 photograph indicates significant retreat of Assateague Island. Breaking waves offshore of the inlet indicate the region of the ebb

shoal, which has apparently grown in size and moved offshore. Assateague Island again shows characteristics of overwash processes. The breach on Assateague Island that formed during the 1962 “Ash Wednesday” storm was still active in 1964, and the breaking wave pattern indicates initial formation of an ebb shoal offshore of the breach.

Longshore Sediment Transport Rate. Several researchers

have estimated values of longshore sediment transport for Ocean City. DEAN and PERLIN (1977) estimated that the north jetty was fully impounded by 1972, with an impoundment rate ranging from 115,000 to 153,000 cu m/year. There is also a generally-accepted nodal area in the net longshore sediment transport at the Maryland-Delaware state line. The location of this nodal area can vary annually. DOUGLASS (1985) estimated an average net longshore sediment transport rate equal to 214,000 cu m/year based on hindcast data from 1956–1975. Based on this work and the growth of the ebb and flood shoals, UNDERWOOD and HILAND (1995) adopted a southerly-directed net transport equal to 212,800 cu m/year. In an application of a morphologic change model, KRAUS (2000) specified 150,000 cu m/year as an upper limit to the net longshore sediment transport rate.

For the sediment budget herein, an average net longshore sediment transport rate north of the inlet, outside the impoundment zone of the north jetty, was taken as 150,000 cu m/yr with an uncertainty of $\pm 50,000$ cu m/year.

Transport rates to the offshore were estimated to be 10% of the volume change within the cell, with an uncertainty of 10%.

Calculations

The shoreline position data were used to calculate volume change, ΔV (m³/year), for each ocean and bay shoreline cell,

$$\Delta V = \Delta y A_D \Delta x \quad (11)$$

where Δy is the average shoreline change rate for the sediment budget cell (m/year), A_D is the average active depth for the cell (m), and Δx represents the length of the sediment budget cell (m).

These data were entered into SBAS, and a regional sediment budget was developed as shown in Figure 12. Cells may be color coded to indicate net accretion or erosion of the cell. The net volume change from 1933 to 1962 resulted in accretion areas in the vicinity of the inlet channels and shoals, on the updrift beach, and overwash of the barrier islands into the bay. The remaining adjacent beaches lost sediment through longshore transport and overwash processes.

SBAS allows the user to record uncertainty for each value entered in the sediment budget. Then, for each cell, collapsed cell, and the entire budget, SBAS calculates the root-mean-square (rms) uncertainty. The user can apply the rms uncertainty to indicate the relative confidence that can be given to each cell in the sediment budget, and in comparing alternatives that represent different assumptions about the sediment budget. Figure 12b shows the percentage uncertainty for each cell. The percentage of uncertainty is calculated as the total magnitude of uncertainty for that cell divided by the absolute value summation of the fluxes, volume change, placement, and removal for that cell. Uncertainty for the bay cells and flood shoal is greater than uncertainty in the vicinity of the inlet and adjacent beaches, indicating the level of confidence we can use when interpreting the budget. A sediment budget formulated with a more extensive bay data set would have a lower value of uncertainty. Integrating uncertainty into the sediment budget allows engineers, managers,

local government officials, and community members to readily grasp an understanding of the reliability of values within the budget.

CONCLUSIONS

Sediment budgets are a time-tested means of understanding the sediment patterns and magnitudes for riverine and coastal areas. With knowledge gained through numerous applications and the advent of visually-based computer interfaces, several new concepts have emerged that streamline the formulation process and improve the reliability of sediment budgets. These concepts were demonstrated for regional sediment budgets at Long Island, New York, and Ocean City Inlet, Maryland within the Sediment Budget Analysis System (SBAS). Considering the regional budget and developing values of root-mean-square uncertainty are an essential component of modern sediment budgets. Calculation of the uncertainty together with the sediment budget itself allows the reliability of this methodology to be estimated, and to improve its value as a framework for coastal and riverine planning and project design.

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NOTATION

The following symbols are used in this paper:

a	= constant with no uncertainty
A_D	= active depth for sediment budget cell
B	= berm crest elevation for sediment budget cell
D_c	= depth of closure for sediment budget cell
n	= exponential constant
P	= placement of sediment within sediment budget cell
Q_{gross}	= gross longshore sediment transport rate
Q_L	= longshore sediment transport rate to the left (seaward-facing observer)
Q_{net}	= net longshore sediment transport rate
Q_R	= longshore sediment transport rate to the right (seaward-facing observer)
Q_{sink}	= sediment flux exiting a sediment budget cell
Q_{source}	= sediment flux entering a sediment budget cell
R	= removal of sediment from sediment budget cell
<i>Residual</i>	= balance for sediment budget cell
t	= time
X	= engineering quantity to be estimated
x	= independent variable
y	= independent variable

- z = independent variable
 δA_D = uncertainty in active depth
 δB = uncertainty in berm crest elevation
 δD_c = uncertainty in depth of closure
 ΔV = volume change rate for sediment budget cell
 Δt = time period of calculation
 δx = uncertainty in independent variable x
 δX = uncertainty in engineering quantity X
 Δx = length of sediment budget cell
 $\delta \Delta x$ = uncertainty in length of sediment budget cell
 δy = uncertainty in independent variable y
 Δy = average shoreline change rate for sediment budget cell
 $\delta \Delta y$ = uncertainty in average shoreline change rate for sediment budget cell
 δz = uncertainty in independent variable z

Subscript

- max = maximum
 rms = root-mean-square

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Are "Stable Shorelines" and "Broad Beaches" Mutually Exclusive Management Goals Along Southern Monterey Bay?

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Preface

Coastal erosion threatens both public and private lands in Monterey County. On January 18, 2005, a panel convened to investigate strategies for managing coastal erosion along southern Monterey Bay. The members of the panel and subsequent working group include representatives from USGS, California Coastal Commission, Monterey County, CSU Monterey Bay, City of Monterey, City of Seaside, NOAA, private consulting firms, Naval Postgraduate School, UC Santa Cruz, and the Monterey Bay National Marine Sanctuary.

This report summarizes the relevant work of Dr. Douglas Smith and students at CSU Monterey Bay. The report details some of the key coastal geomorphic concepts presented to the coastal erosion panel by Ed Thornton on January 18, 2005 and Douglas Smith on March 21, 2005. This brief report does not cite all the original studies that contribute to our understanding of the regional coastline. The reader needing further original references are directed to the recent publications of Dr. Ed Thornton and Dr. Gary Griggs (UC Santa Cruz).

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It may be accessed on the internet on the Central Coast Watershed Studies publications page: <http://science.csumb.edu/%7Eccows/> .

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Dr. Ed Thornton and colleagues at the Monterey Naval Postgraduate School have developed the most complete accounting of the sand budget in the southern Monterey Bay region. Dr. Thornton presented his unpublished data to the coastal erosion panel on January 18, 2005. His forthcoming papers will be the best reference to date of the sand budget and nearshore processes in southern Monterey Bay. With Dr. Thornton's permission we report here some of the preliminary estimates of sand transport from his work.

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1 Executive Summary

The coastline of southern Monterey Bay has moved many kilometers east and west in response to oscillating sea level changes and vertical tectonics active over the last 2 million years. The most recent episode of coastal retreat began about 18,000 years ago as the most recent ice age began to wane, replenishing the Earth's sea water volume through ice cap melting. An internet-based animation introduced with this report (Hofmann, 2004) illustrates the inexorable eastward progress of the coastline during the most recent sea level advance. Long term average retreat rates of somewhat less than 1 m/yr can be estimated from bathymetric charts and the fact that sea level was located approximately 130 m lower 18,000 years ago than it is today. More detailed surveys of coastline position in aerial photographs from the past few decades, and more recently obtained LIDAR data and GPS records indicate modern retreat rates average approximately 1 m/yr, but are variable along the coast. The seaward end of the north jetty of Moss Landing Harbor projects into the Monterey Canyon head, so virtually all the sand moving south from Santa Cruz is guided into the canyon head, leaving little to add to the southern Monterey Bay sand supply.

A systematic sand-budget approach to analyzing the coastal morphology suggests that sea cliff erosion may provide a very significant input of sand to the nearshore region. If that conclusion is true, then the broad beaches that typify most of southern Monterey Bay in large part owe their existence to coastal retreat, and would be compromised by coastal armoring. This apparent paradox is important for coastal management decisions. Armoring the coastline to reduce sea cliff erosion would clearly remove an important source of beach sand, probably leading to narrower or absent beaches. Reducing the loss of beach sand to offshore storage through wave energy dissipation offers an alternative approach. However, offshore structures designed to reduce wave energy would be technically challenging, and would alter the Monterey Bay Sanctuary ecosystem in both predictable and unforeseen ways. Structures may have unforeseen physical results as well. It is clear that a knowledge of geomorphic principals and local erosion rates are critical components in the decision matrix for treating coastal erosion in southern Monterey Bay. Cost-benefit analysis for engineering solutions to coastal retreat should have contingencies for eventual failure and decommissioning at the end of the predicted life of the project in the estimated cost.

2 Introduction

Coastal erosion is a global problem that is felt in every coastal state of the U.S (Fig. 1). The most obvious negative result of coastal erosion is the loss of valuable public and private land area. The chief environmental variables that generally contribute to high coastal erosion rates include sporadic high surf, global sea level rise, coastal subsidence, sediment trapping behind dams, floodplain storage along low-gradient coastal valleys, and human endeavors such as sand mining and structural modifications of the coastline (e.g., Morton, 2003; DBWSCC, 2002).

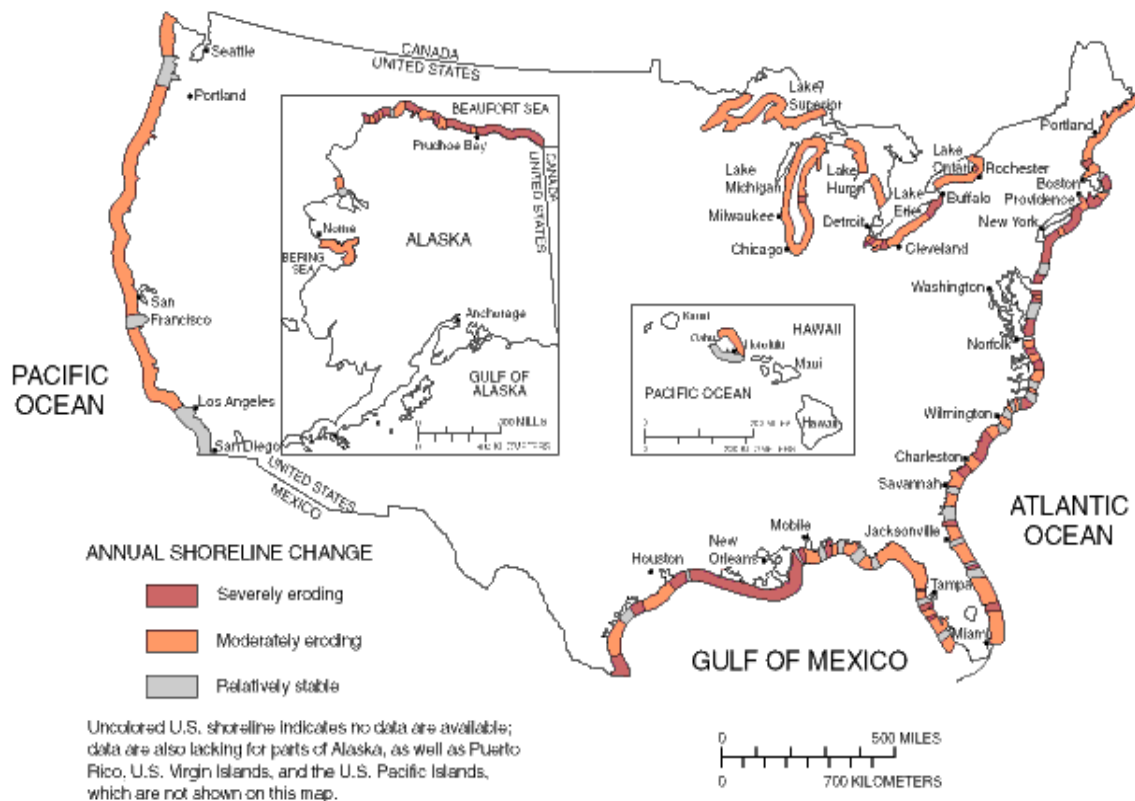


Figure 1: Coastal erosion hazards along the U.S. coastline (USGS, 1985).

Monterey Bay (Fig. 2) was classified by the USGS (1985) as relatively stable (Fig. 1). The existence of broad beaches (Fig. 3) along the reach of coastline between Moss Landing and the Municipal Wharf in Monterey has been incorrectly interpreted to mean that the coastline is fixed in space, and not subject to coastal retreat.

It is our hope that an accurate understanding of the data and physical processes of the southern Monterey Bay coastline will be used to create sound coastal management policy. In this report, we introduce the following data and concepts with the goal of developing a shared understanding of the how the southern Monterey Bay coastline system works.

- Geological and geomorphic setting, focusing on sea cliff materials
- Long term erosion estimates based upon sea level rise
- Methods employed to determine coastal retreat rates
- Results of recent studies placed into a geomorphic and sand budget framework
- Systematic sand budget approach to making management decisions

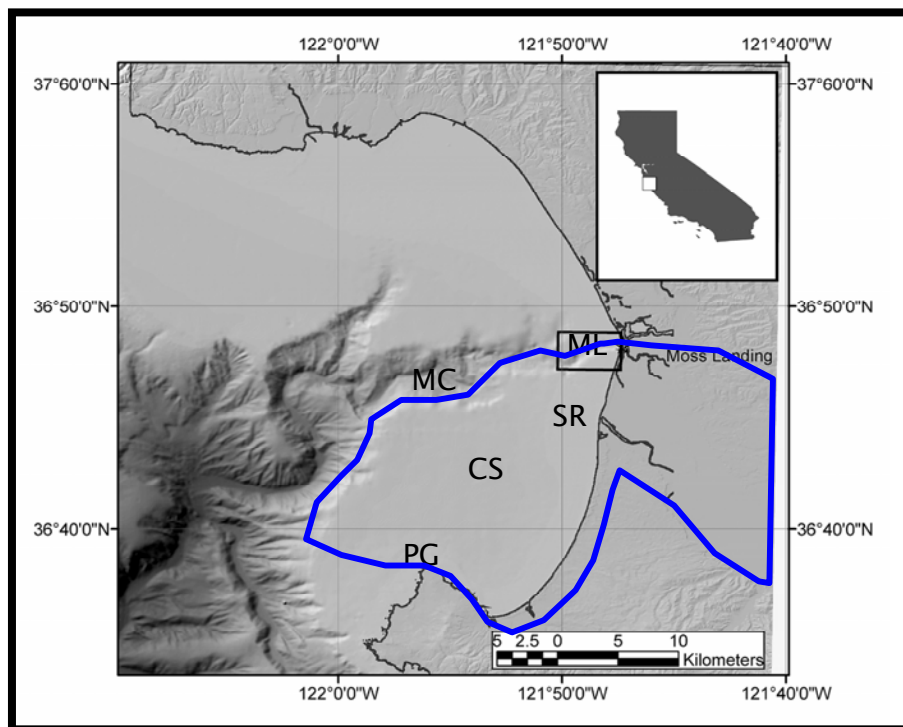


Figure 2: Southern Monterey Bay extends from Moss Landing (ML) to Pacific Grove (PG). The system is bounded on the north and west by Monterey Canyon (MC). The beaches rim a broad continental shelf (CS). The outline generally defines the region discussed in this report. The Salinas River (SR) delta forms a bulge in the coastline south of Moss Landing.

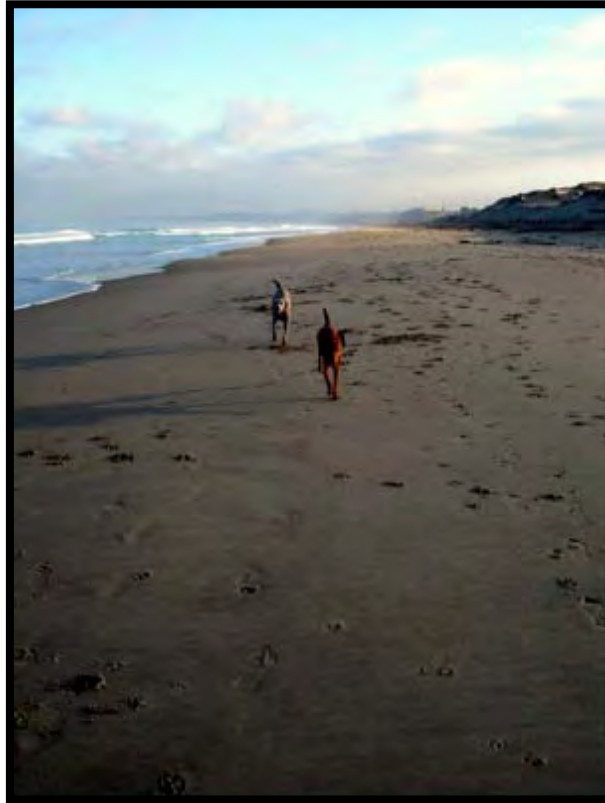


Figure 3: Broad sandy beach located in Monterey.

3 Geologic and Geomorphic Setting

The coastline of southern Monterey Bay comprises a broad, sand and mud draped continental shelf (Fig. 2). The eastern edge of that continuous sediment carpet is the intermittently-dry sand called the beach (Fig. 4). Along southern Monterey Bay, the eastern border of the beach is typically either an easily eroded sea cliff face (Fig 5) or active dunes (Fig. 6). In a few places, the beach is bounded by a sea wall or other structure meant to reduce erosion rates (Fig. 7).

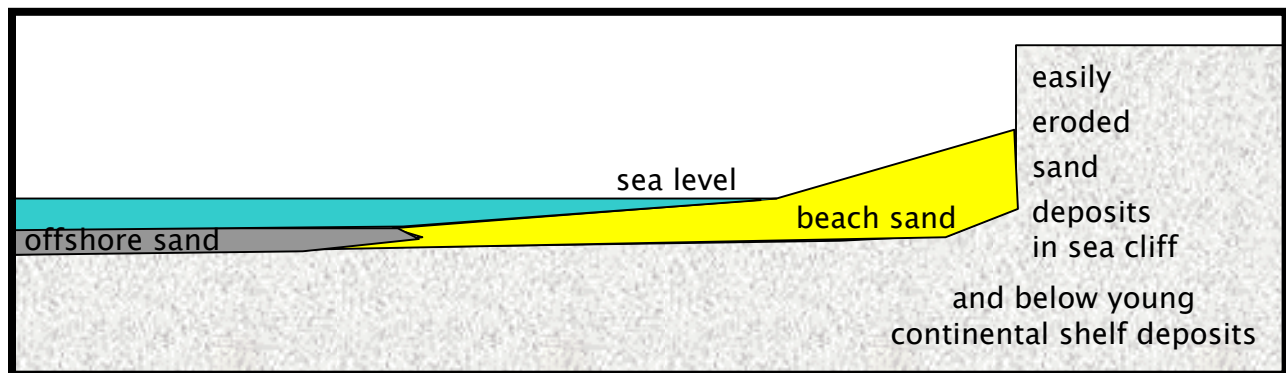


Figure 4: Schematic cross section showing thin sand veneer atop older sand deposits that compose the sea cliff. This diagram is typical of the sea cliff from Marina to Sand City, and south of the Monterey Beach Resort until a kilometer northeast of the Monterey Municipal Wharf.



Figure 5: Sea cliffs along Marina composed of old, eroding dune deposits (October 31, 2004).



Figure 6: Vegetated modern dunes behind near Monterey Beach Resort (Gref, 2005)



Figure 7: Sea wall protecting Ocean Harbor House Condominiums. December 9, 2004.

The material comprising the eroding sea cliffs is older sand dune deposits from a now relict system of dunes. Some of the sea cliff derived sand is blown back inland to feed modern dunes that are sporadically present. As discussed later, most of the sand eroded from the cliffs is thought to drift offshore after a short residence time in the sand beach (Thornton, 2005).

4 Sea Level Rise and Long Term Coastal Retreat Rates

There have been long periods in Earth's history when there were mild, well-buffered temperatures over much of the planet. Occasionally the mild climate is punctuated by a series of ice ages. The most recent series of ice ages began 2 million years ago, marking the beginning of the Quaternary Geologic Period.

During the Quaternary Period there have been as many as 20 distinct ice ages, where temperatures have plummeted, polar ice caps have formed, and sea levels have dropped as water was frozen into the caps. During each ice age, shorelines and all their associated physical processes and ecosystems migrated offshore. With each warm period between ice ages, ocean basins refilled (Fig. 8) and the shorelines migrated back up onto the continents.

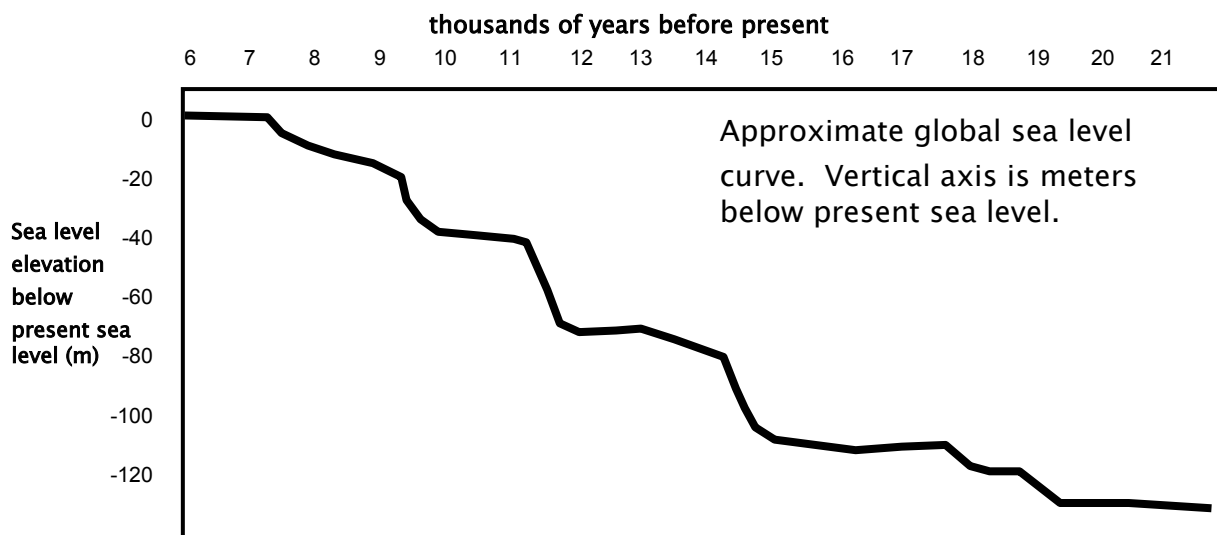


Figure 8: Sea level rise over the past 18,000 years. This curve is compilation of data from Tahiti, Barbados, and Caribbean sites, from data compiled by Dr. Thomas Rockwell, San Diego State University.

The acme of the most recent ice age was about 18,000 years ago. At that time sea level was approximately 130 m (425 ft) lower than present sea level along central California (e.g. Pinter and Gardner, 1989), and the beach was located along the rim of Monterey Canyon (Figs. 9 and 10).



Figure 9: Digital elevation model of low sea level (blue) in Monterey Canyon head. View extends from Moss Landing Harbor (ML) out to sea 4 km, to a depth of 270 m. The rectangular box around “ML” in Figure 2 shows the position of this view. Bathymetric data from the CSUMB Seafloor Mapping Lab (<http://seafloor.csumb.edu/index>).

Figure 10 shows southern Monterey Bay 18,000 years ago. During the low stand of sea level (Fig. 10), the exposed continental shelf (gray color) was partly (or completely) covered by sand dunes in a dune field that spanned the Salinas Valley and migrated inland to parts of Fort Ord lands where relict dunes are still preserved. In fact, the last 2 million years have left several layers of dune deposits in the region, including the Aromas Sandstone. These dune deposits are the weak substrate exposed in sea cliffs that the present sea level is eroding in southern Monterey Bay. We can speculate that the dune field may have been locally vegetated adjacent to the extensions of the Salinas River, Canon Del Rey Creek, Iris Creek, and other smaller drainages on the Monterey Peninsula that coursed through that ancient coastal plain. Respectively, Figures 11 and 12 show sea level at today’s location and a predicted position in the year 2200, 200 years from now. In the future (Fig. 12), the Salinas coastal lagoon will expand into a broad estuary like historic Elkhorn Slough.

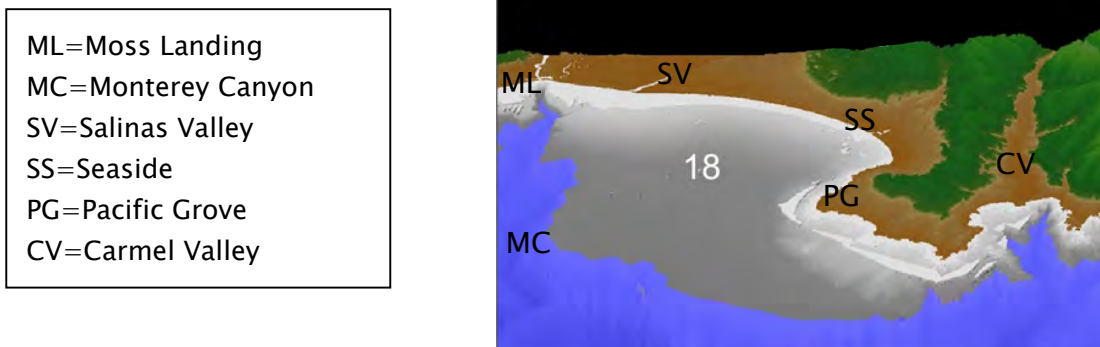


Figure 10: Shoreline position at approximately 18,000 years ago, at the acme of the most recent ice age (Hofmann, 2004).



Figure 11: Shoreline position in 2005 (Hofmann, 2004).

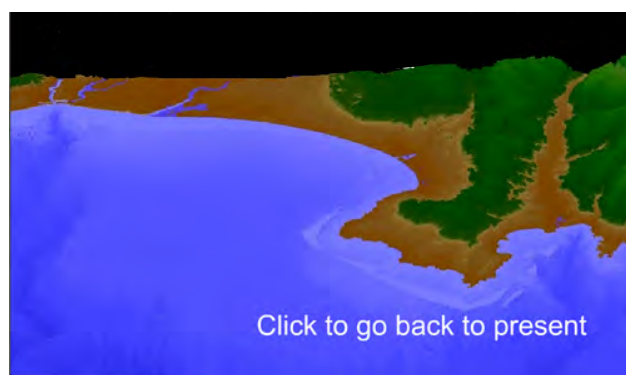


Figure 12: Shoreline position in 2200 (Hofmann, 2004).

The animation of sea level rise (Hofmann, 2004) simplifies the sea level curve by assuming a constant rate of rise. The rate has been variable, and has been very slow for the past 5000 years (Fig. 8). Despite the recent slow rate of sea level rise, shorelines have continued to rapidly retreat (Fig 1) as wave energy inexorably wears away shoreline rock and sand.

The coastal retreat rate is the velocity at which the shoreline is moving inland, converting dry land into marine continental shelf. The retreat rates are estimates based upon the distance of shoreline retreat divided by the length of time over which occurs. The rate of coastal retreat averaged over the 18,000 years since the most recent sea level low stand is the distance from the modern shore to the 130 m depth contour on the continental shelf (ancient shoreline position) divided by 18,000 years. The rate derived for southern Monterey Bay at approximately Seaside is approximately 14,000 m divided by 18,000 years or 0.8 m/yr (2.6 ft/yr).

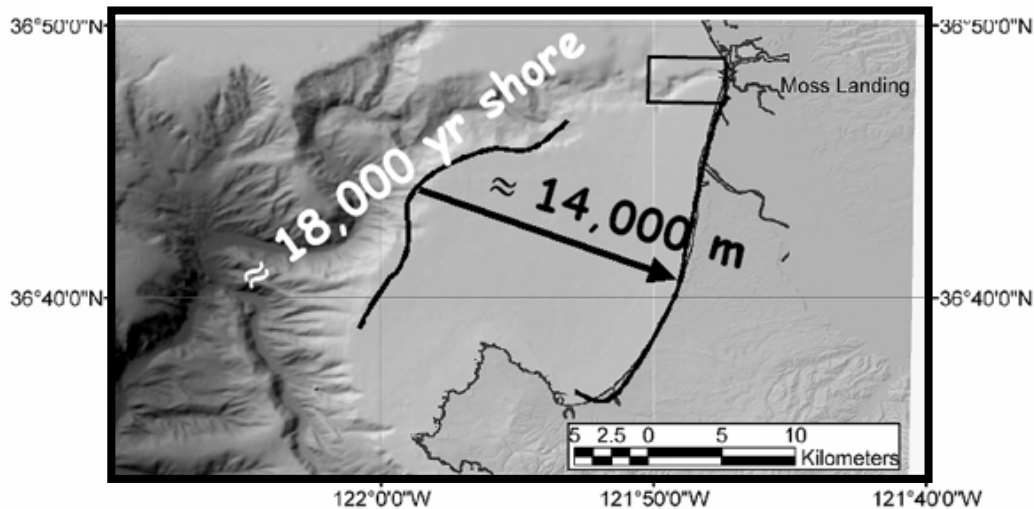


Figure 13: Figure for calculating 18,000 year coastal retreat rate. Black line offshore represents shoreline 18,000 years ago when sea level was approximately 130 m below present sea level. See more accurate bathymetric chart in Appendix A.

5 Recent Surveys of Coastal Retreat

Coastal retreat can be monitored in a variety of ways. Each method has its unique spatial coverage, precision, accuracy, and cost. Recently employed monitoring and survey methods have increased our understanding of coastal retreat in southern Monterey Bay including direct observation, oblique photos from the ground and air, analysis of historic and recent aerial photographs, GPS surveys, and serial aerial LIDAR surveys. Future high-resolution surveys will likely include oblique terrestrial LIDAR surveys. Below we present some examples of each kind of data, and some recent results from Gref (2005).

5.1 Oblique Photos

Snapshot photographs from the ground or air can provide a valuable record of instantaneous geometry (Fig 14). Such photographs convey information about landscape condition and recent processes and can be part of a series of similar shots that record geomorphic change through time (e.g., Figure B1 and B2). USGS (1999) provides a catalog of oblique aerial photography documenting coastal change associated with the 1998–99 El Nino season. Smith (2005) includes an annotated documentation of seasonal changes at the Monterey Beach Resort and other local sites.

Figure 14 shows a typical southern Monterey Bay sea cliff composed of relict sand dune deposits with very low resistance to erosion. The brown streak in the cliff is an exhumed ancient soil horizon within the dune deposits. The base of the cliff is an apron of loose sand sloughed from the constant incremental retreat of the seacliff. The basal sand apron is perennially present, and is intermittently refreshed by sloughing from above, and intermittently depleted as the sand is transferred to the beach by wind, gravity, and tides.

There are several other examples of oblique photography in this report text and in Appendix B.



Figure 14: Oblique aerial photograph of Seaside sea cliff taken on October 31, 2004.

5.2 Historic aerial photos and GPS

The most accurate method for estimating coastal retreat is to identify a conspicuous feature of the beach system, and track its position through time by comparing dated, well-matched, and georeferenced aerial photographs and digital aerial photographs. Features that are easy to see in photographs include the cliff edge, or intersection of dunes and back beach.

Retreat rates of the coast have been estimated in this way by several independent workers. In each case the results are similar, lending credence to the high retreat rates they found. The Department of Navigation and Ocean Development reports an average shoreline retreat rate of about 1.5 m/yr rate between 1946 and 1967. Arnal et al (1973) reports an increase in shoreline erosion rates in Fort Ord from 0.5–0.6 m/yr in the 1920's, to about 0.9 m/yr in the 1950's, increasing to 1.5 m/yr in the 1960's. Historically, the highest average dune/bluff retreat rate occurs in the Fort Ord area, "...approximately up to 2.4 m/yr at Stillwell Hall, due to wave refraction patterns over Monterey Submarine Canyon that produce large waves in this area" (Griggs and Savoy, 1985). Farther south the retreat rate decreases to an average of 1.8 to 1.5 m/yr in the Marina area and diminishes to an average of 0.9 to 1.5 m/yr in the Sand City area (Griggs & Savoy, 1985).

More recently Gref (2004) estimated coastal retreat rates at four sites between Marina State beach and Del Monte State beach. The four sites are Marina State Beach, Stilwell Hall, Monterey Beach Resort, and Ocean Harbor House Condominiums (Fig. 15). These areas were selected because there are landforms for easy georeferencing, the locations were representative of several locations along the Bay, and most of the areas had buildings on or near the coast that may be impacted by further coastal retreat. Gref (2004) used historic aerial photography, high resolution digital aerial photographs from 2002, and GPS technology to map the most recent geometry.

At each site several transects were measured orthogonal to the beach on each pair of photographs (Fig. 16), and the average retreat rates were determined for four time steps representing the past 28 years. The data are summarized in Figure 17 and Table 1.



Figure15: Four sites studied by Gref (2004). From top to bottom Marina State Beach, Stillwell Hall, Monterey Beach Resort, and Ocean Harbor House Condominiums. See Figure B2 for Stillwell Hall, Figure B5 for Monterey Beach Resort, and Figures B3 and B4 for Ocean Harbor House Condominiums.

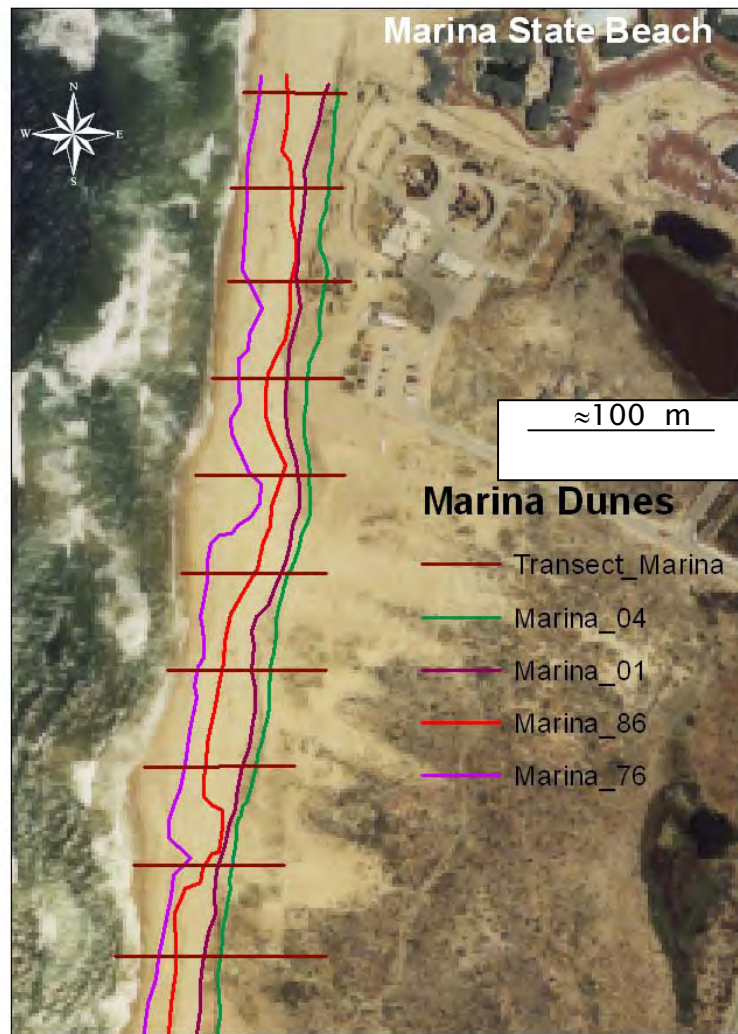


Figure16: Method of determining retreat rate at Marina Dunes study site. Long lines are dune-beach intersections of 2004, 2001, 1986 and 1976 plotted on the 2001 digital aerial photograph. The short lines are ten transects across the images used to determine average retreat rates at the site. Each of the four study sites (Marina, Stillwell, Resort, Condominiums) were similarly assessed.

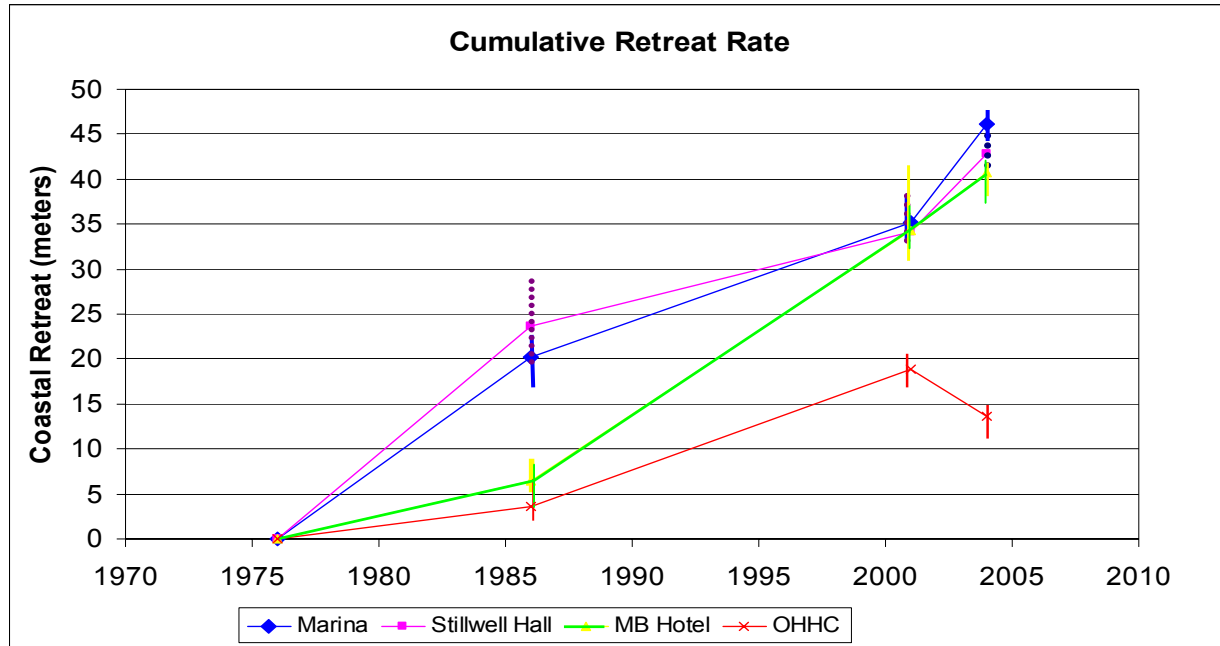


Figure 17: Cumulative coastal retreat over 28 years for each site. Error bars use the 95% confidence level found in Table 1.

Table 1: Coastal retreat rates at four study sites in southern Monterey Bay

Marina State Beach Based Upon 10 Transects						
Data Years	Time (yrs)	Coastal retreat (m)*	Standard Deviation (m)	95% Confidence Interval (m)	Retreat Rate (m/yr)	Cumulative Retreat (m)
1976	0	0	0	0	0	0
1976-1986	10	20.2	7.0	5	2.0	20.2
1986-2001	15	15	7.1	5	1.0	35.2
2001-2004	3	10.9	3.9	3	3.6	46.1
Stillwell Hall Based Upon 14 Transects						
Data Years	Time (yrs)	Coastal retreat (m)*	Standard Deviation (m)	95% Confidence Interval (m)	Retreat Rate (m/yr)	Cumulative Retreat (m)
1976	0	0	0	0	0	0
1976-1986	10	23.6	16.4	9	2.4	23.6
1986-2001	15	10.5	10.7	6	0.7	34.1
2001-2004	3	8.7	5.7	3	2.9	42.9
Monterey Beach Resort Based Upon 14 Transects						
Data Years	Time (yrs)	Coastal retreat (m)*	Standard Deviation (m)	95% Confidence Interval (m)	Retreat Rate (m/yr)	Cumulative Retreat (m)
1976	0	0	0	0	0	0
1976-1986	10	6.4	5.8	3	0.6	6.4
1986-2001	15	27.8	21.4	12	1.9	34.2
2001-2004	3	6.6	4.6	3	2.2	40.8
Ocean Harbor House Condominiums Based Upon 6 Transects						
Data Years	Time (yrs)	Coastal retreat (m)*	Standard Deviation (m)	95% Confidence Interval (m)	Retreat Rate (m/yr)	Cumulative Retreat (m)
1976	0	0	0	0	0	0
1976-1986	10	3.7	4.6	5	0.4	3.7
1986-2001	15	15.2	5.1	5	1.0	18.8
2001-2004	3	-5.3	5.0	5	-1.8	13.6

5.3 Aerial LIDAR

Aerial “Light Distance And Ranging” (LIDAR) technology produces accurate and precise three-dimensional coordinates of points at the surface of the Earth along the flight path of the aircraft carrying the instrument. Figure 18 is an example of a shaded relief image produced from digital LIDAR data. LIDAR data has been collected along southern Monterey Bay on several occasions, most recently in 2004. Since the data sets are digital, the individual pixels in the images can be compared from year to year to detect changes. Dr. Ed Thornton (Naval Postgraduate School, Monterey) is currently publishing a series of papers that use LIDAR data to estimate both the lateral erosion rates and sand volume loss along much of southern Monterey Bay.

We found that the 2004 LIDAR data are very accurate and precise using an electronic total station and RTK GPS receiver to independently survey features that are visible in the LIDAR data set in the Elkhorn Slough, inland of Moss Landing (Appendix C). The study indicates that the elevation of every 1m² pixel in the LIDAR data set is known with an error of less than 10 cm. Horizontal positions were reasonably accurate as well.

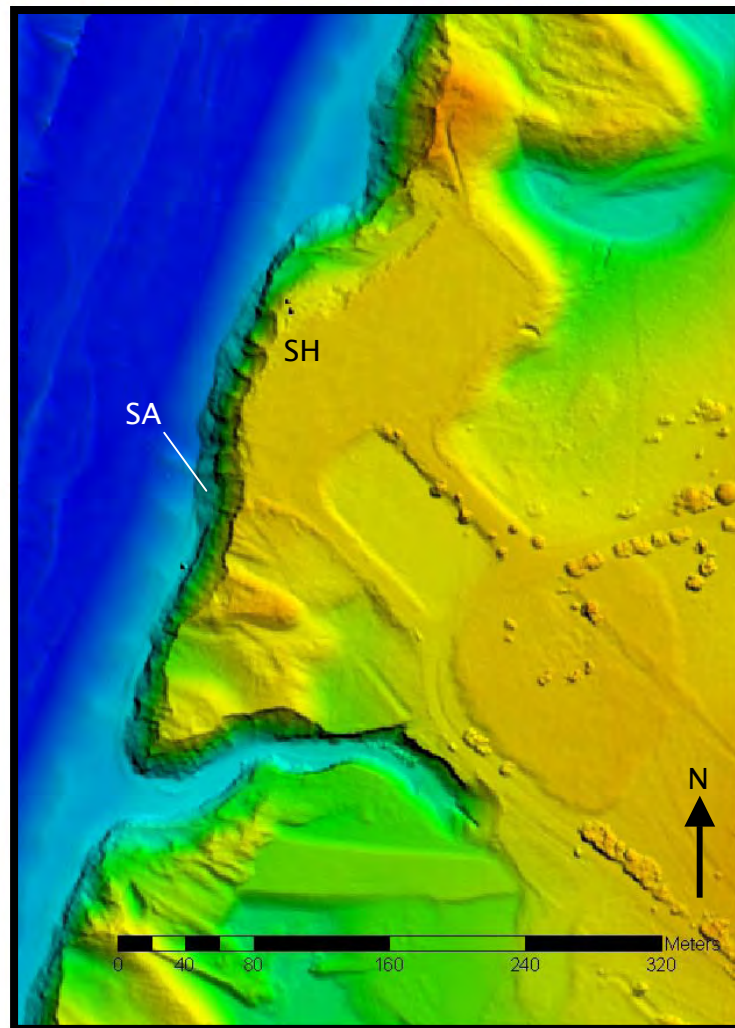


Figure 18: Shaded relief image from 2004 LIDAR data shows former Stillwell Hall site (SH). Sand aprons are visible at the base of steep sea cliffs (e.g., SA). Canyon (near the scale bar) rapidly eroded in response to broken storm drain. The storm drain had been undercut by coastal retreat. See Figures B8 and B9 for oblique ground photographs of the mouth and apex of the canyon. Data courtesy of Dave Lott (Monterey NOAA).

5.4 Terrestrial LIDAR

Terrestrial LIDAR systems are used on a tripod rather than in an aircraft. The instrument is aimed at the landscape to be digitized, and the LIDAR system acquires the three dimensional coordinates of millions of individual points in the view. This technology could be rapidly used to determine local coastal retreat rates with a precision of 4 mm. To our knowledge no such data sets exist yet for southern Monterey Bay.

6 Sand Budget and Beach Equilibrium

Our beaches are fed sand from a few sources and, in turn, lose sand to the continental shelf. If there is a balance between sand entering and leaving the beach, then the beach maintains its shape. If there is an imbalance in sand moving in and out of the beach, then it either grows or shrinks, depending upon which process prevails. Interestingly, the beach can maintain its average size even in the context of coastal retreat (Fig 19). Average beach size will remain constant when the sand provided by sea cliff retreat balances the sand lost to the continental shelf (Fig. 20), whether the coastline is stationary or migrating through space. The amount of sand provided to the beach by the process of seacliff retreat along southern Monterey Bay has recently been estimated to be 270,000 m³/yr (Thornton, 2005).

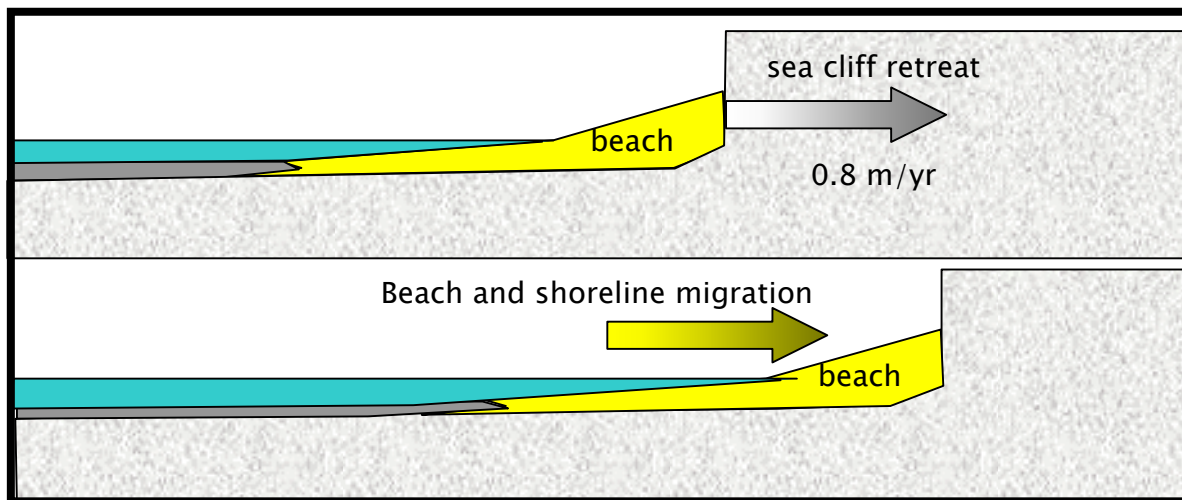


Figure 19: As coastal retreat progresses, the whole system moves eastward as an intact triad of offshore sand, beach, and seacliff. The beach geometry in the bottom figure is the same as in the top figure, except that the system has migrated eastward. In this example, the beach size has not changed because net sand input balances net sand output.

A useful tool for understanding beach processes is to create a sand budget for the beach. In the budget the inputs and outputs are measured as closely as possible, and the balance between the two is the change in storage of sand on the beach (Figures 21 and 22). The analytical process is the same as managing a checkbook and bank account, where the volume of beach sand at any point in time represents the amount of money in the bank. Creating a sand budget can also allow predictions to be made about the likely result of various coastal management options.

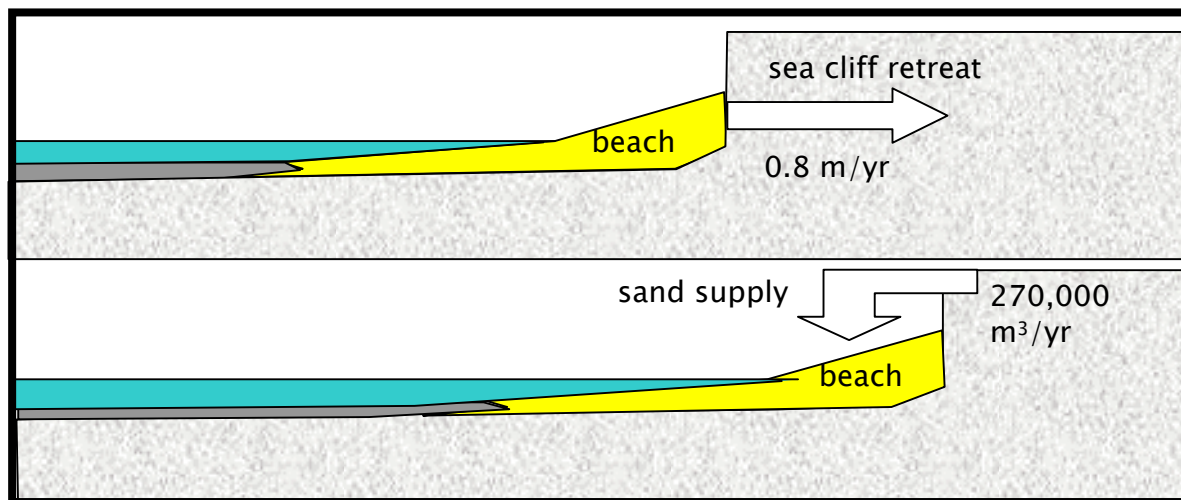


Figure 20: As coastal retreat progresses, the cliff erosion supplies the beach.

Figure 22 represents a conceptual framework of the physical processes that add, transport, store, or remove sand from any specific reach of the beach. It is analogous to knowing where your dollar earnings come from and where they go, but without assigning dollar values to the transactions. A more useful model would have at least some of the volumes of sand storage and some input and output rates. Sediment transport rates are, by nature, very difficult to assess. The transport estimates are complicated by the strongly episodic nature of the process. For example, much of our decadal erosion occurs during the few strong storms generated by El Niño events (Thornton, 2005; DBWSCC, 2002; Storlazzi and Griggs, 1998; Dingler and Reis, 2002). Thornton (2005) presented unpublished results that represent the best estimates of sediment transport rates for southern Monterey Bay (Table 2). The total amount of sand reaching the beach from rivers and seacliff retreat is approximately 310,000 m³/yr. That input is not balanced by 40,000 m³/yr blown inland by wind, but the beaches have not been growing annually, so there must be loss to the continental shelf. If we assume that the beaches are not growing, and are in geomorphic equilibrium, then the remainder of the input, 270,000 m³/yr, is probably transported offshore for long-term storage on the continental shelf. Although California beaches typically grow in the summer and thin in the winter, there is apparently a great imbalance in how much sand is transported back to the Monterey beaches once the winter rip tides have moved it offshore. Thornton (2005) suggests that the southern Monterey Bay sand budget is greatly influenced by rip currents that carry sand to offshore storage, and that lateral movement of sand in littoral currents is not as prevalent.

Before 1984, sand mining from the surf zone removed a substantial amount of sand from the coastal sand budget (Table 2). Since 1990, sand has not been extracted directly from the surf zone, but continues to be mined in Marina from a pit just inland from the beach berm (Fig. 23).

Average volume of sand (m ³ /yr)	Sand sources and sinks
	Inputs to the Beach
40,000	Input to the surf zone from the Salinas River
270,000	Input to the beaches from seacliff erosion
	Outputs from the Beach
40,000	Output from wind moving sand into coastal dunes
128,000 (pre 1984) 0 (post 1990)	Historic output from mining sand from surf zone
144,000 (pre-1984) 270,000 (post 1990)	Output from rip tides transporting sediment to permanent(?) offshore storage.

Table 2: Sediment budget details (modified from Thornton, 2005)

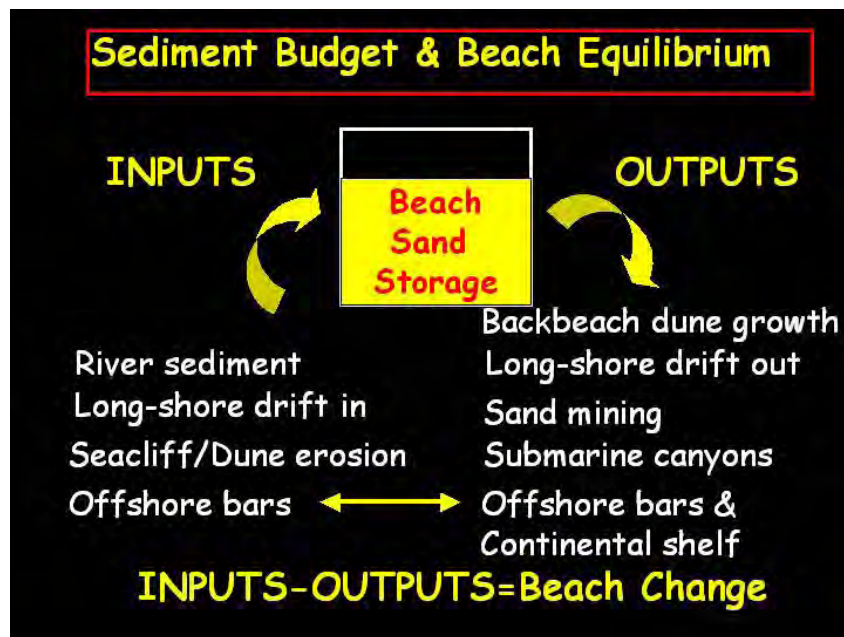


Figure 21: Principal inputs and outputs of sand to the beach along southern Monterey Bay.

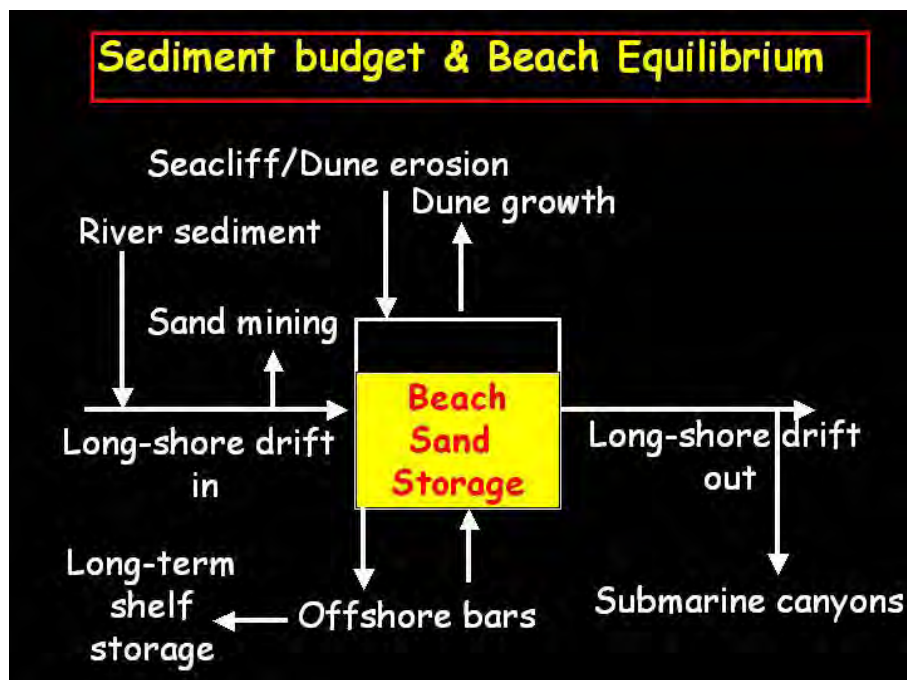


Figure 22: Conceptual systems diagram illustrating the main linkages among inputs and outputs of sand in the beach budget of southern Monterey Bay.

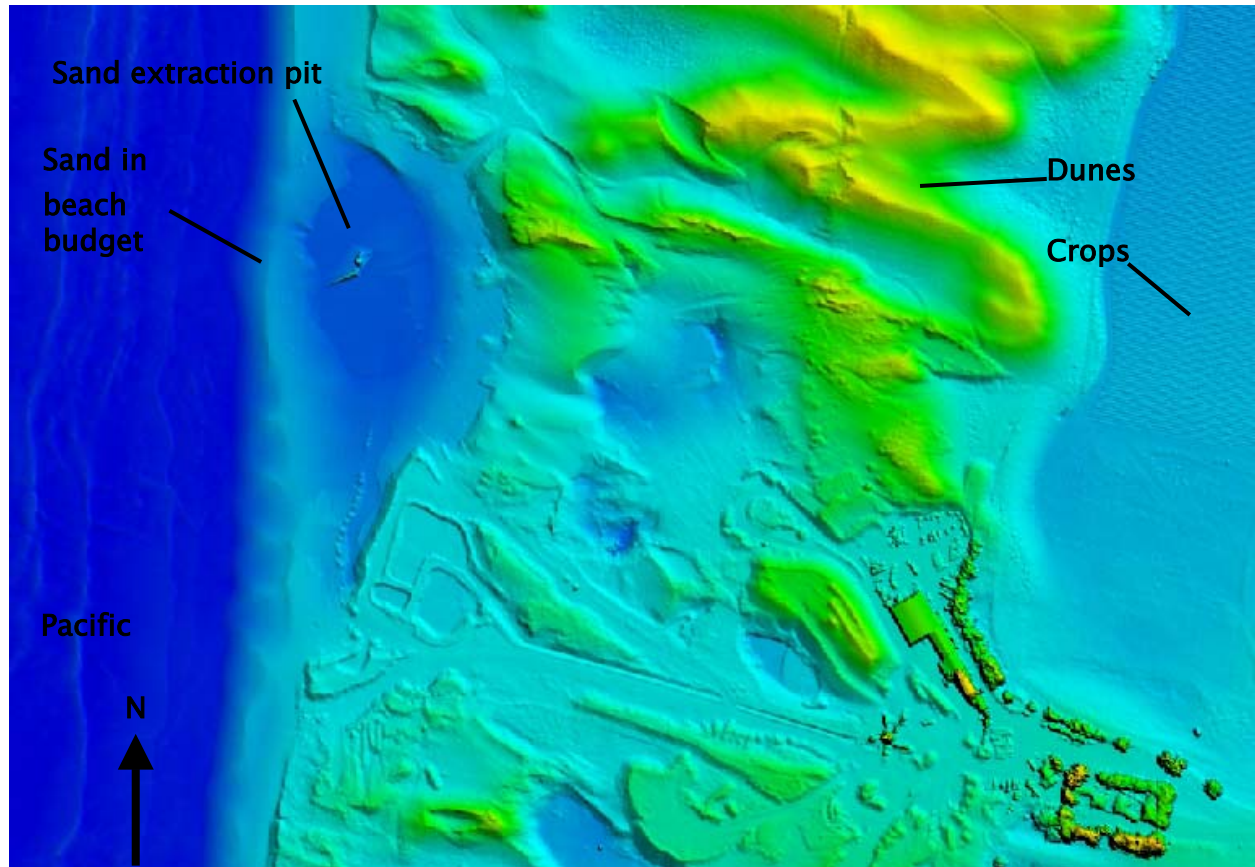


Figure 23: 2004 LIDAR view of sand mining operation located between downtown Marina and the Salinas River. Warm colors are higher elevations. The extraction pit is very close to the active transport zone of the beach. The beach shape is deflected around the western rim of the extraction pit. LIDAR data courtesy of Dave Lott (NOAA, Monterey).

7 Discussion

It is clear that coastal retreat in southern Monterey Bay is a long term process that has been active for the past 18,000 years, and continues unabated today. There is no indication that this natural process will end in the foreseeable future. Even when sea level is held constant, the strong wave energy impacting Monterey Bay (Figure 24) can erode the weak geologic materials composing the coastline. When global sea level again begins to fall, the regional economy will reclaim land now lost to the sea.

Our analysis suggests that there is an obvious conflict in the two coastal management goals of “stable coastlines” and “broad beaches.” In simplistic terms, the broad beaches of Monterey Bay are the result of coastal retreat, which provides the bulk of the sand passing through the beach system. Thus, stabilizing the sea cliffs will doom the beaches.

Four conclusions arise from this analysis.

- 1) The southern Monterey Bay coastline is retreating at approximately 1 m/yr, and has been retreating for a long time. The retreating coastline will continue to impact existing structures and convert both public and private lands to marine continental shelf at a rate of about 1 m/yr. If global change is accelerated by anthropogenic global warming, then the retreat rates will accelerate as well.
- 2) Armoring the coastline would effectively remove the input of sand to the beaches, without reducing the flow of sand from the beaches to offshore storage, which would likely result in smaller or absent beaches.
- 3) Beach nourishment and jetties would likely fail because the local coastline is dominated by rip currents rather than lateral drift.
- 4) Stemming the flow of sand from the beach to offshore storage is an engineering challenge that will generate unforeseeable ecosystem changes in addition to any primary benefits.

The following sections detail the above bullet points. We briefly discuss the advantages and challenges of various management strategies. Other strategies for coastal management may exist, but they do not follow from primary analysis of the coastal sediment system (Figs. 21 and 22), and are not in the scope of this report.

7.1 Letting the Coastline Erode

One coastline management option is to let the coastline erode. This management option does not directly impact the Monterey Bay National Marine Sanctuary. The long term and recent short term coastal retreat rates of southern Monterey Bay are approximately 1 m/yr. If the coastline is left alone, the beaches will likely remain broad, and the retreating coastline will continue to impact existing structures, converting both public and private lands to marine continental shelf at a rate of about 1 m/yr. The local rate of retreat is spatially and temporally



Figure 24: Large surf generated in far off storms occasionally batter the Monterey coastline. On March 9, 2005 a large swell attracted surfers who rode waves with faces up to 55 feet tall off of Pebble Beach, CA. Photo used with permission from Tony Harrington / www.harroart.com.

variable, so local decisions about development restrictions or relocating existing structures should be made with local retreat rate data. The coastline is generally stable near Monterey Municipal wharf, with retreat rates generally increasing to the north toward former Stillwell Hall. The retreat rates will naturally drop if the sea cliff erosion exhumes a harder, less sand-rich geologic formation, or climate change brings reduced peak ocean wave energy.

7.2 Armoring the Coastline

Armoring the coastline to reduce coastline retreat rates will result in a loss of sand reaching the beaches, causing the beaches to rapidly shrink as sand stored in the beaches moves offshore. Natural analogs for coastlines with “extensive coastal hardening” exist in Pacific Grove. The resistant granitic rocks that underlie Pacific Grove and the adjacent coastline to the south provides no erodible sea cliff to nourish the sand supply. That lack of sand supply for the coastline results in small, disconnected pocket beaches composed of very coarse sand and gravel (Fig. 25).

There are also examples of “local coastline armoring” at the Monterey Beach Resort, Ocean Harbor House Condominiums, and former Stillwell Hall. Local coastline armoring has resulted in a nascent “peninsula effect,” where the armored portion of the coastline does not erode, but adjacent, natural parts of the coast continue to retreat, leaving the armored portion protruding seaward. This effect is well exemplified in the case of the Stillwell Hall seawall, where the peninsula effect lead to lateral failure of the sea wall (Figs. B1 and B2). Likewise, at highest tides, the beach is now impassable in front of the Monterey Beach Resort (Fig. 26) and Ocean Harbor House Condominiums (Fig. 7). At present, there are still broad beaches fronting both the Resort and Condominiums during most tide conditions, but their adjacent shorelines have respectively experienced 41 m and 14 m of coastal retreat in the past 28 years (Table 1),

leaving these structures at risk. The resulting peninsula effect gradually leaves the armoring more exposed to the force of the ocean and further reduces public beach access. Local armoring without managing adjacent beaches apparently leads to failure of the local armoring project (e.g., Fig. B1).

7.3 Beach Nourishment and Jetties

Beach nourishment will likely fail as a management strategy in southern Monterey Bay because of the natural very high loss of sand to the marine continental shelf. Thornton (2005) emphasizes that the sand in Monterey Bay is rapidly moved offshore by rip currents, with less prevalent lateral movement along the beaches. Thus, jetties, which heavily rely upon littoral drift for success, are also not a likely solution to regional coastal retreat.

Littoral drift brings between 200,000 m³/yr and 250,000 m³/yr of sand and fine gravel from Santa Cruz to the Moss Landing, which is the northern end of the “southern Monterey Bay” study area (Fig. 2; Best and Griggs, 1991). It is unclear whether a significant fraction of that large sediment load historically bypassed Monterey Canyon to feed southern Monterey Bay. Smith et al. (2005) showed that very little sand can presently reach southern Monterey Bay because the northernmost canyon tributary now terminates north of the north jetty of Moss Landing Harbor (Fig. 27). There is presently very little space for sand to bypass north jetty without being directed down the canyon.



Figure 25: Diminutive pocket beaches are present along rocky coastlines where sand supply is low. Rocky coastlines are natural analogs for sea walls and other artificially hardened coastlines.

7.4 Reducing the Loss of Sand to Offshore Storage

The retreat rates, sediment budget, and photos in this report suggest that sand grains in the beach budget have a rapid, one-way transit from the sea cliff, to the beach, and then out to sea for storage on the marine continental shelf. One logical solution is to reduce the loss of sand to the sea, rather than reduce the contribution of sand from the sea cliffs through armoring (Fig. 22). Sand loss can be achieved by reducing the wave energy impacting the coast, with special care to reduce the influence of very erosive El Niño-driven storm waves. Wave energy can be dissipated by engineered offshore structures that dissipate or redirect wave energy. Although the idea is conceptually simple, the engineering of such structures would be challenging and costly in the dynamic Monterey Bay setting. Furthermore, there would be unforeseen and unpredictable consequences in the broader ecosystem of the Monterey Bay Sanctuary since submarine structures strongly affect marine ecosystem function and physical movement of sediment. The unpredictable effects of offshore structures may ultimately be positive or negative.

If offshore structures are successful at reducing wave energy only “locally,” then the locally protected beach would have a lower retreat rate than adjacent beaches, so it would eventually become a peninsula as adjacent shorelines continued to retreat inland. Wave energy refracts to preferentially attack peninsulas, so the structures and locally protected beach would ultimately be subject to attack from the front and sides.

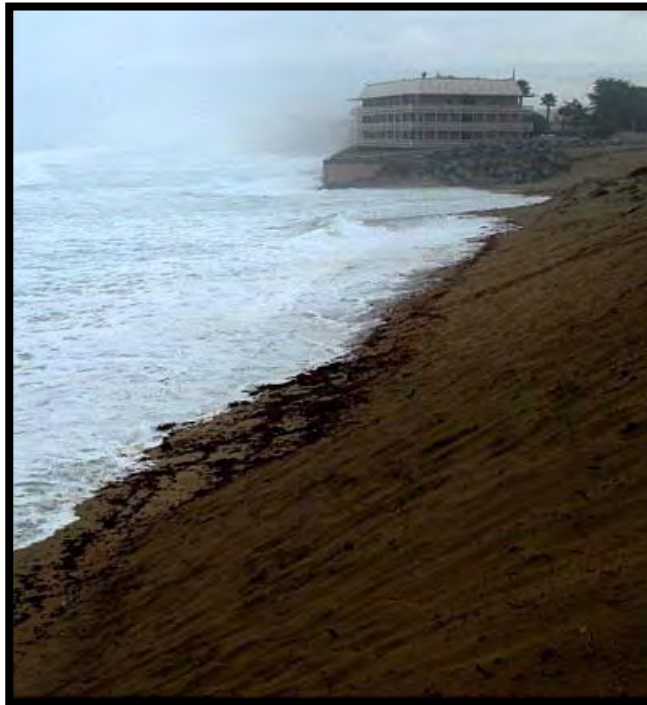


Figure 26: Peninsula effect present at Monterey Beach Resort at very high tides (5.98 ft) and high swells (15.5 ft; 16 second period) of December 9, 2004. Note large rock placed along wall damaged by high seas in December 2002 (Smith, 2005). There is normally a broad beach in front of the Resort, during lower surf and normal tides.

7.5 Coastline Management within the Context of Sea Level Rise

Global sea level will continue to rise an additional few feet during the next 100 years. It is unclear how much of that rise will be anthropogenic and how much will be natural waning of our recent ice age. Given that sea level rise is a virtual certainty, and that coastline retreat is very sensitive to the position of sea level, Monterey Bay will experience perennial coastal retreat. The challenges associated with stabilizing this dynamic, high-energy coastline, and the likelihood of unforeseen physical and ecological results of an engineering approach, dictate that a realistic cost-benefit analysis will include the cost of adaptive management, periodic maintenance, and eventual decommissioning in case desired results are not achieved, environmental impacts become unacceptable, or the project success becomes diminished by sea level rise.

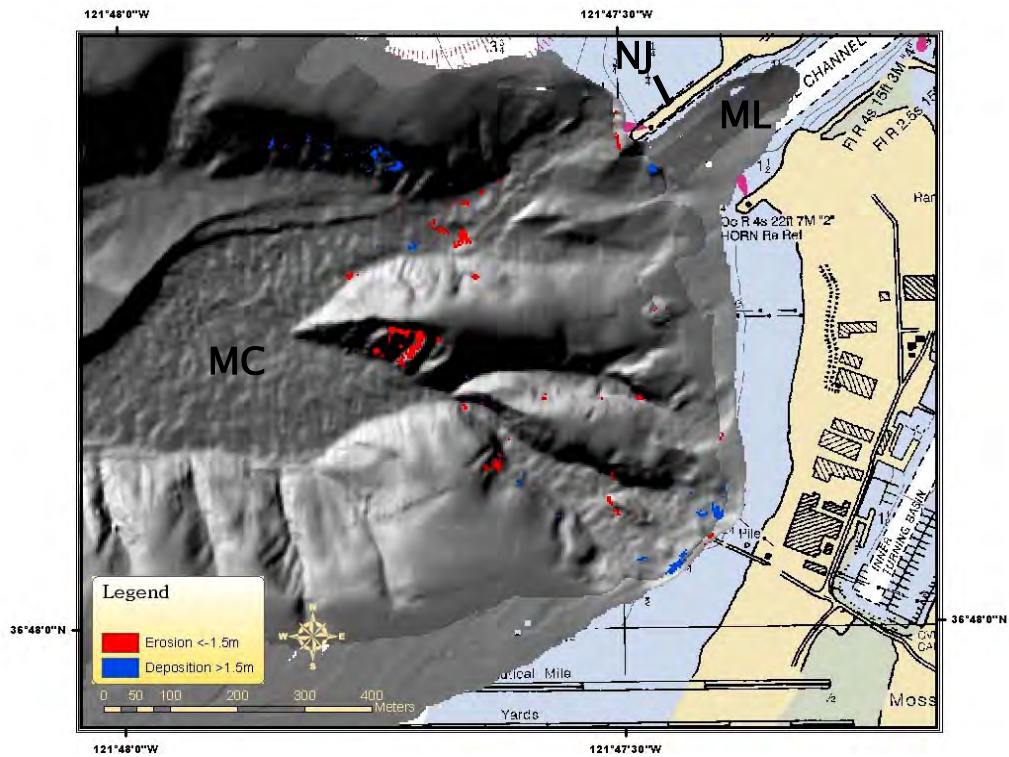


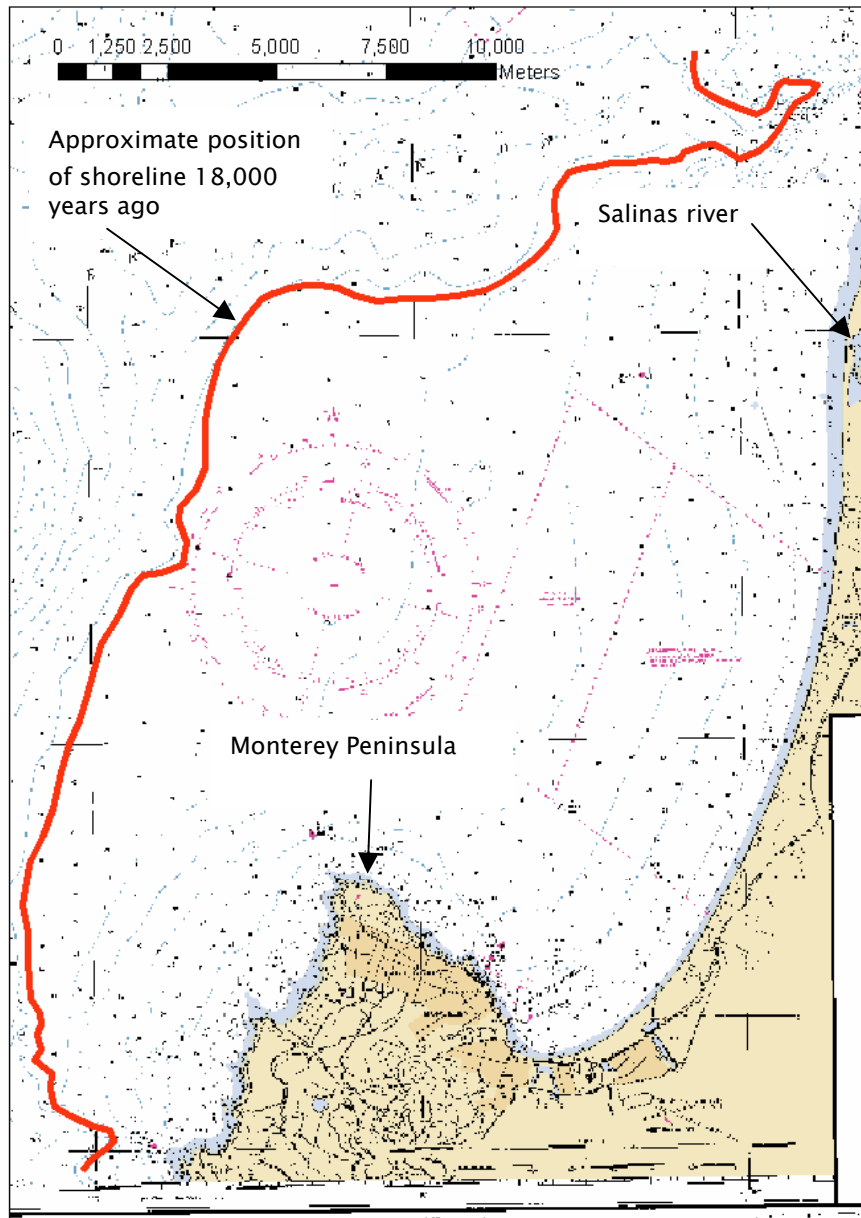
Figure 27: Digital shaded relief image of the head of Monterey Canyon (MC). Northernmost tributary to the canyon is located north of the Moss Landing Harbor (ML) north jetty (NJ). See Figure 2 for location. 2004 Data from the CSUMB Seafloor Mapping Lab. Digital image from Astilla (2005).

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9 Appendix A: Bathymetric Chart



NOAA nautical bathymetric map. The red line is drawn at 130 m (71 fathoms) water depth, the 18,000 year old shoreline.

10 Appendix B: Miscellaneous Oblique Aerial Photographs



Figure B1: Stillwell Hall in 2003 showing sea wall compromised by unrestricted retreat of adjacent sea cliffs. This photo illustrates the “peninsula effect” produced by local hardening of a retreating coastline. Note sand cones and sand aprons transferring large volume of sand from sea cliff to beach.



Figure B2: Stillwell Hall on October 31, 2004 showing site after building and seawall were removed.



Figure B3: Historic storm drain(?) outfall exposed by many meters of recent coastal retreat adjacent to sea wall at Ocean Harbor House Condominiums. December 9, 2004.



Figure B4: Ocean Harbor House Condominiums on October 31, 2004 showing site after large rock was placed to create a sea wall.



Figure B5: Monterey Beach Resort on October 31, 2004.



Figure B6: Sea wall at end of Tioga Avenue, October 31, 2004.



Figure B7: Close up of sea wall at end of Tioga Avenue, October 31, 2004.



Figure B8: Storm drain outfall on Former Fort Ord compromised by coastal retreat. Canyon is formed by rapid undercutting and vertical failing of buried storm drain pipe (see Fig. B9). Photo by David Norris September 2002. See Figure 18 for map view of the eroded canyon.



Figure B9: Storm drain outfall on Former Fort Ord compromised by coastal retreat. Waterfall undercuts weak sandstone substrate causing subsequent collapse of storm drain pipe sections. (see Fig. B9 for original location of outfall). Photo by David Norris September 2002. See Figure 18 for map view of the eroded canyon.

11 Appendix C: Assessment of Aerial LIDAR Precision and Accuracy

Preliminary accuracy assessment of recent LIDAR data at Elkhorn Slough (11/15/04)

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Elkhorn Slough LIDAR data are elevations of georeferenced, 1 m x 1 m pixels. We assessed the accuracy and precision of the pixel elevations by direct comparison with accurate and precise elevations obtained with RTK-GPS and laser total station.

Methods

The total station data were registered to NAVD88 using the RTK-GPS. Following that vertical registration, RTK-GPS elevations and total station elevations were in close agreement, usually less than 2 cm difference, on subsequent readings on a variety of targets. Therefore, we consider both the RTK-GPS and total station estimates of elevation to be comparable in quality. The following analysis includes 91 independent comparisons between survey point elevations and LIDAR pixel elevations in the region near Kirby Park in Elkhorn Slough. The variate being analyzed is “LIDAR” minus “survey,” so a significant positive bias in the variate would indicate an accuracy error with the LIDAR values too high on average.

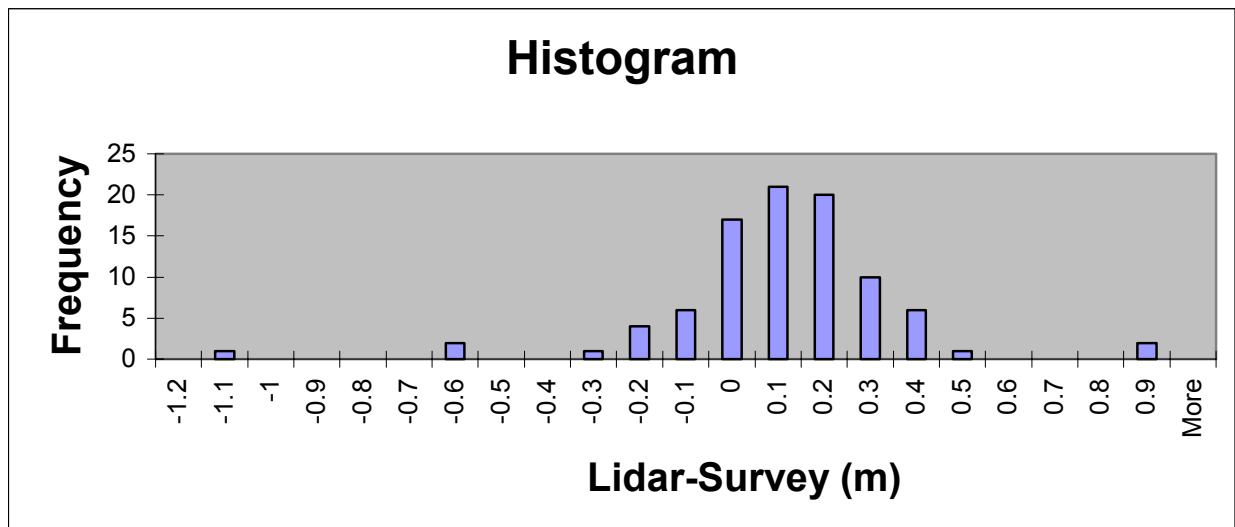
Results

Table C1 shows that the full range of difference values is approximately ± 1 m. However most of the differences were surprisingly close to 0 m (Figure C1), the average difference is positive 5 cm. The 95% confidence bounds on the mean difference include the value 0 m, indicating reasonable accuracy in the LIDAR data (Table C1).

An R^2 of 0.95 indicates a high degree of correlation between the LIDAR and survey elevations (Fig. C2). The best fit line has a slope of 0.92, slightly below a value of 1.0, which would have indicated perfect accuracy. The 95% confidence limits on the slope span 0.88 to 0.97, so the slope is significantly different from 1.0. The low slope suggests a slight bias toward low LIDAR values. However, Figure C2 contains a single high value point that may be heavily leveraging the results. When the single leverage point is removed, the R^2 value is still a very significant 0.93, but the slope value now ranges from 0.89 to 1.0, using 95% confidence limits. This further step suggests that there is no significant bias (accuracy error) in the LIDAR elevation data.

Table C1: Descriptive statistics of LIDAR-SURVEY (meters)

Mean	0.052495
Standard Error	0.027313
Median	0.055
Mode	0.175
Standard Deviation	0.260551
Sample Variance	0.067887
Kurtosis	6.607241
Skewness	-0.90769
Range	2.041
Minimum	-1.159
Maximum	0.882
Sum	4.777
Count	91
Confidence Level (95.0%)	0.054262
Upper 95% bound	0.106757
mean	0.052495
Lower 95% bound	-0.00177

**Figure C1: Distribution of differences between LIDAR pixel elevations and survey elevations.**

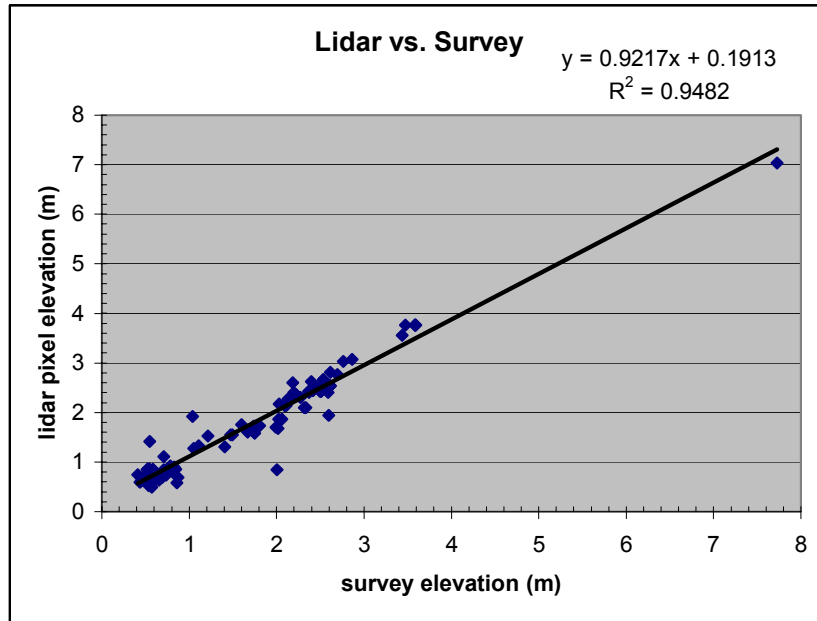


Figure C2: Scatterplot of LIDAR and survey elevations.

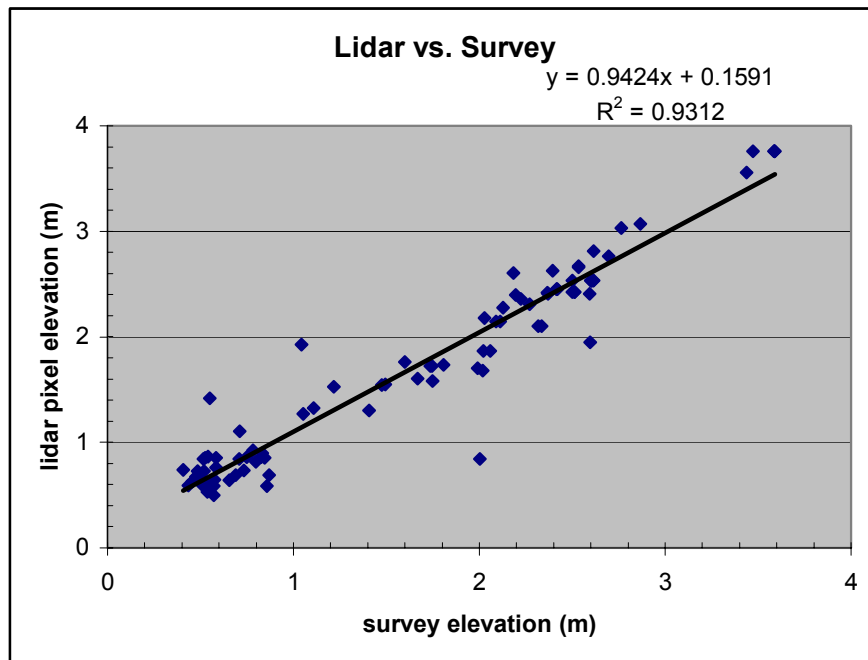


Figure C3: Scatterplot of elevation differences with leverage points removed.

COASTAL EROSION AND ARMORING IN SOUTHERN MONTEREY BAY

A Technical Report in support of the
Monterey Bay National Marine Sanctuary
Coastal Armoring Action Plan

Version 1.1

June 2005



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Note From the Author

This report is intended to be a living document that will be updated as relevant information is gathered through future working group meetings of the Monterey National Marine Sanctuary's (MBNMS) Coastal Armoring Action Plan. In particular, MBNMS staff may add additional data on the alternatives to mitigate coastal erosion and on the progress of specific armoring permits. It is also recommended that a section on management recommendations be included as these decisions are reached in the action plan process.

I would like to thank the following people for their scientific input and cooperation: Dr. Gary Griggs, Dr. Edward Thornton, Dr. Kiki Patsch, Dr. Douglas Smith, Dr. Cheryl Hapke, Mr. David Reid, and Mr. John Kasunich. In addition, I would like to thank Dr. Andrew DeVogelaere, Brad Damitz and Dr. Holly Price of the MBNMS for thoughtful review of this report.

Cover photo credit: aerial view of the Monterey Beach Hotel, copyright © 2002 Kenneth & Gabrielle Adelman (<http://www.californiacoastline.org/>).

I. INTRODUCTION

Development at the edge of California's highly erosive coast has led to increased pressure to protect both private and public infrastructure with various types of coastal protection structures, such as seawalls and revetments. The cumulative environmental impacts of this coastal armoring within the Monterey Bay National Marine Sanctuary (MBNMS; Figure 1.1) has been of growing concern, as they may interfere with the natural sediment dynamics, lead to the loss of public beaches, hinder public access to the coast, and have the potential to alter marine biological communities either during construction or via their long-term impacts (Stamski 2005).

In response to these concerns, the MBNMS is playing an increased role in the issue of coastal armoring as part of the congressionally-mandated update of its Management Plan. The sanctuary, in collaboration with other stakeholders, has developed an action plan with the goal of developing and implementing a proactive, regional approach to address coastal erosion and to minimize the negative impacts of coastal armoring on a sanctuary-wide basis.

As part of this action plan, the MBNMS has initiated a collaborative pilot effort with a number of partners to develop a regional planning approach that addresses the issue of coastal erosion and armoring in the southern Monterey Bay sub-region of the MBNMS, from the Salinas River mouth to Wharf #2 in Monterey. Participants in the Southern Monterey Bay Coastal Erosion and Armoring Workgroup include: representatives from the various local, state, and federal government agencies involved in studying and regulating these issues; scientific experts; and local decision makers.

The purpose of this report is to summarize scientific information on coastal erosion and armoring for southern Monterey Bay to support the sanctuary's Coastal Armoring Action Plan and the efforts of the Southern Monterey Bay Coastal Erosion and Armoring Workgroup as they consider effective ways to address this issue. This report provides background information on the geomorphic history of the area, summarizes the results of regional erosion studies, documents coastal development that may be threatened by erosion, and lays the groundwork for an investigation of alternatives to coastal armoring that are available in responding to coastal erosion.

a. Geologic Setting of Monterey Bay

Monterey Bay is a large, lowland coastal embayment, with rocky headlands at the north and south extremes and a sweeping arc of sandy, dominantly dune- and cliff-backed shoreline in between (Figure 1.2). The submarine Monterey Canyon is the most prominent feature of the Bay; the main canyon and its tributaries provide bathymetric extremes in which geology and oceanography coalesce to shape the seafloor as well as the adjoining coast. Two main rivers drain into the bay, the Pajaro and the Salinas, located to the north and south, respectively, of a major estuary, Elkhorn Slough, which is situated just landward of the head of Monterey Canyon. Prior to the last glacial maximum, 18,000 years ago, vast areas of the broad continental shelf were exposed, on which dune fields formed as sand from coastal rivers was transported inland by prevailing onshore winds. For the past 18,000 years, sea level has been steadily rising, eroding those dune fields at an average rate of approximately 0.7 meters per year (m/yr) (Smith et al. 2005; Thornton et al. in press). The more resistant, rocky headlands at Santa

Cruz and Monterey have eroded significantly slower, and this gradient in erosion has sculpted the arcuate Monterey Bay.

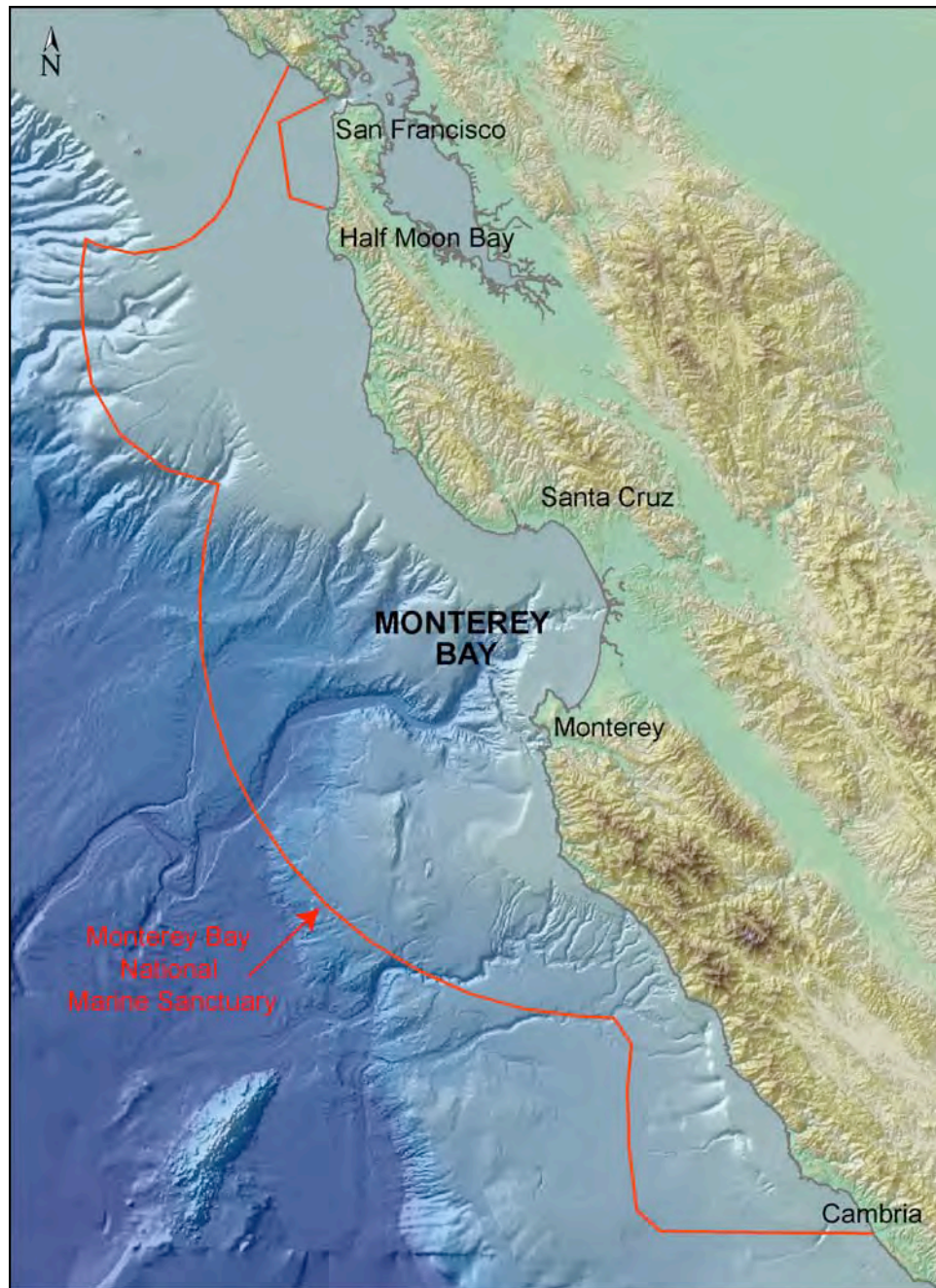


Figure 1.1: Map of the Monterey Bay National Marine Sanctuary (outlined in red).

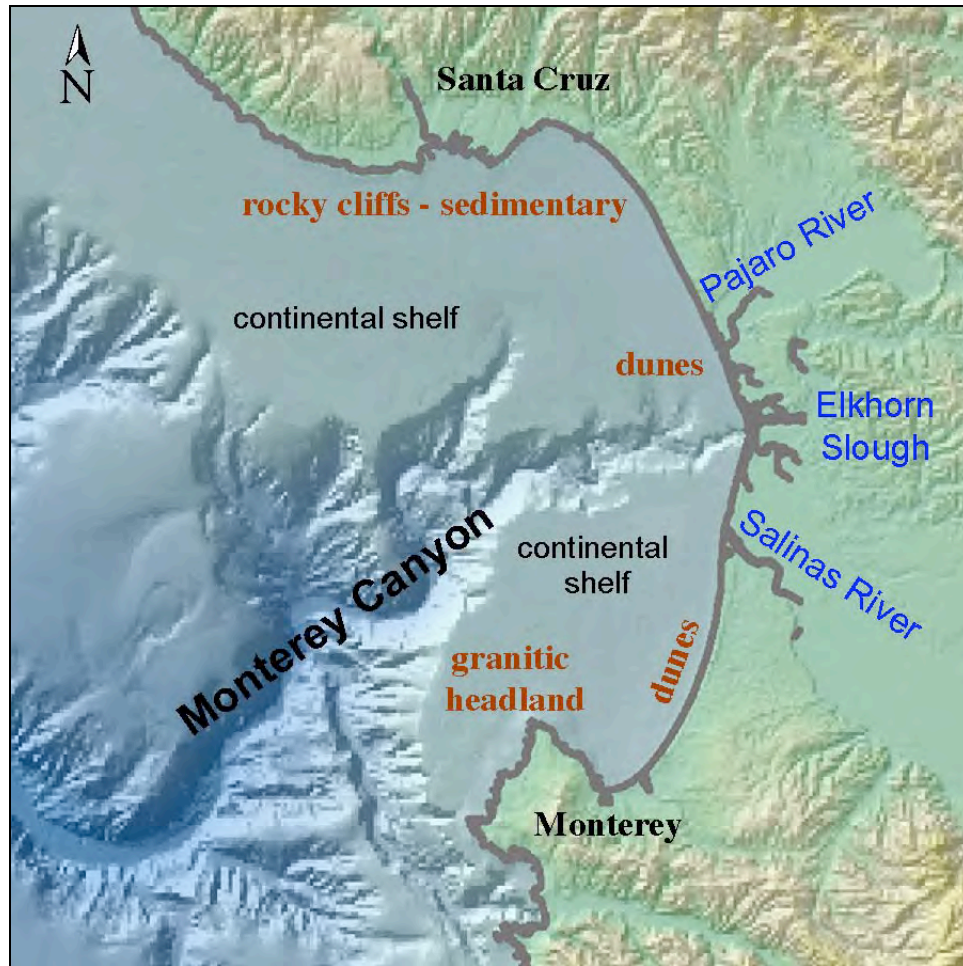


Figure 1.2: Map of Monterey Bay region with major geomorphic features labeled.

b. Monterey Bay Littoral Cells

Monterey Canyon effectively bisects the bay, dividing the region into two major littoral cells (Figure 1.3). A littoral cell is a self-contained compartment of the coast, which includes all sources and sinks for littoral, or beach-sized, sand. In Monterey Bay, sources of beach sand include discharge from coastal rivers and erosion of coastal bluffs; natural sinks or losses can occur where submarine canyons intersect the nearshore zone, where wind transports sand from beaches into coastal dunes, or where sand gets dispersed offshore onto the continental shelf. Littoral drift is driven by longshore currents, which

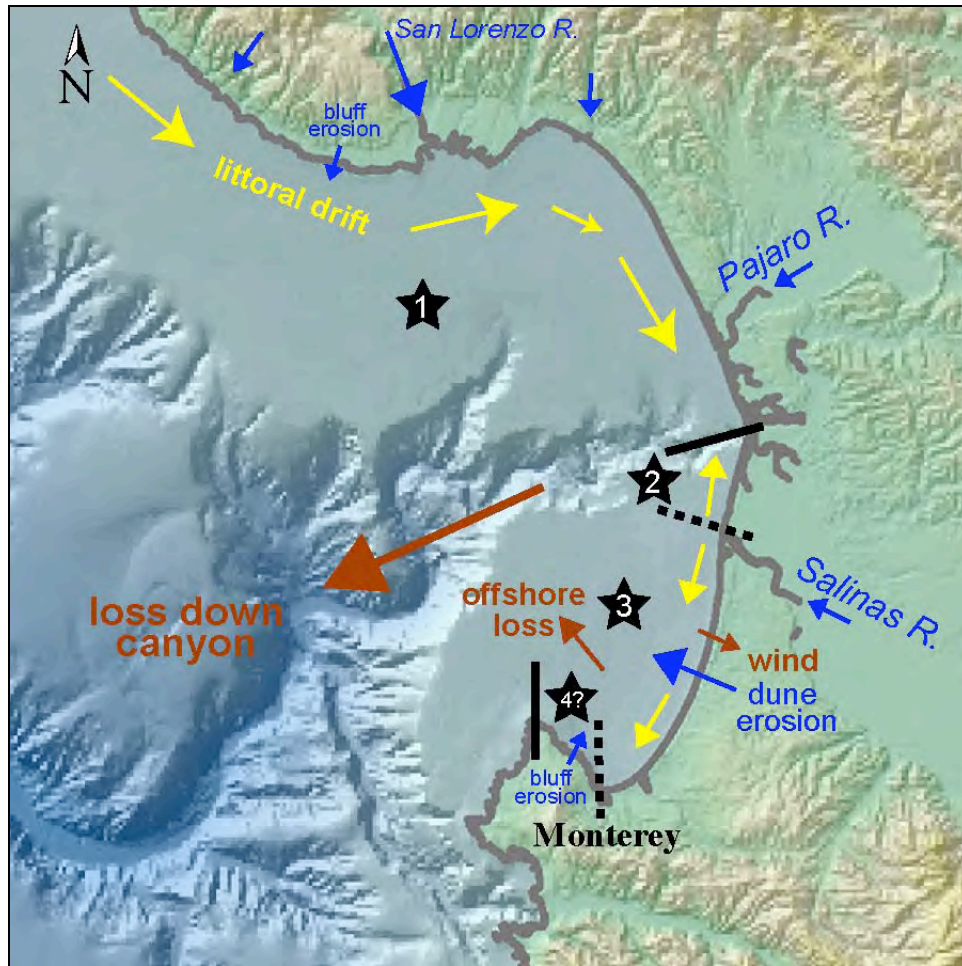


Figure 1.3: Schematic map of Monterey Bay littoral cells. Black bars represent divisions between littoral cells, which are highlighted with stars. Dashed divisions are not as fully constrained as solid divisions. Blue arrows represent major inputs of sand to the system, brown arrows represent significant losses of sand from the system, and yellow arrows represent the approximate path of littoral drift. Arrows are not to scale.

move sand from sources down the coast like a river within the nearshore zone; the direction of this movement is dictated by the incident angle of the dominant wave patterns. In theory, there is no transfer of sand between adjacent cells. Understanding the boundaries of these cells is therefore vital to managing coastal resources because activities that interrupt sand movement in one portion of a cell can impact areas down-coast within the same cell.

Every year, approximately 230,000 m³ of sand travels from beach to beach along northern Monterey Bay, driven in a southerly direction by the dominant northwest waves (Griggs and Johnson 1975) (Littoral cell #1 on Figure 1.3). This is equivalent to 23,000 dump truck loads of sand annually moving down the coast. That sand gets channeled offshore when it reaches the canyon and is removed from the littoral system. In southern Monterey Bay, the definitive boundaries of littoral cells and rates of transport are not well documented. It is generally agreed upon that there are at least two sub-cells in this region: a small cell in which sand is transported from the Salinas River north into the canyon (#2 on Figure 1.3); and a larger cell that extends from the Salinas River south towards the Monterey granitic headland (Dorman 1968; Arnal et al. 1973; Griggs and Jones 1985; Thornton et al. in press) (#3 on Figure 1.3).

Sources of sand in southern Monterey Bay are the Salinas River, though this is thought to contribute a minor amount of sand-sized material, and erosion of coastal dunes. Unlike northern Monterey Bay, lateral transport of sediment appears to be minimal in this region, as evidenced by the lack of sand build-up against the north side of Wharf #2 (PWA 2004; Thornton 2004). Rip currents are likely the dominant sand transport mechanism in southern Monterey Bay, moving sand predominantly offshore instead of laterally down the coast (Smith et al. 2005; Thornton et al. in press). Potential sand sinks in the system include losses into Monterey Canyon, offshore transport onto the continental shelf, sand mining, and removal by wind onto adjacent dunes. The focus of this report is on the larger of these southern Monterey Bay (SMB) cells, from the Salinas River to the southern end of Del Monte Beach (#3 on Figure 1.3).

An additional sub-cell may exist between the Monterey Harbor (at the end of Del Monte Beach) and Point Pinos, the northernmost tip of the Monterey peninsula (#4 on Figure 1.3) (Thornton 2004). Lines of evidence that support division of the littoral cell at this location include drastic differences in lithology, coastal orientation, and beach mineralogy. The northeast-facing peninsula is composed of resistant granite that receives muted wave energy, while the northwest-facing inner bay coastline is made up of unconsolidated dunes that are routinely pounded by intense wave action. Together, these two factors indicate that the processes and rates of erosion are not comparable between the peninsula and the inner bay and may necessitate separate analyses. In addition, beaches on the peninsula are composed dominantly of granitic materials (*e.g.*, coarse-grained, angular potassium and sodium-rich feldspar, quartz, mica, amphibole, etc.), yet beaches to the north of the harbor are made up of grains that originated from erosion of southern Monterey Bay dunes (*e.g.*, finer-grained, rounded quartz and sedimentary lithic fragments). This distinction in beach mineralogy suggests that littoral drift is not transferring eroded dune sand to the peninsula and therefore, there may be a subdivision in the overall littoral cell at this point (as drawn on Figure 1.3).

c. Geomorphology of Coastal Landforms

The shoreline of SMB is an 18 km stretch of continuous sandy beach, being wider at the southern end than at the northern end (Figure 1.4). The morphology of beaches in this region varies from season to season, but they are generally wider and gently sloping in summer and narrower and steeper in winter. The dunes at the back edge of the beach have an average height of 10.3 m, but can be as high as 46 m (Thornton et al. in press)

(Figure 1.5). Most of the dune surfaces that are not directly exposed to wave energy are vegetated, indicating that the dunes are stabilized in some areas. Yet, drifting sand across Highway 1 is evidence of some inland dune migration because of prevailing onshore winds (Figure 1.6). Erosion of these dunes, which has been occurring since sea level began to rise at the end of the last glacial period, is the dominant sand supply to the SMB littoral cell (Figure 1.3).



Figure 1.4: Relative beach width (green text) and adjacent dune morphology (brown text) in southern Monterey Bay. Distances from Wharf #2 in Monterey are shown in kilometers (black triangles). Coastline descriptions from Coyne (2001).



Figure 1.5: Aerial photograph of wave-cut dunes near the relatively undeveloped area of Fort Ord, California. This type of erosion provides much of the sand for the southern Monterey Bay littoral system. Despite the fact that this photograph was taken in summer, the beach is relatively narrow. During storms and/or high tides, waves wash up the beach and undercut the dunes. See Figure 1.4 for location of Fort Ord. Photograph copyright © 2002 Kenneth & Gabrielle Adelman (<http://www.californiacoastline.org/>).



Figure 1.6: Aerial photograph of the Monterey Beach Hotel (Seaside, CA) in summer, showing a wide beach, low back-beach area, and migrating dunes. In contrast to Figure 1.5, there is significant development along this stretch of southern Monterey Bay. See map Figure 1.4 for location of the hotel. Photograph copyright © 2002 Kenneth & Gabrielle Adelman (<http://www.californiacoastline.org/>).

d. Wave Climate

Differences in erosion of coastal landforms along SMB appear to be dependent upon the amount of wave energy reaching the coast and how that energy is related to tides. The most dominant wave pattern affecting SMB is from Northern Hemisphere Swell; the resultant northwesterly wave trains refract over Monterey Canyon and impact the central part of the bay most intensely (Figure 1.7). Northern Hemisphere Swell is most prominent from October to May. Southern Hemisphere Swell, which produces smaller waves than its northern counterpart, is most prevalent in summer. The southern part of SMB receives less direct wave energy than the central section of the bay because it is partially protected from southerly waves by the Monterey Peninsula and because northwesterly waves have dissipated slightly compared to when they hit the central bay coast. Local swell can also arise from regional low-pressure systems (Storlazzi and Griggs 2000). Overall, the destructive force of waves is greatest when high tides and strong storm waves are coincident, a situation that commonly occurs during El Niño events (Storlazzi and Griggs 2000; Dingler and Reiss 2002).

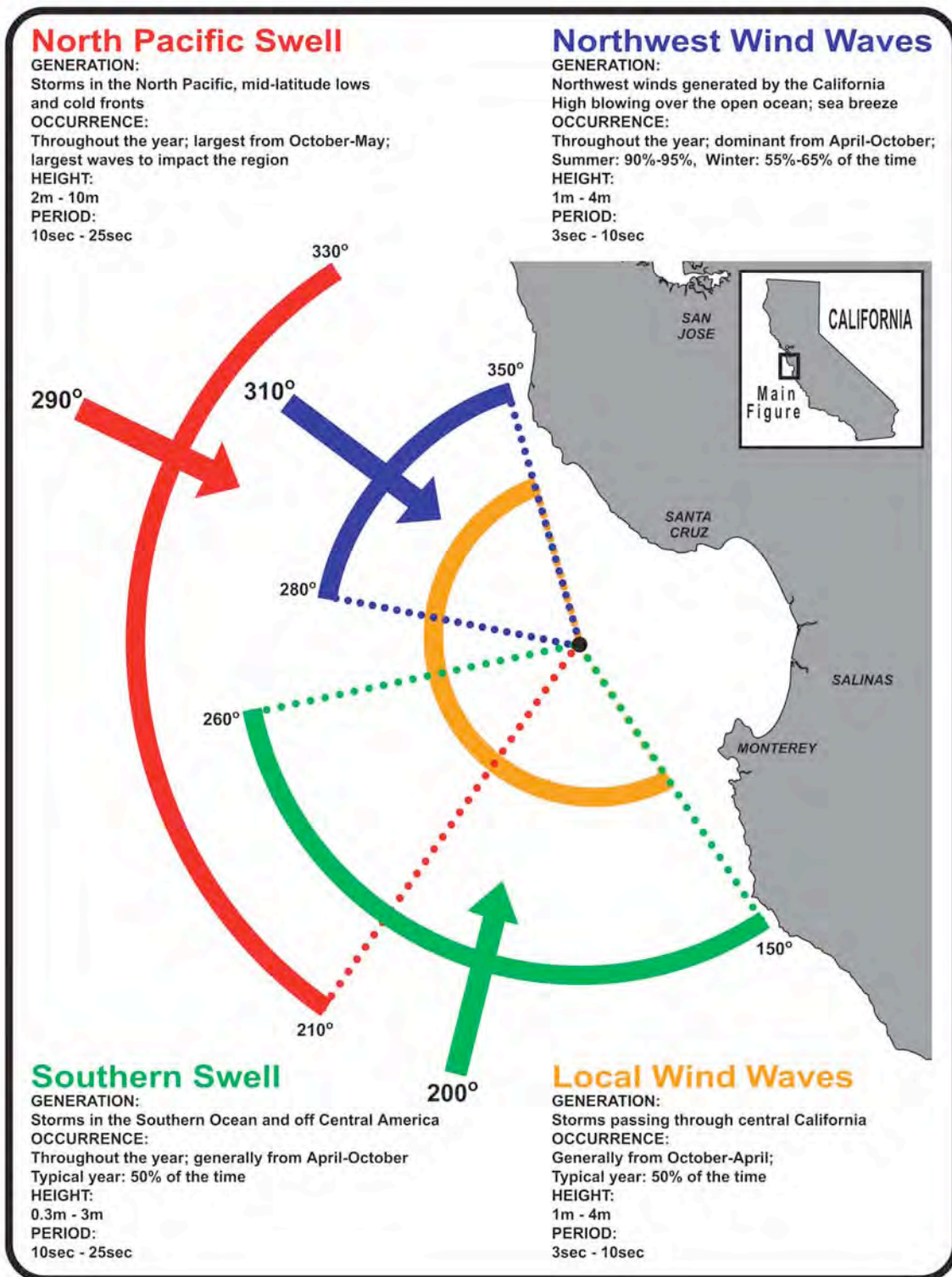


Figure 1.7: Major wave patterns impacting the Monterey Bay. This compilation was generated by analyzing almost ten years of hourly buoy data on wave height, period and direction, as well as wind speed and direction (Storlazzi and Wingfield 2005).

e. Erosion and Sand Supply in Southern Monterey Bay (SMB)

The interaction of waves with the shoreline of SMB serves to shape beaches and sculpt coastal dunes. Prevailing onshore winds prevent the seaward migration of dunes in this region; the main forcing on their development is wave erosion. The erosion of dunes by waves occurs more often in winter months, when beaches are narrow and storms are stronger and more frequent. Erosion in this region is highly episodic, occurring in steps when high tides coincide with large, storm-generated waves (Dingler and Reiss 2002). At these times, swash climbs up the beach and undercuts the base of the dune, causing the overlying sand to slump onto the beach where it is washed out with retreating waves and moved into the littoral system (McGee 1987).

A significant, but generally historical, human-induced change to the coastal environment in SMB has been the mining of sand from beaches and dunes. Exporting sand is a form of primary erosion and can potentially induce secondary erosion by reducing the sand supply to beaches down-coast in the littoral cell. Less sand moving along the coast can decrease beach widths, which allows waves to more readily attack back-beach dunes and erode the coast. In this manner, the removal of sand from the surf zone is the most important type of mining in relation to sand budgets. Sand that is within back-beach dunes has already been effectively taken out of the littoral system; therefore mining dune sand would have less of an impact on the littoral cell (Thornton et al. in press).

The sand in this region is of superior quality for numerous industrial uses, such as the manufacture of abrasives and stucco, and for water filtration (Griggs et al. in press). Mining started as early as 1906, with up to six different plants between Marina and

Seaside by 1972; these mining companies operated unregulated until 1968 when leases were issued and managed by the State Land Commission. The Army Corps of Engineers put additional regulations in place in 1974. Leases on all mining operations expired in the late 1980's and all mining of the surf zone was supposedly discontinued as of 1990. Mining of dune sand is still underway in Marina (Figure 1.8). While the current mining in Marina is not technically considered to be a loss of sand from the littoral system, questions have arisen as to whether the methods being employed there are extracting valuable beach sand. The operations of this plant should be investigated to further to ensure that they are collecting only dune sand that has no natural means for returning to the littoral system.



Figure 1.8: Sand mining operations in northern Marina, California. The company has dredged a lagoon from which they extract sand. Some argue that the lagoon actually traps beach material in addition to dune sand. See Figure 1.9 for location of mine. Aerial photograph taken in October 2004; copyright © 2002 Kenneth & Gabrielle Adelman (<http://www.californiacoastline.org/>).

Damming of coastal rivers is another anthropogenic mechanism by which sediment supply to the beach can be reduced, thereby exacerbating erosion of back-beach features. As hillsides in a watershed erode, fine sediment is carried down rivers in suspension and larger grains are transported by bouncing along the river bottom (referred to as bedload). In general, the stronger the flow of a river, the more sediment it can carry and the larger the grain size it can transport. When dams are placed on coastal rivers, the bedload gets trapped behind the dam, building up in the reservoir over time, instead of being carried out to the littoral system.

Beaches in this region are composed dominantly of medium-grained sand and, in northern Monterey Bay, rivers provide 75-90% of that littoral material (Best and Griggs 1991). In contrast, clay and silt particles that reach the coast are generally resuspended by wave action and carried offshore. Thus, when dams block bedload transport, only fine-grained sediment makes it down the river, which does not support beach development. Sand supply reduction from coastal dams is an issue for the health of many littoral cells along the California coast and removing dams could be an option for erosion management (Willis and Griggs 2003).

The impact of coastal dams is not always straightforward, and may warrant a case-by-case analysis. For example, a recent study found that there was a 33% reduction in the amount of sand reaching the SMB littoral system because of dams on the Salinas River (Willis and Griggs 2003). Yet, as the gradient of the Salinas River has lowered over the past several thousand years, its contribution of sand to the SMB littoral system has decreased naturally. Sand-sized material is transported down the gentle slopes of the lower Salinas River only during the heaviest storms, and much of that sand will get

deposited on the wide flood plain adjacent to the channel instead of being carried out to the coastal zone. Therefore, while a 33% reduction in Salinas sand supply seems considerable, the impact on SMB beaches may not be significant (Thornton et al. in press). In this case, erosion of coastal dunes, not river runoff, appears to be the major contributor of sand to the SMB littoral cell.

f. Land Use and Coastal Protection Structures

The coastal zone in SMB is relatively undeveloped, which is consistent with the inherent hazards of building in dynamic beach and dune environments (Figure 1.9). Many kilometers of the sandy shoreline and back-beach area are protected as state parks, including Marina State Beach, the new Fort Ord Dunes State Park, and Monterey State Beach. These long stretches are used primarily for recreation, including hiking, hang-gliding and picnicking; strong rip currents make swimming and surfing hazardous.

At present, there are a handful of structures built in the coastal zone that are being threatened by wave attack. These developments include a 196-room hotel built directly on the beach, a 172-unit condominium complex built on coastal dunes, and various drainage and sewer outfall pipes, each of which will be discussed in detail later in this report. Most of this construction took place in the 1960's and 1970's, a relatively quiet La Niña period, with few major storms. The ensuing El Niño events of the 1980's and 1990's caused extreme and unpredicted erosion, with several meters of coastal retreat at some isolated locations over the course of one winter (Griggs et al. in press). In response to these storms, owners of coastal developments and infrastructure were forced to place protective structures, or armoring, in front of their property to block wave energy and

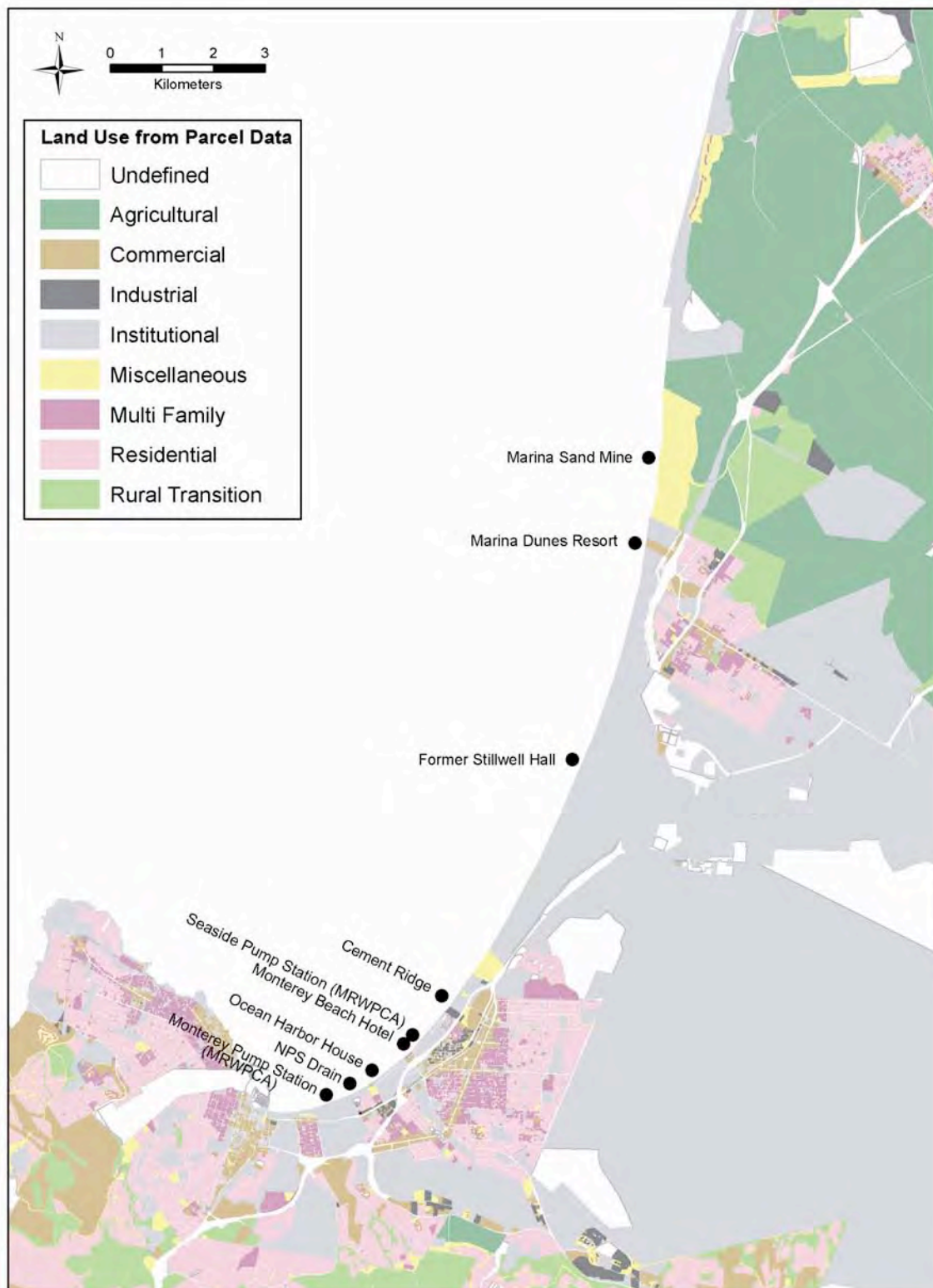


Figure 1.9: Generalized land use in southern Monterey Bay, adapted from Monterey County parcel data. Coastal development features, discussed in later in this report, are also highlighted.

slow down or halt erosion. Approximately 1 km between the Monterey Harbor and the mouth of the Salinas River is currently armored (Thornton et al. in press). Armoring of the shoreline, particularly in an area with high erosion rates, is an expensive and, quite often, an ultimately unsuccessful effort. The potential impacts of that armoring are discussed in a National Marine Sanctuaries Conservation Series Report entitled, “The Impacts of Coastal Protection Structures in California's Monterey Bay National Marine Sanctuary,” which can be downloaded at:

http://sanctuaries.nos.noaa.gov/special/con_coast/coast_study.html (Stamski 2005).

The population is growing in the southern Monterey Bay region, as is the desire to live and work on the coast. Creation of a comprehensive coastal erosion plan will be crucial in exploring options to manage coastal erosion beyond traditional armoring techniques, and in developing a system for improving coordination among agencies and jurisdictions involved in the permitting of coastal armoring structures. A long-term plan will also be essential in predicting when and where structures will be threatened by wave attack, and can be used to identify hazardous areas where construction should be regulated to promote sustainable development. The purpose of this report is to provide scientific background information on coastal erosion and armoring for southern Monterey Bay in support of the sanctuary’s Coastal Armoring Action Plan and the efforts of the Southern Monterey Bay Coastal Erosion and Armoring Workgroup.

II. COASTAL EROSION DATA

a. Erosion Rates

The most common method of assessing coastal erosion is to determine an erosion rate, which is generally the amount of linear coastal retreat (perpendicular to shore) that has taken place over a given period of time. These rates are essential for establishing coastal land use planning measures, such as setbacks. Yet, obtaining site-specific erosion rates is not a trivial task. One of the most robust methods for calculating erosion rates is to digitally compare historical aerial photographs (a technique referred to as stereo-photogrammetry). A comparable shoreline feature is digitized on each set of photographs and the difference between them, divided by the number of years spanning between the photographs, yields the erosion rate (reported as a unit length per unit time (e.g., meters per year (m/yr))). There are many ways to analyze aerial photography, which involve differing degrees of accuracy and precision that should be quantified.

More emergent techniques include the use of LIDAR (LIght Detection And Ranging), a method using airborne scanning laser surveying, and GPS (Global Positioning System) surveys, which determines coastal positions from satellites (see Smith et al. (2005) for a more detailed discussion of these techniques). These data sets can be expensive and historical photographs may not be available. In addition, a substantial amount of training is often necessary to correctly analyze and interpret the data with scientifically reproducible results.

Controversy in coastal planning can arise because different, yet valid, erosion rates can be calculated for a single stretch of coast. The key factor in these discrepancies is usually the time interval over which the analysis was made. For example, Geologist A calculated a retreat rate of 0.2 meters per year (m/yr) by comparing aerial photographs from 1965 and 1975. Geologist B used aerial photographs from 1980 to 1990 and calculated a rate of 1.5 m/yr. Both geologists calculated erosion rates with the same, reproducible method over a period of ten years; yet, because the time interval used by Geologist B included one of the most severe El Niño events in recent history, his/her erosion rate is much higher.

In the example above, a 50-year setback distance would be 10 meters for Geologist A and 75 meters for Geologist B. Given the exorbitant costs and low availability of coastal parcels, this discrepancy could dictate where, and even if, a building is constructed. Thus, it is imperative that a representative time interval is assessed in erosion rate calculations to derive long-term average retreat. Yet, even with a long-term rate, the episodic and somewhat unpredictable nature of coastal erosion suggests that erosion rates should only be used as guidelines in coastal planning, not as irrefutable facts.

In a recent consulting report produced for the Monterey Regional Water Pollution Control Agency (MRWPCA) by Philip Williams and Associates, Ltd. (PWA), a distinction was made between *short-term* or *event-based* erosion versus *long-term* erosion (PWA 2004). Short-term erosion occurs in a single event or series of events (e.g., an El Niño winter), the mechanisms of which include not only direct wave impact, but also flooding, undermining by scour, and removal of overburden (in the case of buried pipelines). Long-term erosion was defined by PWA as the, “landward migration of the

shoreline over the 50-year planning horizon.” The difference between the short and long term rates was drastic. For example, over the 1997-98 El Niño winter, an erosion rate of 13.0 meters/year (42.6 feet/year), was reported at Fort Ord, compared to a long-term rate of 1.1 meters/year (3.6 ft/yr). Erosion rates utilized by PWA were derived predominantly from work of L. A. Egley (short-term rates) and J. Conforto Sesto (long-term rates), both graduate students at the Naval Postgraduate School (NPS); Dr. Edward Thornton of NPS has compiled these studies with others in a comprehensive manuscript that will be described in detail later in this report.

Using these two types of rates, PWA classified the risk of a series of MRWPCA facilities. High risk facilities were those that: 1) would be located within the zone that could be significantly impacted by short-term (or event-driven) erosion; or, 2) would be located seaward of the predicted 50-year shoreline, as determined via long-term erosion rates. This report was able to assess risk for important infrastructure relative to erosion that occurs on both the short and long term, a methodology that could be valuable for MBNMS coastal plans.

Studies of coastal retreat in southern Monterey Bay, such as the Philip Williams and Associates report described above, are a testament to this potential variability in erosion rates. The analyses described herein have different scopes and degrees of scientific accuracy, and were carried out by: the University of California at Santa Cruz (UCSC), California State University in Monterey Bay (CSUMB), the Naval Postgraduate School (NPS), the United States Geological Survey (USGS), and Haro, Kasunich and Associates, Inc. At this point in time, the researchers who completed these studies are the key points of contact for questions on regional erosion (see Appendix 1). An assessment of all the

available data is intended to assist sanctuary planners in understanding how erosion changes along this sandy stretch of coast.

b. Living with the Changing California Coast

In 1985, Dr. Gary Griggs, professor of Earth Sciences at UCSC, and others published a book entitled, *Living with the California Coast*, an exhaustive compilation of hazards and resources for the state's entire shoreline (Griggs and Savoy 1985). An updated edition, *Living with the Changing California Coast*, will be published in 2005, including a set of maps depicting coastline geomorphology, erosion rates, and relative hazard zones along the coast (Griggs et al. in press). The book is intended to be a descriptive guide for the public; yet the data on erosion and the historical narratives are a valuable resource for regional planners as well.

Local experts provided information to establish hazard zones and contributed detailed descriptions of geology, oceanography and development history in each coastal region. The erosion rates were collected from a wide variety of technical consulting reports and scientific studies; these rates have been partially updated since the 1985 edition. From a regional analysis perspective, it is difficult to compare the various retreat data because many methods and time periods were utilized to calculate the rates. Yet, the rates and hazard zones documented in *Living with the Changing California Coast* provide important overall trends for shoreline change.

Just south of the mouth of the Salinas River mouth, retreat rates were reported at 41 centimeters per year (cm/yr) (1.3 feet per year (ft/yr)) and 86 cm/yr (2.8 ft/yr) (Figure 2.1). Low, active dunes and a lagoon, formed by the Salinas River, back this area (Figure

1.4). Further south at Marina State Beach, near the end of Reservation Road, erosion increase dramatically, with rates of 163 and 155 cm/yr documented (5.3 and 5.1 ft/yr, respectively). A low, narrow strip of active dunes is situated immediately adjacent to Marina State Beach, with older and higher dunes further inland. The stretch from the mouth of the Salinas River to approximately the southern end of Marina State Beach was deemed a “moderate risk” area for coastal hazards.

A 9-km long “high risk” hazard zone begins at the north end of Indian Head Beach and extends south to approximately Ocean Harbor House condominiums, as demarcated by the *Living with the Changing California Coast* authors. This region is classified as hazardous because the coast receives the most direct, intense wave energy at that location, the beach is relatively narrow and the high, unconsolidated dunes are easily eroded. This is reflected in the extreme erosion rates reported for this region. In proximity to the former Stillwell Hall site (Fort Ord), an erosion rate of 244 cm/yr was recorded (8.0 ft/yr). Further south, at the beaches of Sand City, slightly slower rates of 122 and 188 cm/yr (4.0 and 6.2 ft/yr, respectively) are recorded. The backshore in this section is composed of active dunes and, in general, the beach is slightly wider than the beach at Fort Ord. A more moderate rate of 61 cm/yr (2.0 ft/yr) was calculated near the Monterey Beach Hotel seawall.

Approximately halfway down Del Monte Beach, the *Living with the Changing California Coast* hazard level drops from high risk to moderate risk, just southwest of the Ocean Harbor House condominiums. From this point to the Monterey Harbor north breakwater, the beaches are slightly wider than those in the more hazardous zone to the north and the backshore area consists of lower dunes (Figure 1.4). The lowered hazard

status is reflected in lower erosion rates as well, with rates of 28 to 30 cm/yr (0.92 to 0.98 ft/yr, respectively) near Monterey State Beach, just east of the breakwater.

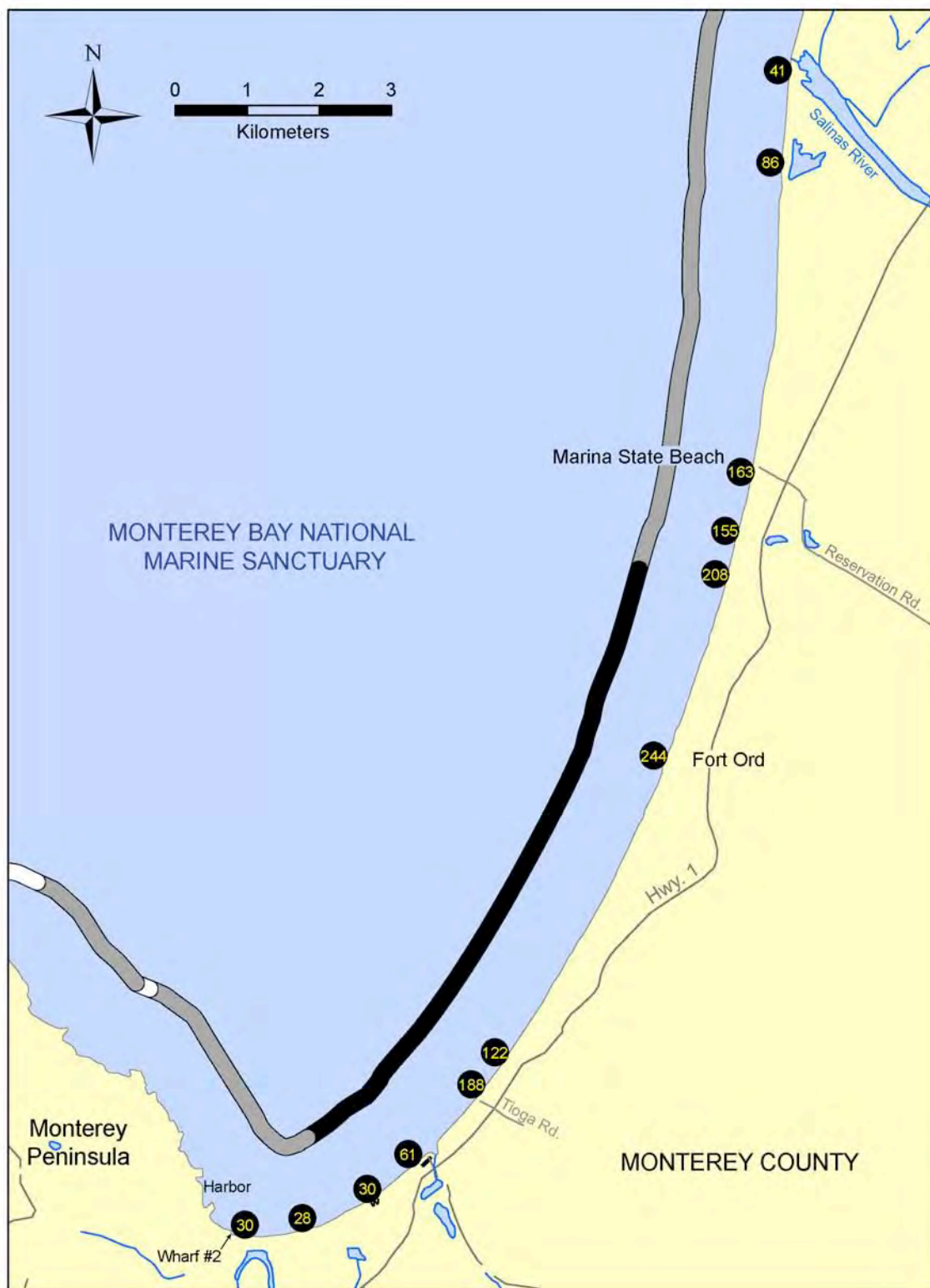


Figure 2.1: Coastal erosion rates, reported in centimeters per year (black circles), and relative hazard zones (black=high risk, grey=moderate risk, white=low risk) as documented in *Living with the Changing California Coast* (Griggs et al. in press). For reference, 100 cm = 3.28 ft.

c. Southern Monterey Bay Critical Erosion Sites (CSUMB study)

A recent study from the California State University, Monterey Bay (CSUMB), utilized a combination of historical aerial photographs and GPS surveys to assess erosion at four armored, or historically-armored, stretches of the SMB coast (Gref 2005). The research was completed as part of an undergraduate senior capstone project and, as of the completion of this report, has yet to be peer-reviewed for a scientific journal. Dr. Douglas Smith, professor of Earth System Science and Policy at CSUMB, supervised the project. The data are included here because of their relevance; Smith et al. (2005) provide a robust discussion of the methodology and results for this analysis as well.

Gref digitized the coastline on historical aerial photographs from 1976, 1986 and 2001; the intersection of the cliff or dune with the active beach was chosen to represent the coastline. In 2004, this datum was mapped via GPS surveys. The four years of data were digitally compared and erosion rates were determined as the amount of coastal retreat from 1976 to 2004, along transects across the beach, perpendicular to the shoreline (shore-normal). An average rate was then calculated for each site from the various transects.

For Marina State Beach, at the end of Reservation Road, Gref calculated rates along 10 shore-normal transects and found a total retreat rate of 150 cm/yr (4.9 ft/yr) (Figure 2.2). Near the former Stilwell Hall site, on Fort Ord coastal property, 14 transects were averaged to yield an erosion rate of 200 cm/yr (6.6 ft/yr). Erosion across 14 transects for the 4 years of measurements was 160 cm/yr (5.2 ft/yr) near the Monterey Beach Hotel in Seaside. Rates were calculated for the areas adjacent to, not in front of, the hotel's seawall, because the seawall has fixed the coastline since 1968. Finally, Gref determined

erosion rates along 6 transects in front of, and adjacent to, the Ocean Harbor House condominiums, calculating an average retreat rate of 70 cm/yr (2.3 ft/yr). Riprap placed in front of the condominiums since 1984 has slowed erosion; therefore natural coastline retreat rates at this site may actually be greater than 0.7 m/yr.

The rates calculated by Gref support the general patterns documented by other researchers. Erosion has been most severe at Fort Ord, with Marina State Beach and Monterey State Beach having slightly less retreat. Yet across the region, coastal erosion creates hazardous conditions, with average rates from 2.3 to 6.6 feet per year. The role of coastal protection structures (armoring) is very important in the areas highlighted by Gref and will be discussed in detail later in this report.



Figure 2.2: Coastal erosion rates reported in centimeters per year (purple circles), as determined by Gref (2004) of CSUMB. Rates were calculated over the years 1976-2004. Distances from Wharf #2 in Monterey are in kilometers (black triangles). For reference, 100 cm=3.28 ft.

d. Southern Monterey Bay Dune Erosion (Naval Postgraduate School)

Dr. Edward Thornton, of the Naval Postgraduate School (NPS) in Monterey, has compiled the one of the most comprehensive coastal erosion studies to date for the southern Monterey Bay (in press). The paper will most certainly become a valuable resource for planners in this erosion-prone region. Five graduate theses and NPS studies were combined to create a coherent, long-term assessment of coastal retreat and dune erosion from the Salinas River mouth to the Monterey north breakwater (Wharf #2); the region of interest selected by the sanctuary for this report was partially based on the area analyzed in the Thornton et al. study.

Statistically-valid average retreat rates were reported for six locations between Wharf #2 and the Salinas River mouth using a variety of methods. From 1940 to 1984, dune recession (defined as the retreat of the cliff-top edge of the dune, or the seaward extent of possible land use) was calculated using stereo-photogrammetry. A detailed LIDAR survey was utilized to quantify erosion that occurred over the 1997-1998 El Niño winter. Finally, a walking survey was completed in 2004 using a backpack-mounted kinematic GPS system for precision location of the dune cliff edge. The 1984 aerial photographs were re-analyzed to allow accurate comparison with the more recent LIDAR and GPS datasets.

Thornton et al. presented their data in several ways that may be useful for land use planning. Results are split up into two time periods, 1940 to 1984 and 1984 to 2004, based on the cession of swash-zone sand mining in the 1980's (see Section I-e). An estimated 128,000 m³/yr of sand was removed from the littoral system between 1940 and 1984 because of mining, which is nearly 50% of the total annual volume of sand eroded

from dunes over the same time period (270,000 m³/yr). This interval also included two El Niño events (1956-57 and 1982-83) and linear coastal erosion rates ranged from 30 to 193 cm/yr (1.0 to 6.3 ft/yr). Erosion was most severe near Fort Ord, with slightly more subdued erosion to the north and south (Figure 2.3). Smith et al. (2005) also provide a comprehensive evaluation of this study in the context of shoreline management.



Figure 2.3: Coastal erosion rates in centimeters per year (blue circles) for the time period 1940-1984, as documented by Thornton et al. (in press). Distances from Wharf #2 in Monterey are in kilometers (black triangles). For reference, 100 cm=3.28 ft.

Despite intense erosion documented during the 1997-98 El Niño winter, when 1,820,000 m³ of dune sand was lost, erosion rates for the 1984 to 2004 time period were lower than those reported from 1940 to 1984. From 1984 to 2004, coastal retreat was highest (143 cm/yr or 4.7 ft/yr) just south of Reservation Road, at Marina State Beach. Three erosion measurements in the middle of the study region, from a site approximately 1.5 km south of the former Stillwell Hall locale to Sand City Beach, ranged from 70 to 83 cm/yr (2.3 to 2.7 ft/yr). Two relatively low erosion rates were documented in the southern end of the study area: 26 cm/yr (0.85 ft/yr) near the Monterey Beach Hotel and 11 cm/yr (0.46 ft/yr) 0.9 km east of Wharf #2 (Figure 2.4).



Figure 2.4: Coastal erosion rates in centimeters per year (blue circles) for the time period 1984-2004, as documented by Thornton et al. (in press). Distances from Wharf #2 in Monterey are in kilometers (black triangles). For reference, 100 cm=3.28 ft.

According to Thornton et al., erosion rates appear to have decreased since sand mining was stopped. The rate of erosion has slowed more in the region south of Sand City. This may be because sand mining had been more intense in Sand City (81,000 m³/yr) than in Marina (47,000 m³/yr), therefore the relative slowing of erosion would be greater in the region downcoast of the former. Thornton et al. emphasize that, while removal of sand by mining may have impacted retreat rates to some degree, wave erosion is still the overriding erosion mechanism in SMB.

Planners will have to decide what their goal is when using the data presented by Thornton et al: if they want to compare this study with other studies that go back prior to 1984, it appears that an averaged (1940-2004) rate would be the most appropriate; if they want to get an idea of what current coastal retreat rates are, the 1984-2004 rates may be relevant. Yet Thornton et al. stress that caution should be taken when relying upon just the 1984-2004 rates because only 4 data sets were used in the calculation. Given the episodic nature of dune erosion in this region, a more conservative estimate of erosion would come from more robust, longer-term data (e.g., 1940-2004), despite the cessation of sand mining (Figure 2.5).



Figure 2.5: Coastal erosion rates in centimeters per year (blue circles) for the time period 1940-2004, averaged from Thornton et al. (in press). Distances from Wharf #2 in Monterey are in kilometers (black triangles). For reference, 100 cm=3.28 ft.

e. USGS National Assessment of Shoreline Change

The United States Geological Survey (USGS) has a substantial project underway to calculate consistent, long-term erosion rates for all open coasts of the United States. Dr. Cheryl Hapke and Dave Reid, M.S., have been the lead west coast scientists working on this project entitled: *National Assessment of Shoreline Change: Historical Shoreline Changes and Associated Coastal Land Loss Along the Sandy Shorelines of the California Coast* (NASC) (Hapke and Reid in press). There are two main components of coastal retreat on the west coast: sandy shorelines and cliffs. The erosion rates for these distinct coastal landforms are calculated using different methods; together they provide a coherent picture of erosion. The sandy shoreline erosion rates will be completed first, followed closely by rates for cliffs. The NASC project is unique because it assesses erosion on a large scale, using consistent methods with quantifiable error. This will be especially useful for the sanctuary, which encompasses 276 miles of coastline.

The area of interest for this report, southern Monterey Bay, is entirely composed of sandy shoreline; thus, the NASC erosion rates may become available to MBNMS staff as early as spring 2005. Official public release of the NASC data will occur only after all relevant metadata and corresponding text has been compiled and reviewed as a USGS Open-File Report, most likely late in 2005. Due to liability issues, the NASC data may be used only for regional characterization and are not intended to be used for regulatory purposes. Sanctuary staff can work with the USGS to determine ways to use the rates for developing policies, while keeping within the bounds of their liability disclaimer.

USGS retreat rates for the 18 km stretch of beach from the Monterey Harbor to the mouth of the Salinas River will be reported continuously at 50 m intervals. Four datasets were used to derive these rates, spanning over 120 years:

- 1) The earliest data were derived from National Ocean Service (NOS) T-sheets, historic survey maps created from the 1850s to the 1880s. The original maps have been scanned into a digital format and correlated with real-world latitudes and longitudes, a process known as georectification. Because of their age and the limitations of technology used to do the original mapping, accuracy of erosion rates derived from these maps is considered to be +/- 0.2 meters per year (m/yr); this error will be re-evaluated after the NASC processing is complete.
- 2) T-sheets from the 1930s were also used in the NASC study; these maps have similar limitations as described above (1).
- 3) Digital topographic maps, originally derived from aerial photography, were used to map the shoreline between the 1950s and the 1970s. These maps are also called Digital Raster Graphics (DRGs). DRGs generally have less error than T-sheets, meaning the difference between the digital map positions and real-world locations is smaller with DRGs.
- 4) The most recent dataset used in the NASC study was a 1998 LIDAR survey, which has excellent geospatial control and accuracy.

For each dataset, a shoreline was digitized in a GIS based on the available imagery (T-sheet or DRG); for the LIDAR imagery, the shoreline was determined by a computer program. Once all four shorelines were created in a digital format, a rate of change was calculated by linear regression at 50-meter intervals along the coast. This provides a high

density of coastal retreat data, representing the longest possible time period, given availability of historical maps and imagery. In addition, retreat rates for different time periods can also be compared (e.g., 1880's to 1970's vs. 1970's to 1998). It is important to note that this sandy shoreline analysis assesses retreat of the entire coastline, not beach width change. In each set of imagery, a distinct shoreline is chosen that represents the same geomorphic position at each time interval analyzed. The selection of this shoreline feature is unrelated to how wide or narrow the beach is at that point in time.

f. Sand City Coastal Recession Evaluation (Haro, Kasunich and Associates, Inc.)

In 2003, Haro, Kasunich and Associates, Inc. (HKA) completed a comprehensive coastal recession evaluation for the city of Sand City, California (HKA 2003a). The purpose of the report was to review and update a 1989 shore erosion study for the area and to establish 50-year setback distances based on this revision. Retreat of the entire shoreline of Sand City, situated in between Seaside and Fort Ord, was established using 7 sets of maps and aerial photographs spanning from 1933 to 2003. While it appears that stereo-photogrammetry was not part of the methodology, HKA did use digital analysis that allowed them to match up features on each sets of photos for accuracy. There is no error analysis provided in the HKA report.

HKA determined that the average, long-term shoreline retreat rate for Sand City was 94 cm/yr (3.1 ft/yr), based on data from 1933 and 2003. The analysis was further narrowed to examine dune retreat rates, which, in theory, should be equal to the shoreline retreat rate on long time scales, for a section of coast from Bay Avenue to Tioga Road. According to these analyses, the bottom of the dune has retreated at an average rate of 73

cm/yr (2.4 ft/yr) in this region. HKA suggested that the discrepancies in these two rates are due to: an abnormally intense erosion event that affected the shoreline position in 2002; and differences in the shoreline mapping techniques between the 1933 (which was mapped as an average shoreline position) and 2003 (which shows the shoreline at a snapshot in time from a photograph). The erosion rate for the Sand City area is therefore assumed to be 73 cm/yr, a value which was used to establish 50 year setback locations in the HKA report. In addition, HKA recognized that cession of sand mining may cause a change in coastal erosion, presumably a decrease in the rate, but their cursory analysis of this effect was not sufficient enough to warrant a decrease in the erosion rate of 73 cm/yr.

g. Regional Synthesis of Available Erosion Data

Combining all available erosion rates described above serves to highlight the general erosion trends in this area (Figure 2.6). Rates are highest near Fort Ord and generally dissipate to the north and south. This is in agreement with the overall oceanographic patterns, which focus wave energy in the Fort Ord region, and with the extreme erosion witnessed around the former Stillwell Hall (see Figure 4.1). This trend is also consistent with preliminary results of the USGS *National Assessment of Shoreline Change* project (Reid 2005). It is important to note that, because of the diversity of time scales and methods by which erosion rates were measured in these various studies, Figure 2.6 should be used only to highlight general erosion patterns and as a guide to focus future erosion hotspot analyses.

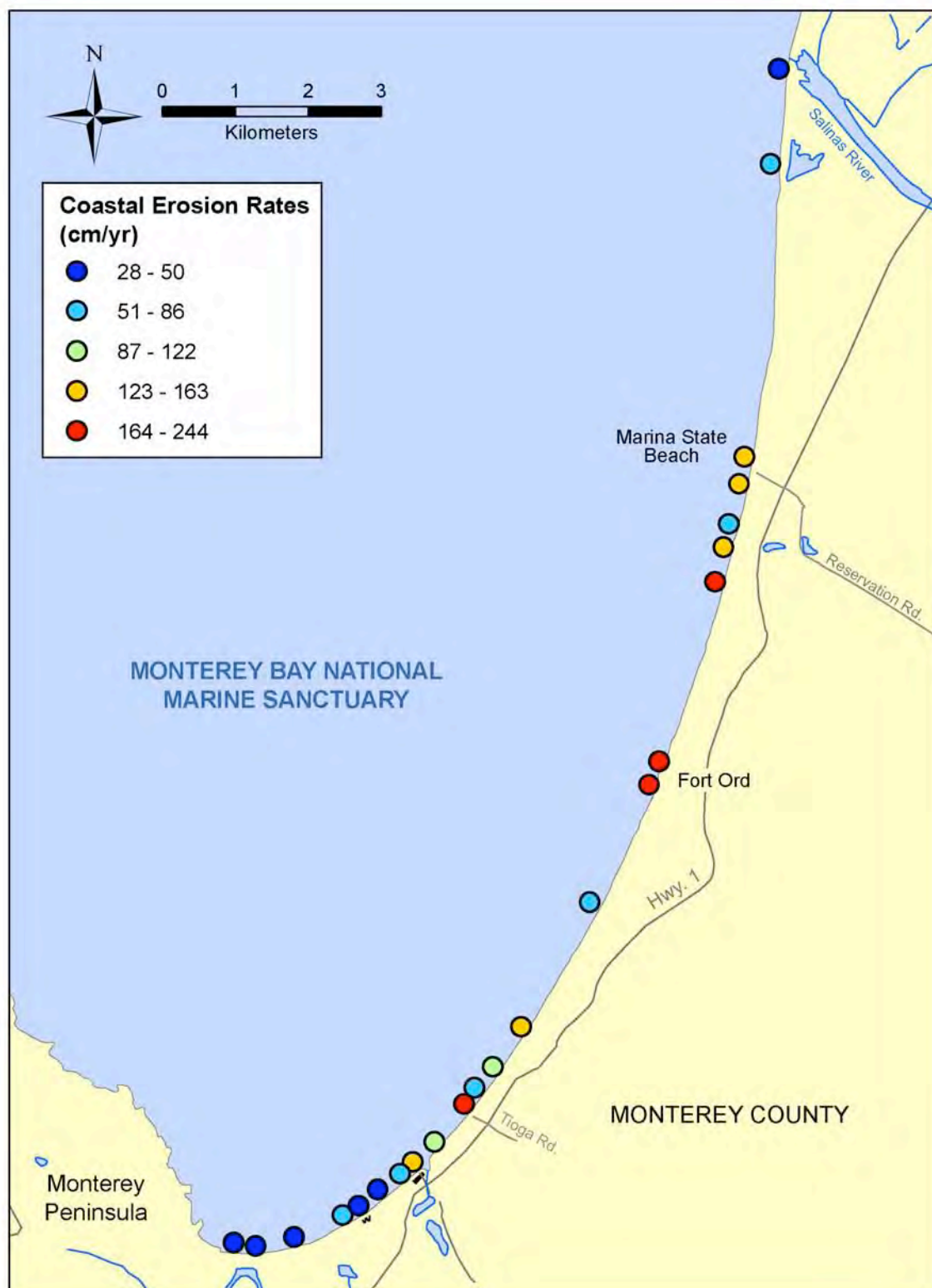


Figure 2.6: Coastal erosion rates for the study area, combining all available data (HKA 2003a; Gref 2005; Griggs et al. in press; Thornton et al. in press). Warm colors indicate more intense erosion than cool colors. For reference, 100 cm = 3.28 feet. See Appendix 2 for erosion rate data.

III. BEACH WIDTH CHANGE

All of the erosion studies described above assess overall retreat of the shoreline by measuring change in the location of a feature at the landward margin of the beach over time. Beach width change is a related, yet distinct, process. Seasonal changes in beach width due to changes in wave dynamics (Figure 1.7) are apparent to even the casual observer; beaches in southern Monterey Bay are generally narrow and steep in winter, yet wide and gently sloping in summer. Beach width can also change because of shifts in sand supply, either from natural or anthropogenic processes, such as sand mining, armoring, or damming coastal rivers. The relationship between beach width and coastal erosion is elucidated when beaches become narrower allowing waves to more readily attack the back-beach dunes, cliffs or bluffs, thereby increasing the rate of coastal retreat. Narrowing of beaches is also significant because of its impact on recreation and tourism. Thus, an understanding of the long-term beach width changes in southern Monterey Bay is important to this analysis of coastal erosion.

A recent USGS-UCSC study by David Reid, M.S., calculated beach width changes across the entire Monterey Bay, with aerial photography and NOS T-sheets spanning 70 years (2004) (see section II-e of this report for an explanation of NOS T-sheets). This long-term study provides an important understanding of trends in beach width, transcending seasonal fluctuations. Through his analysis, Reid showed that beaches in Monterey Bay are remaining approximately the same width over time; the system appears

to be steady-state. Thus, while the overall shoreline has retreated over the past 70 years, beach widths have remained somewhat constant. Notable exceptions occurred when the back-beach landform (*e.g.*, a dune or cliff) had been fixed by coastal armoring. In these instances, shoreline retreat was prevented by the coastal armor and beaches narrowed in front of the structure, a process known as passive erosion (see Stamski (2005) for a description of this and other impacts of coastal armoring). According to Reid, the narrowing of beaches caused by fixing the cliff or dune with armor appears to extend beyond the edges of the structure, decreasing beach width on adjacent beaches as well.

Ironically, the erosion of coastal dunes, which occurs during times when beaches are narrow, is the dominant sand supply mechanism for beaches of southern Monterey Bay. A positive feedback relationship appears to exist between erosion and beach stability in this region. Over time (*e.g.*, 70 years), beach width has remained in steady-state, despite, and in fact because of, erosion of coastal dunes. The only time this system seems to be perturbed is when armoring prevents coastal retreat and beaches narrow permanently due to passive erosion. Thus, any attempts to prevent coastal erosion in this region will likely decrease beach width over the long-term, which may in turn increase the rate of dune erosion.

IV. ALTERNATIVES TO MANAGE COASTAL EROSION

Given the extreme erosion rates in southern Monterey Bay, progressive planning is essential for all parties involved in management of the coastal zone. The alternatives to

cope with coastal erosion are numerous and new technologies are continually being developed. The most common approaches are discussed herein to provide sanctuary planners with information about how different management techniques may influence sanctuary resources; see Smith et al. (2005) for additional management options and suggestions.

a. Hazard Avoidance

The hazards associated with coastal retreat can theoretically be avoided if buildings and infrastructure are set back from the shoreline enough to ensure that erosion will not threaten the structures within their projected lifespan. For many coastal planners, including the California Resources Agency (2001), the California Coastal Commission (2005), and the City of Monterey Planning Department, this has been the primary, preferred alternative for zoning of new development. Unfortunately, establishment of adequate setbacks or rezoning are often not possible for existing structures, so other alternatives must be explored.

b. Planned Retreat or Demolition

When a structure is threatened by coastal retreat, property owners can demolish the building or relocate it landward, either on the same parcel or on an entirely different inland location. Neither of these choices is ideal for property owners, though they should be considered as serious, long-term solutions to this inevitable dilemma, given the rising costs of other alternatives (Griggs 1986). For example, Stillwell Hall, built in the 1940's as

the Fort Ord soldier's club in Seaside, California, was torn down in March 2004 because the cost of both coastal armoring and relocating were too high (Figure 4.1).



Figure 4.1: The former Fort Ord soldier's club, Stillwell Hall, was demolished in 2004 because attempts to save the structure from collapsing into the ocean by emplacing riprap in front of the dunes proved to be too costly and ineffective. Left photo taken August 2003, prior to demolition. Right photo taken October 2004 after removal of structure and all riprap. Photographs copyright © 2002 Kenneth & Gabrielle Adelman (<http://www.californiacoastline.org/>). See Figure 5.1 for location.

c. Increasing Sand Supply to Beaches

i. Removal of Coastal Dams on Rivers

Dams on coastal rivers can severely limit sand supply along some stretches of the California coast (Willis and Griggs 2003). While this may not be an effective remediation technique for southern Monterey Bay, as described in section I-e of this report, this option should be considered for other littoral cells where coastal dams are preventing significant amounts of sand from reaching beaches. The State of California has recognized the need for a more holistic approach to sediment supply issues and is working to restore balance to littoral cells through the California Coastal Sediment Management Master Plan (CCSMW 2004).

ii. Beach Nourishment

Beach nourishment has been highlighted recently as a solution to coastal erosion; proponents of this alternative maintain that increasing beach width, by physically adding sand to a beach, buffers wave energy and slows retreat rates, while adding recreational benefits by augmenting beach width. Federal, state, and local government agencies are pursuing this method as a way to protect property from erosion damage, including the California Resources Agency (2001). The costs are generally very high and the net, long-term benefits of beach nourishment will vary greatly depending on local conditions (Leonard et al. 1990).

A survey of west coast beach nourishment projects determined that only 27% survived more than 5 years and 18% lasted less than 1 year (Leonard et al. 1990). In some cases, sand that was placed on a beach during summer was completely washed away the following winter. This is not unexpected given the high littoral drift rates that characterize most of the coast of California. A cost-benefit analysis of proposed nourishment projects should include site-specific evaluations of littoral budgets. In addition, the availability of an appropriate, cost-effective sand source and potential interference between beach users and sand transportation equipment should be addressed.

As mentioned earlier, there is evidence that lateral sand transport rates are low in the region and that the dominant transport mechanisms is offshore movement by rip currents (Smith et al. 2005; Thornton et al. in press). Thus, most of the sand eroded from beaches and dunes is being carried off onto the continental shelf, rather than being carried downcoast to nourish beaches. Artificially adding sand to beaches would likely be ineffective at building beaches in the littoral cell over more than one winter. Focused

studies, such as those using tracers to track the patterns and volumes of sand transport downcoast, may constrain the likely success of a beach nourishment project in southern Monterey Bay.

iii. Groins

Beach nourishment projects may involve engineered coastal structures, such as groins, to retain sand on a target beach. A groin is essentially an artificial headland, built jutting out into the nearshore zone, perpendicular to the shoreline. Sand traveling downcoast gets trapped behind the groin, widening the beach upcoast of the groin. In many cases, a series of groins (referred to as a “groin field”) are constructed to trap sand in pockets along a coast. By design, groins are situated both above and below the mean high tide line and would necessitate a permit from the sanctuary. The impacts of groins would be similar to those for coastal armoring, as described by Stamski (2005) and Griggs (in press), with even further influence on nearshore hydrodynamics and biology.

d. Offshore Breakwaters or Artificial Reefs

Most options for management of erosion involve alteration of the coastal zone, such as construction of seawalls against cliffs or depositing sand on the beach. Offshore breakwaters (or artificial reefs) are one way to avoid this coastal encroachment.

As a wave approaches the coast and the bottom shallows, the wave begins to feel friction with the seafloor. This slows the wave down, causing the wavelength (length from wave crest to wave crest) to decrease and the wave height to increase. Eventually, the wave will become too high to retain its shape and the wave will “break.” In SMB,

waves generally break right on or close to the beach, where depths are very shallow. The breaking waves are able to wash up the beach and, if conditions are right, coastal dunes and bluffs can be eroded. An offshore breakwater is engineered to create a shallow area away from the coast that will force waves to break. Wave energy is then drastically dissipated by the time it reaches the coast, thereby reducing dune erosion behind the breakwater.

The impacts of offshore breakwaters are not well documented, but the inferred influences are varied and may be severe. Primarily, offshore breakwaters involve an intense alteration of the seabed, necessitating a sanctuary permit. The breakwater would represent a change in habitat that could alter biological community dynamics in the region. During the construction phase, sessile organisms could be smothered and other plants and animals could be harmed by increased suspended sediment. By their nature, breakwaters change local oceanographic patterns, with implications for littoral drift, flow regimes, and wave dynamics. The migration patterns and behavior of organisms may be impacted by such changes to coastal hydrodynamics.

The location and angle of the breakwater must account for variations in regional wave direction and strength (Figure 1.7). Under some oceanographic scenarios, waves may bypass the breakwater, translating wave energy to the coast. Hence, the design and continued maintenance of offshore breakwaters requires significant engineering and impact assessment. As with many of these erosion management alternatives, the impacts and benefits need to be studied and weighed on a case-by-case basis.

e. Coastal armoring

By far the most popular option to manage shoreline retreat in California has been the construction of coastal protection structures (also referred to as coastal armoring). Approximately 10% of California's coastline is currently armored. The costs of armoring can be significant; millions of federal, state, and private dollars have been expended annually on shore protection, which can cost anywhere from \$1800 to \$7600 per linear foot of coast (Griggs in press).

Armoring varies widely in type of material, degree of engineering, and relative success in preventing coastal erosion and providing property protection (Griggs and Fulton-Bennett 1988). Riprap and seawalls are the most common armoring structures used in central California: riprap can be defined as any large (1 to 6 ton) rocks, or other hard material, used for coastal protection, with varying degrees of engineering; seawalls are continuous, rigid structures with vertical or concave faces. To clarify a common misconception, it is important to note that armoring is emplaced to protect buildings and infrastructure, not beaches (Kraus and McDougal 1996). Groin fields and beach nourishment are the common methods by which beaches are expanded, both of which are fundamentally different than armoring, which is constructed to halt erosion of cliffs, bluffs, or dunes that have buildings behind or on top of them, or to protect a building built on the backshore.

As of 1998, 24.3 km (15.1 miles) of the sanctuary's coastline have been armored (Griggs et al. in press). Various physical and biological impacts of coastal armoring may affect the resources of the sanctuary both directly and indirectly. Most coastal protection structures are placed above the high tide line, the official boundary of the sanctuary; yet

some influences of armoring may impinge on the marine realm, and continued sea level rise and the accompanying coastal retreat will force many of these structures below the high tide line over time. The sanctuary recognized the significance of protection structures on the shoreline and has identified it as a critical issue in the Coastal Armoring Action Plan of the Joint Management Plan.

The impacts of coastal protection structures are of great concern to local governments, private property owners, and the public. The most commonly recognized affects of armoring are: visual effects, placement loss, access issues, loss of sand supply from eroding cliffs, passive erosion, and active erosion. In addition, there are potential impacts to the biological communities that utilize the coastal zone. These impacts are explained in detail in a recent National Marine Sanctuaries Conservation Series report (Stamski 2005).

f. Other Alternatives to Investigate

The following structural and non-structural responses to coastal erosion have been brought up at preliminary working group meetings and should be explored in greater detail as this process moves forward.

Site-specific structural responses:

- Seacave plugs
- Creation of a river delta
- Kelp forest restoration
- Jetty design modification (Moss Landing)
- Beach scraping (sacrificial berm)

Site-specific non-structural responses:

- Groundwater control
- Beach de-watering
- Vegetative
- Cobble berm

Other alternatives:

- Rubber dam
 - Floating reef (wave energy dissipation)
 - Inter-littoral cell transfer
 - Dune nourishment
 - Perched beach
-

V. CRITICAL EROSION SITES

Across the Monterey Bay region, coastal armoring has been the preferred solution to deal with coastal erosion. Yet, unlike the northern half of Monterey Bay, the southern coastline has relatively little development that has required emplacement of coastal armoring. There are a few notable exceptions that are referred to herein as “critical erosion sites” because erosion has been intense enough to threaten buildings or infrastructure within their lifespan. Figure 5.1 shows the distribution of coastal development from the mouth of the Salinas River to Wharf #2 in Monterey. The following is a brief description of the armoring in each of these locations.

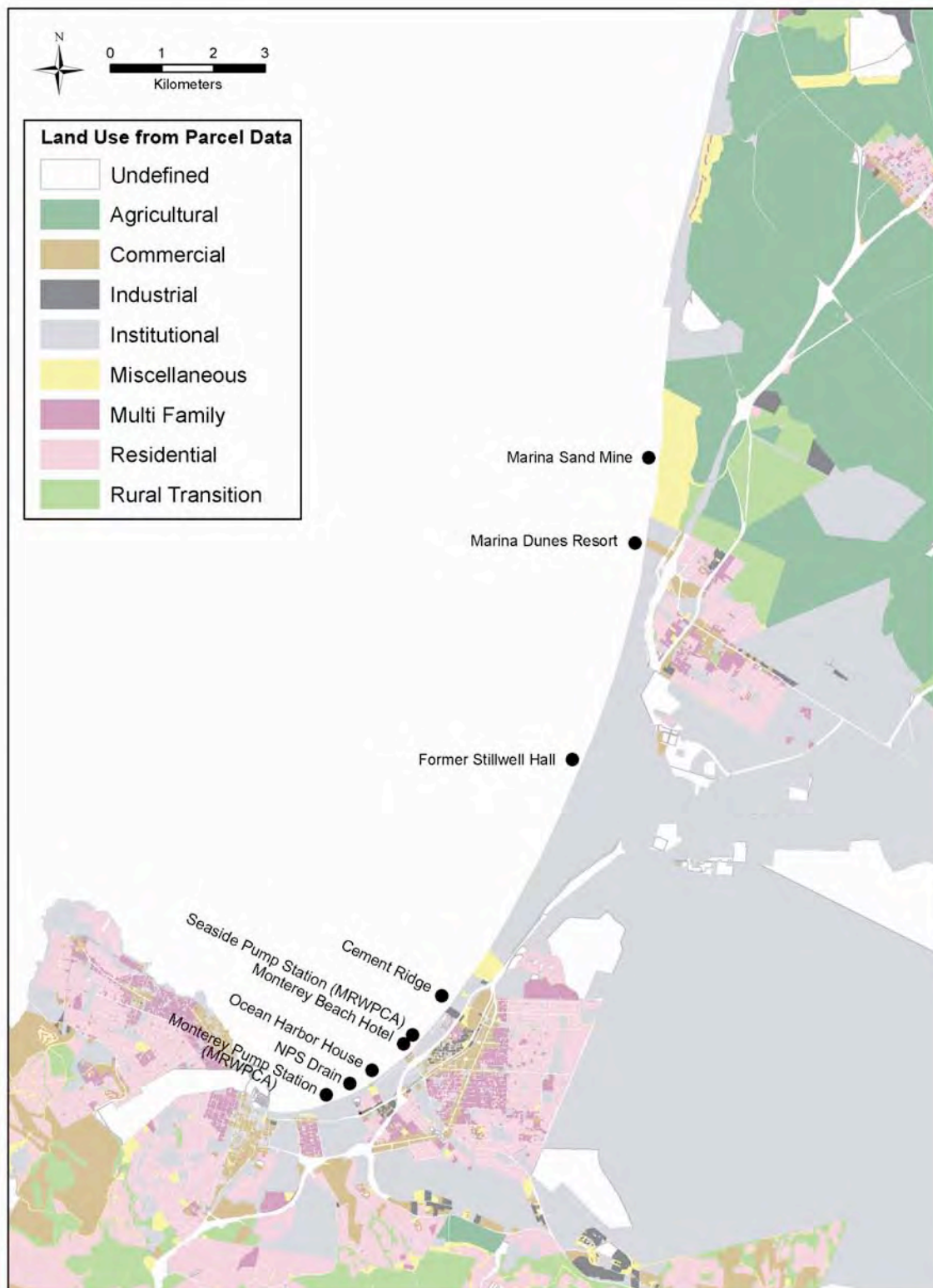


Figure 5.1: Approximate locations of development features along the SMB shoreline. Coastal armoring exists at the sites labeled: Cement Ridge, Monterey Beach Hotel, Ocean Harbor House and Naval Postgraduate School (NPS) Drain. Base layer shows generalized land use derived from parcel data.

a. Cement Ridge (Tioga Road, Sand City)

Remnants of a cement mixing facility are located at the end of Tioga Road in Sand City that forms make-shift coastal armoring (Figures 5.1 and 5.2). Concrete slurry was dumped here in a linear, shore-parallel pattern. The ridge formed by this cement is over 200 meters long and acts much the same way as a seawall (Thornton et al. in press). The impacts of this structure are similar to that of engineered coastal armoring in terms of blocking access, preventing natural shoreline retreat, and losing beach area both for recreation and as a habitat (HKA 2003a). The structure is an eye-sore to the community. In addition, riprap, composed mostly of un-engineered cement blocks, has been emplaced on the seaward side of Tioga Road as it turns parallel to shore.



Figure 5.2: Aerial photo mosaic of the concrete slurry “ridge” and other hard structures (indicated with yellow arrows) at the end of Tioga Road in Sand City, California. Photographs taken October 2004; copyright © 2002 Kenneth & Gabrielle Adelman (<http://www.californiacoastline.org/>).

b. Monterey Beach Hotel

In 1968, a 196-room, 4 story hotel was built directly on the beach in Monterey, which included a large, 100-m long seawall along three sides of the building (Griggs et al. in press; Thornton et al. in press) (Figures 5.1, 5.3, 5.4 and 5.5). The wall is composed of 6-foot wide keyed concrete panels that are jettied into place and anchored into shallow concrete mat slabs on which the hotel building itself is founded. Therefore, the stability

of the hotel and the seawall are interdependent. Only the upper sections of the panels are grouted together, allowing water to get through the bottom half between the panels (HKA 2003b). Analyses by Haro, Kasunich and Associates, Inc. speculated that culvert drainage from Roberts Creek, on the north side of the hotel seawall, may be exacerbating coastal erosion in this region (HKA 2003b).

Given that this is known to be an eroding coast, it is not surprising that the Monterey Beach Hotel seawall came under attack in the early 1980's. In fact, the extreme waves of the 1982-83 El Niño event undermined the concrete and lead to a loss of fill behind the wall. More recently, storm waves coinciding with high tides during the winter of 2002 broke through the south wall and forced the hotel to place emergency riprap in the gap to prevent further damage (Figure 5.4). Large scour holes formed on the inside of the wall, as water penetrated between the panels. Excessive corrosion has occurred because of this damage. The hotel is becoming a prime example of the "peninsula effect:" while the adjacent coastline is retreating due to natural erosion, the seawall has fixed the coastline and is creating an artificial headland out of the hotel (Figure 5.5). As the hotel becomes further isolated, it will experience more and more damage from wave action. In addition, the fronting beach, which is a major attraction of the hotel, will be lost due to this passive erosion.

The seawall is in need of repair and the emergency riprap emplaced in 2002 must be removed if a new armoring permit is not issued. The hotel owners submitted an application to repair the seawall (3-03-022) to the California Coastal Commission (Commission). In 2003, the Commission requested an Alternatives Evaluation for the

Monterey Beach Hotel; Haro, Kasunich and Associates, Inc. (HKA), collaborated with others to determine and analyze these alternatives (HKA 2003b).

HKA addressed 8 alternatives to address the Commission request. The following alternatives were not recommended by HKA because they require unfeasible excavation that may compromise the structural stability of the hotel or because they do not meet the project objectives: 1) Do nothing; 2) Move hotel landward; 3) Reinforce and repair existing perimeter wall; 4) Riprap revetment seaward of existing perimeter wall; 5) New vertical sheet pile wall in same location as existing perimeter wall; 6) Reduce length of wall parallel to shoreline and relocate some parking; and 7) New vertical sheet pile wall landward of existing perimeter wall.

The alternative recommended by HKA was to build a new vertical sheet pile wall approximately 2 feet seaward of the existing perimeter wall. The wall would be longer than the current structure and would incorporate corrosion prevention measures. In addition, it was recommended that the wall be colored and textured to mimic surrounding natural conditions.



Figure 5.3: Aerial photograph of the seawall and riprap (at the far right end of the seawall) protecting the Best Western Monterey Beach Hotel in Seaside, California. Photograph taken October 2004; copyright © 2002 Kenneth & Gabrielle Adelman (<http://www.californiacoastline.org/>).



Figure 5.4: Wave run-up against the Monterey Beach Hotel seawall and riprap during the winter of 2002. Lateral access is cut off because of this coastal armoring. Photo: Doug Smith, CSUMB.

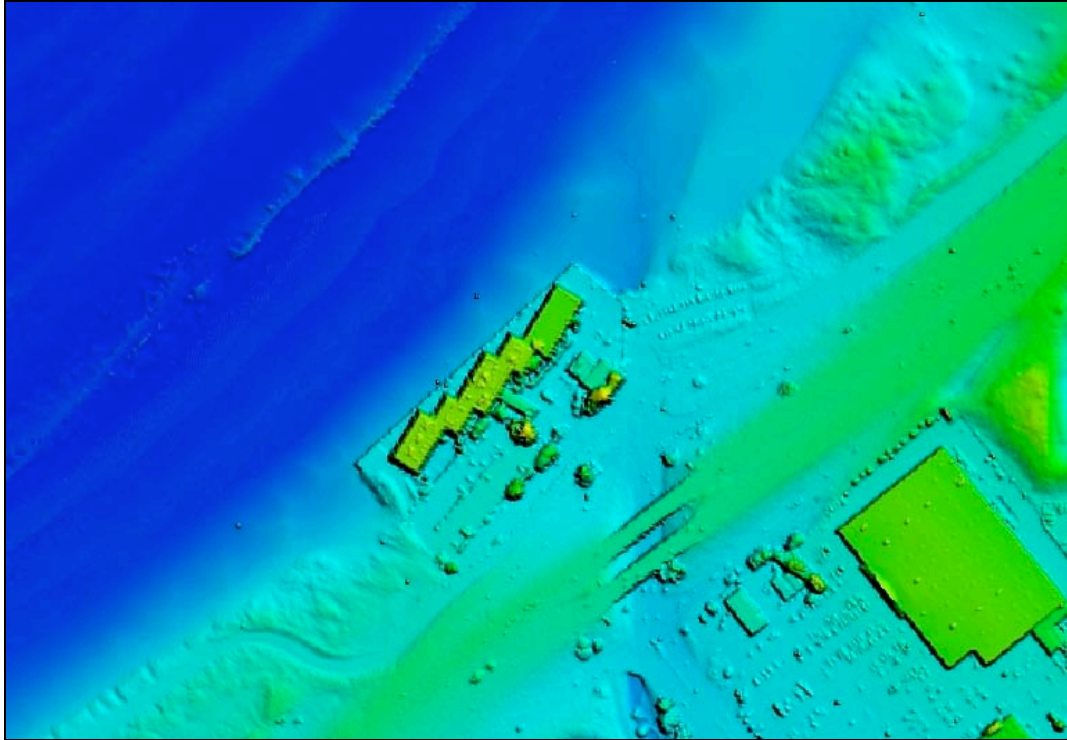


Figure 5.5: LIDAR elevation image of the Monterey Beach Hotel in 2003, showing the obvious erosion on either side of the hotel and the resultant “peninsula effect.” Image: Doug Smith, CSUMB.

c. Ocean Harbor House Condominiums

Between 1972 and 1974, a 172-unit apartment complex, called Ocean Harbor House, was constructed directly on the coastal dunes in Monterey (Figures 5.1, 5.6, and 5.7). Severe erosion occurred in this region during the 1982-83 El Niño event, breaking water lines and posing a threat to sewer and electrical lines in front of Ocean Harbor House. By 1984, the piling supporting the front units were vulnerable to wave attack and 3,200 to 5,000 tons of emergency riprap was placed in front of the complex, despite the fact that the rocks had to be placed across over 100 m of public beach (PMC 2003; Griggs et al. in press).

Eventually, the city of Monterey forced the owners to remove the riprap and the front pilings were reinforced and driven deeper into the sand (50-55 feet). Around the same

time, Ocean Harbor House was converted to condominiums, increasing the number of stake-holders from 1 to 172. Coastal retreat continued and, despite the reinforcements, additional riprap was needed to protect the front condominium units after the 1997-98 El Niño winter (Griggs et al. in press). The riprap is once again on city property and impacts the habitat and beach users in a variety of ways. In addition, the riprap emplaced in the late 1990's appears to be failing, as rocks settle into the sand and disperse (Figure 5.6 and 5.7).

The 172 owners of Ocean Harbor House have proposed removing the riprap and building a concrete seawall to protect their property from wave attack. This plan was approved by the California Coastal Commission, with substantial mitigation fees. The MBNMS has sent official letters of comment regarding the construction of a seawall in this region, requesting serious evaluation of other alternatives, such as planned retreat of the front units.



Figure 5.6: Aerial photograph of extensive riprap in front of the Ocean Harbor House Condominiums in Monterey, California. Photograph taken October 2004; copyright © 2002 Kenneth & Gabrielle Adelman (<http://www.californiacoastline.org/>).



Figure 5.7: Exposed pilings at the Ocean Harbor House condominiums in Monterey. Photo: Doug Smith, CSUMB.

d. NPS Storm Drain

A storm drain on the Naval Postgraduate School (NPS) grounds in Monterey has required emplacement of approximately 50 m of riprap to prevent wave damage (Figures 5.1 and 5.8). There is very little documentation on the history or future of this structure.



Figure 5.8: Aerial photograph of riprap on either side of a storm drain for the Naval Postgraduate School in Monterey, California. Photograph taken October 2004; copyright © 2002 Kenneth & Gabrielle Adelman (<http://www.californiacoastline.org/>).

e. Monterey Regional Water Pollution Control Agency (MRWPCA) Facilities

As discussed in section II-a, Philip Williams and Associates (PWA) completed an assessment of threat to MRWPCA facilities based on a 50-year planning horizon in southern Monterey Bay (PWA 2004). This risk evaluation incorporated threats from both short and long-term coastal erosion. Within the area of interest for this report, from

Wharf #2 in Monterey to the mouth of the Salinas River, several structures were designated as either “moderate” or “high” risk facilities.

According to the PWA report, the buried Monterey interceptor pipeline, from Tide Avenue to the Monterey Beach Hotel, has a moderate risk level and may be damaged in the next 50 years. The integrity of this pipeline may depend on the armoring now in place at Ocean Harbor House and the Monterey Beach Hotel. Other sections of the Monterey interceptor pipeline were designated as high risk: from the Monterey pump station to Tide Avenue and from the Monterey Beach Hotel to the Seaside pump station. The pipeline is threatened not only by lateral coastal retreat, but also by damage because of removal of overburden, and, in the case of the section from the Monterey Beach Hotel to the Seaside pump station, may be compromised within 25-30 years.

The Seaside pump station, situated only 75 feet from the shoreline, near the end of Canyon del Rey Road, was also determined to be high risk. PWA predicted that the facility may be threatened within 20 years and may be damaged by short-term events sooner. While PWA recommended further monitoring studies and reinforcement of the structure to prevent damage of the interceptor pipeline, they recommended relocation of the Seaside pump station because of imminent damage (see Figure 5.1 for locations of these facilities and associated structures).

VI. SUMMARY

The information compiled in this report demonstrates that the shoreline of southern Monterey Bay is actively eroding and that, while major development is somewhat limited

in extent, structures that do exist near the coast are threatened by coastal retreat. On average, the shoreline is stepping back at a rate of 0.5 to 1.0 meter per year in this region. However, caution should be used when combining rates from disparate analyses. A more comprehensive, consistent study of coastal erosion, such as the upcoming USGS National Assessment of Shoreline Change, may be most useful for management within an agency with as much coastline as the Monterey Bay National Marine Sanctuary (MBNMS).

While the overall coastline is retreating over time in this area, the width of beaches along southern Monterey Bay appears to be fairly steady. The most noticeable deviation from this general trend occurs when hard armoring structures, such as riprap or seawalls, are placed at the base of dunes or on the beach, in which case the beach in front of the armor narrows over time. In addition, researchers indicate that the dominant transport mechanism for beach sand in this littoral cell may be rip currents that move sediment offshore, rather than along shore as is common in northern Monterey Bay. Thus, hard coastal armoring and beach nourishment may not be the most effective erosion management options for this region.

The lack of development along much of southern Monterey Bay provides the Monterey Bay National Marine Sanctuary and other agencies with an ideal, and increasingly rare, opportunity to be proactive in terms of land use development. Combining scientific knowledge of the region's dynamic coastline with sound management will undoubtedly help to conserve the natural beauty and value of this resource.

APPENDIX 1: Contact information for regional erosion experts (listed alphabetically).

Dr. Gary Griggs

Professor of Earth Sciences
University of California, Santa Cruz
Director, Institute of Marine Sciences

Interests: Coastal processes and geologic hazards
Relevant Projects: Living with the Changing California Coast; various journal articles
on coastal armoring

Address: Earth Sciences Department
University of California, Santa Cruz
1156 High Street
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Phone: 831-459-5006
Fax: 831-459-3074
E-mail: ggriggs@es.ucsc.edu
Website: <http://es.ucsc.edu/personnel/Griggs/>

Dr. Cheryl Hapke

Geologist
United States Geological Survey
Pacific Science Center

Interests: Coastal hazards, cliff erosion, landslides
Relevant Projects: National Assessment of Coastal Change Hazards, full report for
sandy shorelines for entire sanctuary available September 2005,
cliffed shoreline erosion rates available after that?

Address: USGS Pacific Science Center
400 Natural Bridges Drive
Santa Cruz, California 95060
Phone: (831) 427-4744
Fax: (831) 427-4748
E-mail: chapke@usgs.gov

Alternative USGS Santa Cruz contacts for Dr. Hapke include David Reid and Dr. Bruce Richmond
(below). Dr. Hapke is relocating to a USGS office in Rhode Island.

John E. Kasunich, P.E.

Haro, Kasunich and Associates, Inc.

Interests: Coastal erosion, engineering, armoring
Relevant Projects: Coastal Recession Evaluation for Sand City, Alternatives for
Monterey Beach Hotel seawall

Address: Haro, Kasunich and Associates, Inc.
116 East Lake Ave.
Watsonville, CA 95076
Phone: (831) 722-4175
Fax: (831) 722-3202
E-mail: n/a

David Reid, M.S.

Geologist / GIS Contractor
United States Geological Survey
Pacific Science Center

Interests: Coastal erosion, Monterey Bay geology, GIS applications
Relevant Projects: National Assessment of Coastal Change Hazards

Address: USGS Pacific Science Center
400 Natural Bridges Drive
Santa Cruz, California 95060
Phone: (831) 427-4759
Fax: (831) 427-4748
E-mail: dreid@usgs.gov

Dr. Bruce Richmond

USGS Geologist
United States Geological Survey
Pacific Science Center

Interests: Coastal erosion, coastal hazards
Relevant Projects: National Assessment of Coastal Change Hazards

Address: USGS Pacific Science Center
400 Natural Bridges Drive
Santa Cruz, California 95060
Address: Same as above
Phone: (831) 427-4731
Fax: (831) 427-4748
E-mail: brichmond@usgs.gov

Dr. Douglas Smith

Associate Professor Earth System Science and Policy
California State University, Monterey Bay

Interests: Watershed processes and restoration, geology, sedimentation
Relevant Projects: Karen Gref SMB erosion study (his student); modeling sea level rise in the bay; interest in impacts of coastal armoring

Address: Earth Systems Science & Policy, Bldg. 42
California State University Monterey Bay
100 Campus Center
Seaside, California 93955-8001
Phone: (831) 582-4696
Fax: (831) 582-4122
E-mail: douglas_smith@csumb.edu
Website: <http://home.csumb.edu/s/smithdouglas/world/index.html>

Dr. Edward Thornton

Professor and Associate Chairman, Oceanography Department
Naval Postgraduate School

Interests: Wave mechanics, nearshore hydrodynamics, sediment transport
Relevant Projects: SMB dune erosion study; SMB sediment budget (study in progress); theoretical studies of erosion due to rip currents in SMB

Address: Nearshore Processes Lab
Oceanography Department
Naval Postgraduate School
327 Spanagel Hall
Monterey, California 93943
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E-mail: thornton@nps.navy.mil
Website: <http://www.oc.nps.navy.mil/~thornton/>

Dr. Gerald (Jerry) Weber

G.E. Weber Geologic Consulting

Interests: Coastal processes, former UCSC professor, northern Monterey Bay sand transport, general central California geology
Relevant Projects: Northern Monterey Bay sand transport study

Address: G.E. Weber Geologic Consulting
129 Jewell Street
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Fax: (831) 469-3467
E-mail: jweber@pmc.ucsc.edu

APPENDIX 2: Table of erosion rates, locations, and authors. Coordinates are from the Teale Albers NAD83 projection in meters. These values were used in the creation of figure 2.6.

Author (Publication date)	Time span for rate calculation	Location Name	Rate (cm/yr)	X	Y
Haro, Kasunich and Associates (2004)	(1933-2003)	Sand City	73	-165189.921037	-153482.768572
Gref (2005)	(1976-2004)	Marina State Beach	150	-161395.208525	-144865.551280
Gref (2005)	(1976-2004)	former Stillwell Hall site	200	-162667.169362	-149055.141139
Gref (2005)	(1976-2004)	Monterey Beach Hotel	160	-166125.986791	-154628.093709
Gref (2005)	(1976-2004)	Ocean Harbor House	70	-166828.333047	-155164.227686
Thornton et al. (in press)	(1940-2004)	0.9 km from Wharf #2	36	-168290.160000	-155624.540000
Thornton et al. (in press)	(1940-2004)	2.9 km from Wharf #2	50	-166494.190000	-154853.830000
Thornton et al. (in press)	(1940-2004)	4 km from Wharf #2	101	-165784.860000	-154178.210000
Thornton et al. (in press)	(1940-2004)	6 km from Wharf #2	136	-164577.490000	-152588.500000
Thornton et al. (in press)	(1940-2004)	8 km from Wharf #2	82	-163550.720000	-150876.550000
Thornton et al. (in press)	(1940-2004)	13.5 km from Wharf #2	86	-161690.360000	-145746.730000
Griggs et al. (2005)	undefined	near Salinas River mouth	41	-161161.286272	-139427.382012
Griggs et al. (2005)	undefined	near Salinas River mouth	86	-161265.123928	-140706.493730
Griggs et al. (2005)	undefined	Marina State Beach	163	-161679.251446	-145006.040293
Griggs et al. (2005)	undefined	Marina State Beach	155	-161893.240981	-145823.815655
Griggs et al. (2005)	undefined	northern Fort Ord	208	-162031.805290	-146430.882593
Griggs et al. (2005)	undefined	Fort Ord	244	-162885.266904	-148949.972763
Griggs et al. (2005)	undefined	near Tioga Road	122	-165091.449844	-153071.126111
Griggs et al. (2005)	undefined	near Tioga Road	188	-165423.002492	-153515.895751
Griggs et al. (2005)	undefined	Monterey Beach Hotel	61	-166297.896064	-154485.590529
Griggs et al. (2005)	undefined	Ocean Harbor House	30	-168569.943205	-155469.248409
Griggs et al. (2005)	undefined	Monterey State Beach	28	-167767.274940	-155372.339216
Griggs et al. (2005)	undefined	near breakwater	30	-166866.298840	-154967.895446

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Sand mining impacts on long-term dune erosion in southern Monterey Bay

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Abstract

Southern Monterey Bay was the most intensively mined shoreline (with sand removed directly from the surf zone) in the U.S. during the period from 1906 until 1990, when the mines were closed following hypotheses that the mining caused coastal erosion. It is estimated that the yearly averaged amount of mined sand between 1940 and 1984 was 128,000 m³/yr, which is approximately 50% of the yearly average dune volume loss during this period. To assess the impact of sand mining, erosion rates along an 18 km range of shoreline during the times of intensive sand mining (1940–1990) are compared with the rates after sand mining ceased (1990–2004). Most of the shoreline is composed of unconsolidated sand with extensive sand dunes rising up to a height of 46 m, vulnerable to the erosive forces of storm waves. Erosion is defined here as a recession of the top edge of the dune. Recession was determined using stereo-photogrammetry, and LIDAR and GPS surveys. Long-term erosion rates vary from about 0.5 m/yr at Monterey to 1.5 m/yr in the middle of the range, and then decrease northward. Erosion events are episodic and occur when storm waves and high tides coincide, allowing swash to undercut the dune and resulting in permanent recession. Erosion appears to be correlated with the occurrence of El Niños. The calculated volume loss of the dune in southern Monterey Bay during the 1997–98 El Niño winter was 1,820,000 m³, which is almost seven times the historical annual mean dune erosion of 270,000 m³/yr. The alongshore variation in recession rates appears to be a function of the alongshore gradient in mean wave energy and depletions by sand mining. After cessation of sand mining in 1990, the erosion rates decreased at locations in the southern end of the bay but have not significantly changed at other locations.

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Keywords: dune erosion; beach erosion; sand mining; Monterey Bay

1. Introduction

The leading anthropogenic cause of sediment loss to the littoral zone in the United States is sand and gravel mining (Magoon et al., 2004). Most of the mining is done in rivers and streams before the sediments reach

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the ocean. However, substantial amounts of sand were mined directly from the shoreline until 1990 when it was finally hypothesized that sand mining was a significant contributor to shoreline erosion. The major coastal sand mining in California was along southern Monterey Bay, which started in 1906 at the mouth of the Salinas River and expanded to six commercial sites at Marina and Sand City (Magoon et al., 1972). Only mining from the surf zone is considered here; this does not include mining of the back-beach and dunes that is still ongoing at Marina. Draglines were used to mine the coarse sand deposits within the surf zone, which have a high commercial value. Sand mining was not regulated until 1968, when the State Lands Commission began licensing sand mining operations through the issuance of leases. In addition, the Corps of Engineers began asserting jurisdiction over mining operations in 1974 under the Rivers and Harbors Act of 1899. Both the State Lands and Corps of Engineers mining leases in southern Monterey Bay expired in 1988. An estimated 6.3 million cubic meters of sand was mined before it ceased in 1990 (Magoon et al., 2004). A primary objective of this paper is to assess the impact of sand mining on the erosion of southern Monterey Bay.

Southern Monterey Bay is characterized by a sandy shoreline backed by extensive dunes rising up to 46 m within the Fort Ord and Marina area. The sand dunes, referred to as the Flandarin and pre-Flandarin dunes, were laid down during the Pleistocene from sands originating from the Salinas River, deposited on the exposed continental shelf, and blown onshore by prevailing winds. Approximately 18,000 years ago at a low stand in sea level, these dunes are estimated to have extended 13 km seaward of the present day shoreline (Chin et al., 1988). The shoreline eroded with sea level rise, which equates to an annual recession rate of 0.7 m/yr. Therefore, the southern Monterey Bay shoreline is characterized as an erosive shoreline.

Two littoral cells have been identified in southern Monterey Bay with the demarcation at the Salinas River (Habel and Armstrong, 1978). Refraction of waves over the Monterey submarine canyon and delta offshore of the Salinas river (Fig. 1) results in the mean alongshore sediment transport between the Salinas River and Moss Landing to be directed to the north, most of which eventually empties down the submarine canyon, and the mean alongshore sediment transport south of the Salinas River to be directed to the south. This paper focuses on the southern littoral cell along the 18 km shoreline bounded by Monterey (0 km) and the Salinas River (18 km). The distances alongshore are noted on Fig. 1, and are used as reference locations in the text.

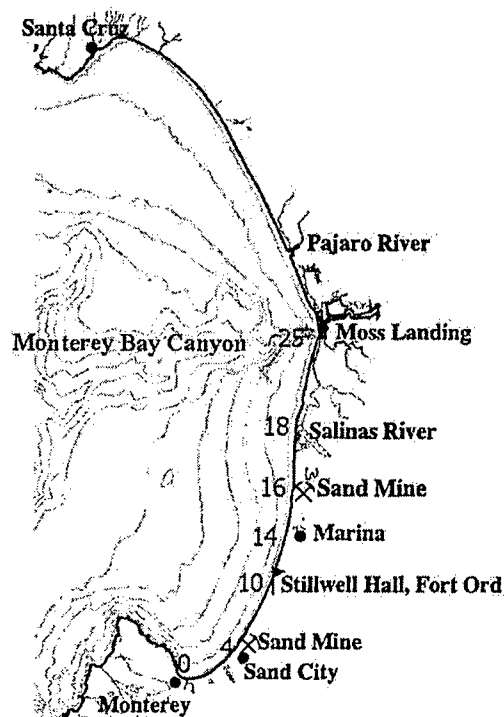


Fig. 1. Monterey Bay shoreline (number of kilometers from Monterey Wharf #2 are indicated) and offshore bathymetry showing the Monterey Bay submarine canyon and the ancient delta off the Salinas River.

Development along this length of shoreline has been limited. A total of approximately 1 km of the shoreline is hardened, which include 50 m of rock revetment to protect culverts and 200 m seawalls to protect a condominium and hotel in Monterey, as well as 100 m of rock rubble and a 200 m concrete wall formed from cement truck tailings in Sand City. In addition, a 200 m rock rubble seawall was constructed to protect Stillwell Hall at Fort Ord in 1978 (Fig. 2), and subsequently removed in March 2004. Armored shorelines neither erode nor contribute sand to the littoral system.

Despite the cessation of sand mining, the beach and dunes are still eroding at a relatively high rate. For example at Fort Ord, a football field existed on the dune between Stillwell Hall (Fig. 2) and the ocean in 1944. After the field eroded into the ocean, rock rubble was placed in front of Stillwell Hall in 1978 and again in 1985 to stop erosion, but even after sand mining ceased, extreme recession continued to occur at the flanks of the rubble. Up to 14 m of recession occurred during the 1997–98 El Niño winter just to the north of Stillwell Hall. Owing to refraction of the prevailing northwest swell over the Monterey submarine canyon, waves converge to form the largest waves in the bay at Fort



Fig. 2. Aerial oblique photo of Stillwell Hall, Fort Ord, California showing rock-rubble sea wall in front and extensive erosion to each side (from USGS 1998).

Ord. These larger waves cause high erosion rates at this location.

The objective of this study is to quantify the impact of sand mining on dune erosion in southern Monterey Bay. To assess this impact, erosion rates during the times of intensive sand mining (1940–1990) are compared with the rates after its cessation (1990–2004). This paper is a compilation of results from various studies (Sklavidis and Lima-Blanco, 1985; McGee, 1986; Oradiwe, 1986; Egley, 2002; Conforto Sesto, 2004) using differing methodologies to survey the dunes of southern Monterey Bay.

2. Methods: measuring dune recession

To obtain an accurate depiction of permanent, long-term erosion, a consistent measurement location must be chosen on the subaerial profile. The waterline is easily identified in aerial photographs, but because of variations in tide elevation and seasonal variability of the shoreline, it is unsuitable as a measurement reference. Similarly, the toe of the dune is often difficult to define owing to material slumping from the dune face. The sharp stereo representation of the dune top edge is not subject to short timescale variability and is used here. The dune top edge for much of the southern Monterey Bay shoreline is easily identified by a vegetation line. Almost the entire 18 km shoreline is adjacent to dunes, which have an average height of ~10 m. The dune slope is at or near the angle of repose because of continual undercutting by waves. Therefore, long-term erosion is defined as the recession of the dune top edge, as this is

the seaward extent of land use. The recession of the dune edge is considered permanent erosion, because the prevailing winds are onshore and there is no modern day mechanism to build out the dune top.

Differing techniques were combined to obtain a dune top recession record spanning the period 1940 to 2004. Mechanical stereo-photogrammetry was used to measure recession from 1940 to 1984. LIDAR survey data of the dunes were obtained spanning the 1997–1998 El Niño winter. The dune top edge was surveyed by walking with a Kinematic GPS in a backpack in 2003. In order to tie together the earlier stereo-photogrammetry studies with recent measurements, stereo-photogrammetry was repeated using digital techniques for the 1984 photos using the same horizontal datum as the LIDAR and GPS surveys. These differing techniques have different accuracies, which are discussed below.

2.1. Stereo-photogrammetry

The erosion in southern Monterey Bay has been measured using photogrammetry by a number of investigators using a variety of methods including mirror-stereoscope (Thompson, 1981), zoom-transfer scope (Jones, 1981), and comparisons with and without field control. Only results obtained using a stereo-comparator with field control are assumed reliable and are presented here.

The erosion rates were quantified using stereo-photogrammetry on 6 sets of aerial photos from 1940 to 1984 to measure dune recession along the southern Monterey Bay shoreline by Sklavidis and Lima-Blanco

(1985) and McGee (1986). These earlier stereo-photogrammetry works used a Zeiss mechanical stereo-comparator interfaced to a PC using digital encoders on the adjustment controls. Photogrammetry errors are due to resolution of the stereo-comparator, image displacement due to relief and tilt, and scale variation. The ground position error (rms radius of the error circle for the two horizontal components) was 0.022 mm, which equates to a 0.2 m error for the 1:12,000 scale photographs used. To minimize tilt displacement errors, only photographs with less than three degrees of tilt were used. To minimize errors of image displacement owing to terrain relief and scale variation, ground control points (GCPs) were selected in the overlapping area of the photo-pair, and scaling points were chosen as close as possible to the measurement region and at nearly the same elevation. The accuracy can be improved by increasing the number of GCPs. GCPs must be identifiable in the images, which makes finding GCPs in the older photos more difficult as these locations may not exist today. In addition, tie-, or homologous, points were used. These are points that can be identified on both photos of the overlapping pair, but whose coordinates are unknown. The GCPs were surveyed using laser ranging for the earlier studies and GPS for the more recent work. The errors for both surveying systems are $O(2 \text{ cm rms})$.

In these earlier studies, the location of the dune top edge was measured continuously (most easily identified by viewing the 3-D image stereoscopically) for sufficient distance alongshore (200–1300 m) to give a representative mean recession rate for sections of shoreline. The elevation of the toe of the dune was measured also so that the height of the dune could be determined. A problem with continuing the recession measurements from the earlier works of Sklavidis and Lima-Blanco (1985) and McGee (1986) was that the absolute horizontal datum was lost, so there is no way to tie together this work with more recent LIDAR and GPS measurements. Therefore, to tie the earlier work with newer measurements, the 1984 photos were redone using modern digital stereo-photogrammetry with the same datum as the LIDAR measurements. Unfortunately, several of the photos were lost, which did not allow completion of the surveys at Fort Ord.

Digital stereo-photogrammetry methods and their associated errors are similar to those of the older mechanical system. The 1984 photos were digitized at $14 \mu\text{m/pixel}$, which gives a 0.3 m resolution. The program automatically finds homologous points at random locations within the pairs of photos and calculates the location and elevation to generate a 3-D

map of the area. The digital terrain model is not as accurate in areas where it is difficult to find homologous points, such as on the beach where the texture is uniform. In addition, because the photo pairs were not taken simultaneously and the waves on the sea surface move between pictures, the algorithm tries to match homologous points that are at different locations, generating erroneous elevations. Erroneous points on the sea surface and the low contrast beach have to be edited. Removing points resulted in some places having too few points to generate an accurate model. Therefore, points had to be manually added using stereographic viewing of the ortho-rectified image pairs to identify and measure elevations at selected points.

The digital stereo-photogrammetry data are acquired at irregular spacing and converted to Universal Transverse Mercator (UTM) coordinates. A rectangular grid is interpolated from the irregularly spaced data using Triangulated Irregular Networks and applying the Delaunay triangulation method. The elevation data points are determined using an inverse distance weighting between adjacent points (Watson and Philip, 1985).

The Imagine OrthoBase software employed in the stereo-photogrammetry calculated total horizontal rms errors ranging from 0.5 to 2 m. The error in determining the dune edge position is calculated using the method of Moore and Griggs (2002). Assuming the rectification and dune edge position have a bivariate normal distribution, the horizontal error is conservatively estimated to be $\pm 2 \text{ m rms}$. The same error is attributed to both the digital and the higher resolution manual stereo-photogrammetry.

2.2. LIDAR measurements

The U.S. Geological Survey (USGS), National Aeronautics and Space Administration and National Oceanic and Atmospheric Administration collaborated to measure coastal change using Airborne Topographic Mapping (ATM) LIDAR to survey the pre- and post-storm topography of the 1997–98 El Niño winter (Oct. 12–13, 1997 and April 15, 17–18, 1998). The ATM system is combined with GPS and inertial navigation to determine position and orientation of the aircraft. The ATM spatial resolution depends on the height and speed of the airplane, laser scan rate, scan angle, and field of view. Errors include system calibration and panoramic distortion. Meridith et al. (1999) discuss the calibration requirements of the ATM, which include corrections for the laser range and angular mounting biases with respect to the aircraft attitude. Elevation errors of less than 15 cm rms were found when LIDAR elevations were

compared with ground surveys, and horizontal accuracy was within 0.8 m with airplane flying at 700 m (Meridith et al., 1999). Stockdon et al. (2002) found a LIDAR horizontal rms error of 1.4 m compared with ground based surveys in determining shoreline position, which is the error estimate used here for dune top edge determination.

Egley (2002) used the LIDAR data to study the erosion along the southern Monterey Bay shoreline before and after the 1997–98 El Niño winter. The LIDAR obtains elevations at arbitrary horizontal locations, so the analysis is treated in the same manner as the digital stereo-photogrammetry. The data were gridded at 1 m resolution, which generally over-sampled the data. There are larger errors in the LIDAR data at the edges of the scan, which generally were over water and in the back dunes. To reduce errors, these areas were masked out. Masking was accomplished by overlaying the LIDAR images onto digital orthophoto quadrangles generated from black and white aerial photographs taken on 21 August 1998. The photographs were scanned to yield a 0.5 m pixel resolution. USGS 7.5 min quadrangle data and USGS digital elevation model data were used as the control. The accuracy and repeatability of this LIDAR data are demonstrated by comparing 1997 and 1998 profiles that bisect the rock revetment and the Stillwell Hall building, which are fixed (Fig. 3). The profiles are able to distinguish the building's irregular roof and chimney, and little variation is found between profiles. Some differences between the 1997 and 1998 profiles are expected because the profiles do not exactly overlay each other; this results in relatively large differences where steep gradients (vertical walls) occur.

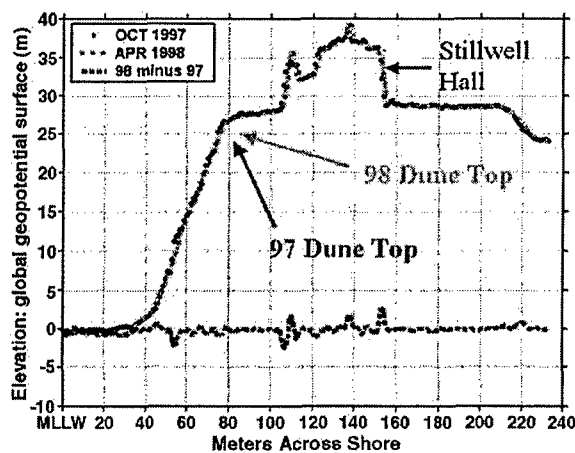


Fig. 3. LIDAR cross-shore profiles in 1997 and 1998 across the hardened shoreline and Stillwell Hall building at Fort Ord, California, demonstrating the repeatability of the measurements.

2.3. GPS surveys

The dune top edge was surveyed by a walker equipped with a Kinematic GPS in a backpack in 2003. The surveyor walked approximately 50 cm from the edge, and the 50 cm was subtracted from the surveys. The toe of the dune was surveyed at the same time with GPS mounted on an ATV. The toe height is determined at the base of dune where the dune face changes from near angle of repose to the milder sloping beach profile. The toe height is most easily identified in early spring after winter waves have cleared off the beach waste. This contrasts with in the fall when the toe is not as easily identified owing to the summer beach berm and rounding of the toe. No recession of the dunes was observed to occur during the 2003–2004 winter, so the December 2003 survey is given a date of 2004 in subsequent analysis.

The accuracy of Kinematic GPS is 5 cm rms in all three directions. Errors occur due to the surveyor not standing straight when climbing the dune top edge and not walking the prescribed distance from the dune edge (the height of the GPS antennae from the ground when the surveyor is standing straight and the 50 cm walking distance from edge are subtracted). It is estimated that the horizontal position error is ± 30 cm. This technique is more accurate than stereo-photogrammetry and LIDAR, and has the added advantage of the surveyor directly observing where the dune top edge and toe are located.

In summary, the horizontal accuracies are estimated ± 2 m for stereo-photogrammetry (mechanical and digital), ± 1.4 m for the LIDAR and ± 0.3 m for walking the dune with Kinematic GPS. Thus, the large dune recessions spanning several years between surveys along Southern Monterey Bay are resolved at $O(1$ m/yr).

3. Dune recession analysis

The objective of the analysis is to determine the long-term recession rate of the dune top edge. Erosion varies spatially alongshore for both the long-term mean and for the short-term seasonal variation. An example of the short-term variability is obtained from the elevation differences calculated between 1997 and 1998 LIDAR measurements for 4 km of shoreline at alongshore distances 6 to 10 km (Fig. 4). The red is an indication of at least 10 m elevation change, which occurs on the dune face, and is therefore an indication of significant dune recession. The alongshore variation occurs on a scale of 200–500 m, associated with large scale shoreline cusps that are erosion features of rip currents of the same



Fig. 4. Elevation differences measured with LIDAR between 1997 and 1998 for 4 km of shoreline centered on Fort Ord. Red and yellow indicate dune erosion, green is no change and blue indicates beach accretion. Large alongshore variations in erosion are indicated.

alongshore spacing (Thornton et al., submitted for publication). The observed short-scale dune erosion occurs at the embayment of these large beach cusps where the beach is the narrowest. The strong variability requires sampling the shoreline at close intervals to avoid aliasing. To obtain a good average for dune recession, the dune top edge was measured continuously alongshore for the stereo-photogrammetry and dune walk for sections of the shoreline ranging from 200 to 1300 m. For the LIDAR data, it was found that cross-shore profiles could be edited more easily to maintain quality control and reduce errors, so the dune recession is determined from the LIDAR-derived profiles every 25 m so as not to alias the data.

In the LIDAR data, the dune top edge is identified as a sharp change in slope in the cross-shore profiles, which is not always obvious. For example, the 1997 and 1998 profiles are compared at a location just north of Stillwell Hall at Fort Ord (Fig. 5), where a large 14 m recession occurred. The dune top edge in 1998 is easy to identify after the recent severe winter erosion. However, the dune top edge in the fall of 1997 is not as obvious, because significant erosion has not occurred recently and the edge has been rounded by wind and rain. This

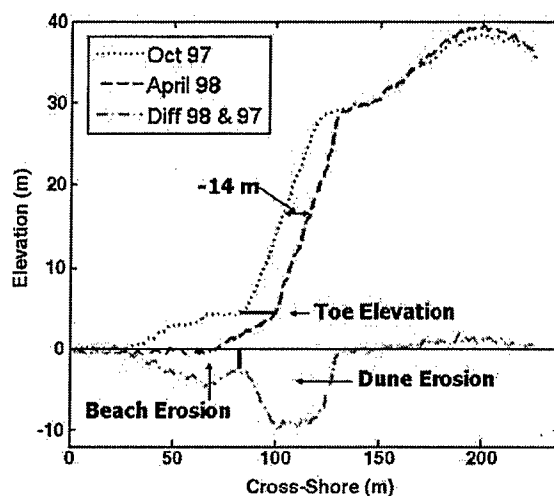


Fig. 5. Cross-shore profiles from LIDAR for 1997 and 1998. The beach and dune erosion are the differences of profile areas and are partitioned at the toe.

leads to some subjectivity in specifying the dune top edge from the profiles. In these cases, a mean recession is more easily measured from the recession of the sloping dune faces (Fig. 5).

The dune top edge is most easily identified on vegetated dune tops, which gives a high contrast in the photographs. The stereo analysis also assisted in the identification of the dune edge where large changes in elevation are easy to identify. The dune top edge is difficult to identify at blow-out locations where there is no vegetation and the dune top is rounded. Identifying the dune top edge at blow-outs was similarly difficult during the walking surveys. Therefore, only sections of

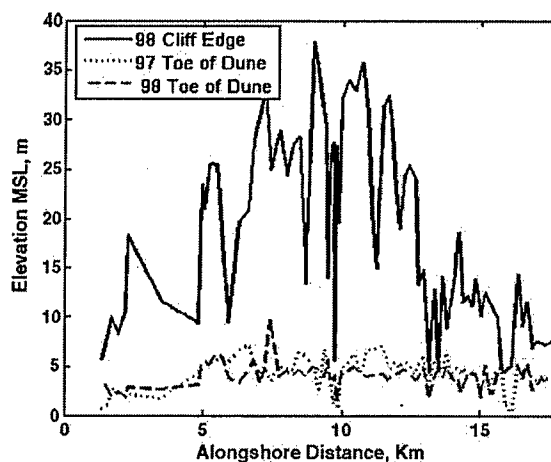


Fig. 6. Elevations of dune top edge in April 1998 and toe in October 1997 and April 1998 relative to MSL as a function of distance alongshore in southern Monterey Bay.

shoreline where the dune top was vegetated are analyzed, which is the majority of the shoreline.

The alongshore variation of the dune top edge and toe elevations measured from the LIDAR profiles for 1997 and 1998 are shown in Fig. 6. Only the elevation of the dune top edge for 1998 is shown, as it varied little from 1997 (even though there was significant recession). However, the dune top edge elevation varies considerably alongshore with elevations up to 9 m in Monterey, 10 m in Sand City, 35 m in Fort Ord, and 15 m in Marina. The toe elevation is low near Monterey and increases to the north, similar to the wave energy. Interestingly, although there were large changes in the beach volume, the mean toe elevation is similar before and after the winter storms with an average of 4.2 m and 4.1 above MSL for 1997 and 1998. The height of the toe suggests that dune erosion only occurs when extreme swash run-up by storm waves coincides with high tides to reach the dune toe (maximum high tide is $\sim +1$ m relative to MSL).

Dune top recessions between the 1940s and 2005, averaged over lengths of shoreline (see Table 1), are plotted against the year the data were acquired at four selected locations in Fig. 7. Average recession rate is measured as the slope of the linear regression line. For most places the dune top edge is steadily recessing. Accretion is observed to have occurred for limited periods at alongshore locations 4 km (within Sand City) and at 13.5 km (in Marina) (Table 1). However, both locations were in an area of sand mining operations where anthropogenic changes occurred. The average recession rates alongshore range from 0.5 to 1.5 m/yr.

The volume of dune erosion is determined using the trapezoidal rule, multiplying the average dune recession by the dune height for sections of the shoreline analyzed from the stereo-photogrammetry and walking surveys. The dune height was measured as the dune top edge elevation minus the toe elevation. The toe elevation was determined from stereo and LIDAR

Table 1
Recession of dune top edge (meters) along Southern Monterey Bay shoreline

	Location (km)								
	1	3	4	5.2	6	8	9.8	10.2	13.5
Length (m)	579	201	540	350	335	692	350	335	1283
Year									
1940			0			0			0
1946	0	0		0	0		0	0	
1956	5.5	8.9	−7.5	25.0	28.0	17.4	19.8	35.7	15.8
1966	12.2	12.8		45.1	48.8	17.5	40.8	45.1	
1970			24.7						31.5
1976	17.2	16.8	32.0	61.0	61.3		48.5	55.8	
1978	19.5	21.2		66.3	66.7		51.4	60.4	
1980						33.4			8.5
1984	23.1	33.4	48.1	74.2	75.5	48.8	62.4	85.3	17.0
Length (m)	1550	1350	550		190	1475			400
1997	23.4		59.7		88.7	53.9			30.2
1998	25.1	36.6	59.1		88.7	57.8			37.5
2004	25.4	38.7	64.8		90.6	63.6			46.4
Average recession rate (m/yr)									
1940–1984	0.61	0.74	1.19	1.94	1.93	0.93	1.57	1.89	0.30
+/-	0.15	0.16	0.12	0.20	0.20	0.13	0.19	0.20	0.11
1984–2004	0.11	0.26	0.83		0.80	0.70			1.43
+/-	0.13	0.15	0.17		0.17	0.15			0.18
<i>t</i> -statistic ^a	−5.11	−1.15	−2.65		−72.49	−27.11			22.67

Location is distance from Wharf #2 in Monterey. Length is alongshore distance over which recession is averaged. Average recession rates based on linear regression along with uncertainty are given for 1940–1984 during the time of intense mining, and for 1984–2004 after the cessation of sand mining.

^a The *t*-statistic is statistically significant at 95% confidence for values $<|4.3|$, based on a two-sided hypothesis test with 2 degrees of freedom.

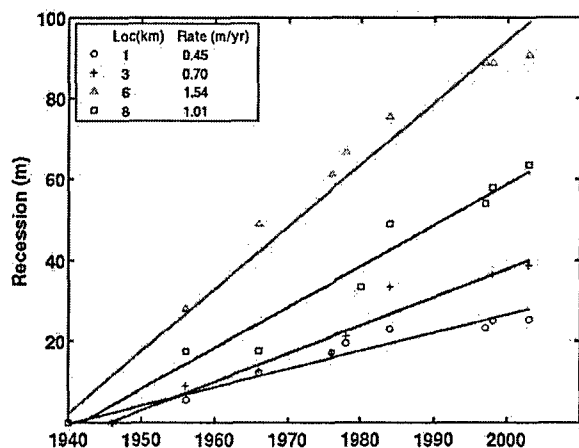


Fig. 7. Mean recession of dune top edge along selected sections of beach (alongshore location in km from Monterey Wharf #2, see also Table 1). The mean recession rate is calculated as the slope of the linear regression line.

terrain models and from surveys of the base of the dune using a Kinematic GPS mounted on an ATV. For the LIDAR data, the change in volume of the dunes and beaches between 1997 and 1998 was measured directly from the profile changes (see Fig. 5) and integrated alongshore.

4. Results: dune erosion rates

The average dune erosion from 1940 to 1984 from Monterey to the Salinas River is calculated as a historical reference value during the time of intensive sand mining, which includes the El Niño events during winters of 1957–58 and 1982–83. The mean annual dune volume loss (volume per unit length of shoreline) is obtained by multiplying the measured mean recession rate, R , by the mean dune height, H (dune top edge minus toe elevations) for each section of beach (Fig. 8). The volume loss is most dependent on the dune height. The total yearly averaged volume of the sand eroded from the dunes in southern Monterey Bay during this 44-year period is obtained by integrating 18 km alongshore and is measured to be 270,000 m³/yr.

The dune loss during the 1997–98 El Niño was an extreme erosion event (Fig. 9), as it was a time of anomalously high tides and high wave energy resulting in significant erosion. Large dune recessions were observed at Fort Ord and Marina, as well as significant recessions at Monterey and Sand City. Starting from the south, recessions at Monterey ranged from 0 to 4 m. Sand City recession ranged from 0 to 2 m. Fort Ord had cuts ranging from 0.5 to 13 m. Large variations in dune recession occurred alongshore. The historical mean annual dune

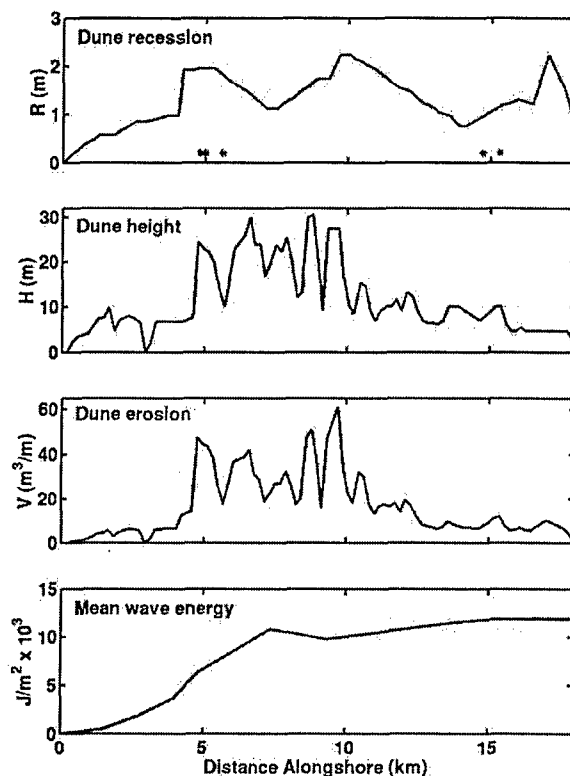


Fig. 8. Annual mean dune top edge recession R with locations of sand mining operations indicated by (*) (top panel), dune height H (top middle panel), volume of dune loss per unit distance V (bottom middle panel), and yearly mean wave energy (bottom panel) versus distance alongshore in southern Monterey Bay.

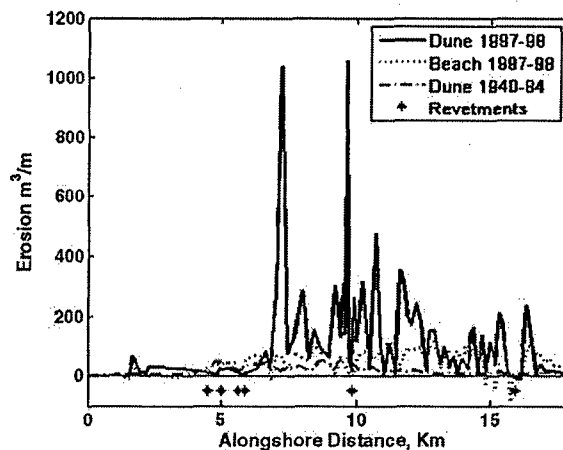


Fig. 9. Alongshore variations in volume loss in southern Monterey Bay of the dune (solid line) and beach (dotted line) measured using LIDAR during the 1997–98 El Niño winter compared with average annual historical dune volume loss (1940–84) measured using stereo-photogrammetry (dashed line). Revetments or seawalls (100–200 m in length) denoted by (*).

volume loss for 1940–1984 is shown for comparison in Fig. 9. Volume loss is also partitioned into permanent erosion of the dune and seasonal beach change for the LIDAR-derived profiles. The seasonal beach change is defined as the profile differences occurring between the shoreline at mean-lower-low water level and the toe of the dune. The total volume loss during the 1997–98 winter was 2,593,000 m³, obtained by integrating the erosion alongshore, of which 1,820,000 m³ is dune loss and 773,000 m³ is beach loss. The dune volume loss during this El Niño winter was almost seven times the historical average annual rate. This emphasizes that erosion can be highly episodic in time, which is not obvious in the regression plots of Fig. 7.

The beach loss of 773,000 m³ is about 40% of the dune loss. The eroded beach sand goes offshore in the winter, building the bar. Sand is moved onshore by the summer swell waves, but there is some permanent loss to the offshore.

5. Discussion: Dune erosion mechanics

Dune erosion is episodic and only occurs when storm waves coincide with high tides to allow the swash to reach and undercut the base of the sand dune. Swash is dependent on wave height (energy) and period and beach slope. The beach slope in turn is dependent on sand grain size and wave energy. It is assumed that long-term wave statistics are steady-state and that sand grain size does not change locally. Mean sea level rise (time scale of centuries) is assumed constant, and that it causes a constant contribution to the rate of dune erosion. It is further assumed that the beaches are in dynamic equilibrium over time owing to a constant supply of sand to the littoral system. This assumption is supported by the observation that the beach widths in southern Monterey Bay appear to be in a long-term (1930–2001) steady-state (Reid, 2004). Therefore, it is hypothesized that any long-term temporal variation in dune recession rates is associated with changes in the amount of sand mined from the surf zone.

Dune erosion varies alongshore. Mechanisms that may explain long-term spatial variability of dune recession include alongshore variations in wave energy, runoff of rainfall, beach slope, width and toe elevation, and variations in the amounts of sand mined. These various mechanisms are discussed next.

5.1. Waves, tides and El Niño events

Wave energy varies spatially over kilometer scales going from small waves at the southernmost part of the

bay in the shadow of a headland to larger waves in the middle of the southern bay, where convergence of waves owing to refraction over Monterey Bay Submarine Canyon results in increased wave heights. Wave refraction across the canyon causes focusing and defocusing of wave energy, depending on wave direction and period. Spatial variability was examined by calculating wave energy at 10 locations in southern Monterey Bay (Oradiwe, 1986). The calculations were based on directional spectra calculated using the Wave Information Studies (WIS) (Resio, 1981) for the twenty year period 1956–1975 and the U.S. Navy Spectral Wave Ocean Model (SWOM) for the eighteen year period 1964–1981. Both models used wind fields generated for the Northern Hemisphere by the U.S. Navy at the Fleet Numerical Meteorology and Oceanography Center to calculate directional wave fields. This precludes swell waves from the Southern Hemisphere, which is a reasonable approach since southern Monterey Bay is protected from waves from the south by the Point Pinos headland (Fig. 1). The directional spectra for every 6 h at a location in deep water outside Monterey Bay were then refracted to shore locations within the bay using linear refraction at one-degree increments over all incident angles of approach. Energy was calculated by integrating the individual directional wave spectra over the sea-swell band (0.05–0.3 Hz and directions), and then averaging over 25 years.¹

Severe refraction occurs as the predominant waves from the northwest pass over the Monterey Submarine Canyon, resulting in focusing of wave energy at Marina and Fort Ord and defocusing of energy at Monterey and Moss Landing. The shorelines of Monterey and Sand City are sheltered by Point Piños for waves from the south and west quadrants and receive a reduced amount of wave energy. The net result is a large alongshore energy gradient, with small waves at Monterey increasing to large waves at Fort Ord and Marina (Fig. 8, lower panel). The dune recession (Fig. 8, top panel) has an alongshore distribution similar to the mean wave energy. This suggests that a primary reason for alongshore variability of erosion is due to the gradient of wave energy.

Wave energy also varies in time. Wave energy and erosion are typically greater during El Niño winters. An El Niño winter occurred at the onset of the study in 1940–41 followed by events in 1957–58, 1982–83, and

¹ Although this is a limited 25-year data set (not previously published, but available) based on using a second generation wave model, the purpose of this analysis is to demonstrate the alongshore gradient of the annual mean energy and not the actual magnitudes.

1997–98. El Niño Southern Oscillation (ENSO) is characterized by weak easterly trade winds, anomalously high sea surface temperatures, high sea level elevations, large rainfall, and large waves along the central California coast (Storlazzi and Griggs, 1998). The incident wave directions were more westerly during 1982–83 and 1997–98 El Niños, which is significant because the shoreline in the middle of the bay is more vulnerable to waves from the west owing to refraction effects.

The potential for erosion increases with increased water level. Mean sea levels tend to be anomalously high during El Niños, a phenomenon that is attributed to a wave of warm water propagating northward along the coast (Flick, 1998). The warm water is piled against the coast to balance the colder, denser water offshore. The sea level records at Monterey only date back to 1973, but San Francisco sea level records started in 1853. Comparing monthly averaged mean sea level from 1973 to 2003 between Monterey and San Francisco, a regression slope of 0.8 is obtained with a correlation coefficient of 0.9. Therefore, the San Francisco record is used to infer sea level at Monterey with a reduced elevation of 0.8. The dune recession at south Fort Ord is compared with temporal changes in MSL (Fig. 10). The inferred monthly averaged MSL record shows large variations coincident with El Niño events. Increased erosion coincides with El Niño events, during which time the MSL is anomalously high with increased storm waves.

Beach profiles at 11 locations within Monterey Bay were measured by Dingler and Reiss (2001) starting in 1983 just after an El Niño winter and ending in 1998 just after another El Niño winter. They found that during El

Niños waves cut back the beach that allowed the swash to attack the dune. The dune retreat at Fort Ord was 21 m between February 1983 and March 1998. Of that retreat, 8 m occurred between February and April 1983 and 9 m over the 1997–98 winter, both during El Niños, and only 4 m during the intervening 14 years. They found that the beach widths required about 2 years to recover from severe erosion after the 1982–83 El Niño. The erosion was greater during the 1982–83 El Niño because storm durations were greater and they occurred during the highest tides.

In summary, storms and higher MSL during El Niño events appear to be a primary cause for coastal erosion. Large erosion occurs during El Niño winters, followed by several ‘normal’ years with less erosion until a new El Niño event occurs again, increasing recession. The long-term erosion rate, composed of episodic El Niño high-erosion-rate years and ‘normal’ erosion years, averages to a recession trend that tends to be constant for a particular location.

5.2. Rainfall and runoff

Casual observation of the shoreline reveals that increased erosion occurs at specific locations where runoff occurs, which is often where the vegetation on the dune has been destroyed by walking paths to the beach (access locations are approximately every 1–2 km alongshore). This leads to the dune being washed onto the beach. High rainfall is associated with the occurrence of El Niños, further exacerbating erosion during these times. However, erosion due to runoff, although not quantified, is considered small compared with erosion due to waves.

5.3. Beach toe elevation

Sallenger et al. (2001) used LIDAR to measure the toe elevation of the dune (T_d) along a 55 km reach of the northern Outer Banks of NC and found that long-term erosion correlated negatively with T_d , i.e., larger erosion occurred for small T_d where run-up can attack the foredune more easily than where T_d is higher. In addition to this cross-shore process, it was found that where there was a deficit of sand, there were lower dunes, which may be related to gradients in alongshore sediment transport. Hence, there may be a feedback between cross-shore erosion processes and alongshore sediment transport gradients. Wave climate along this stretch of open North Carolina coastline is essentially uniform. This contrasts with processes in southern Monterey Bay, where there is plentiful sand (from the

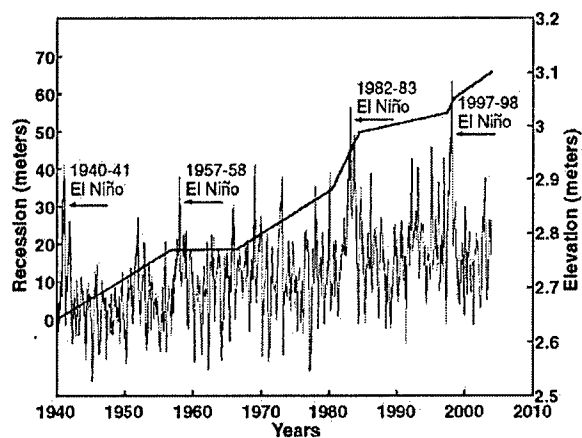


Fig. 10. South Fort Ord dune recession (left ordinate) for 1940–2004 (line) compared with monthly average mean sea level (right ordinate with arbitrary datum) at San Francisco. El Niño winters are indicated.

dune) and a large gradient of wave energy, where both erosion and T_d are positively correlated with wave energy. Hence, larger erosion occurs where wave energy is larger and T_d is higher, just the opposite of what Sallenger et al. (2001) observed.

5.4. Sand mining impact

Although the shoreline in Monterey Bay has historically eroded as sea level has risen, sand mining operations appear to have exacerbated the record of

erosion. Sand was continuously extracted from the shoreface starting in 1906 and continued until the late 1980s, when surf zone sand mining ceased in both Sand City and Marina. The mined sand ranged in size from 10 mm pebbles to 0.15 mm fine sands. The median grain size mined at both Sand City and Marina was approximately 0.85 mm. The sands at both locations are generally finer in the summer months when finer sands are moved shoreward by summer swell waves, during which time the operations were sometimes suspended. In this area, the sand is transported

Table 2
Estimated rates of surf zone sand mining ($\text{m}^3/\text{yr} \times 10^3$)

	Sand City			Approx. total		
	Monterey ^a Sand Co.	Granite ^b Const. Co.	Lone Star ^c Industries			
Loc. (km)	4.8	5.0	5.6			
Year						
27–40	?	?	?			?
40s	15	0	25			40
50s	30–40	15	45–55			100
60s	30–40	15	45–55			100
70s	27	0	60–65 (76) ^f			90
80–83	19 (57) ^e	0	60–70 (76) ^f			84
84	30 ^d (57) ^e	0	31 ^d (76) ^f			61
85	17 ^d	0	32 ^d			49
86	18 ^d	0	34 ^d			52
87	18	0	0			18
88	18	0	0			18
89	18	0	0			18
90	0	0	0			0

	Marina		Approx. total	Approx. total of all operations		
	Monterey ^g Sand Co.	Seaside Sand ^h and Gravel		Min	Est.	Max
Loc. (km)	14.7	15.3				
Year						
44–50	30	0	30	35	70	115
51–57	30	0	30	65	130	220
57–60	30	25	55	78	155	220
60s	30–40	25–30	62	81	162	220
70s	27 (57) ^e	25–30	55	73	145	220
80–83	19 (57) ^e	25–30	46	65	130	220
84	18	0	18	40	79	190
85	18	0	18	35	67	190
86	18	0	18	35	70	190
87	0	0	0	10	18	40
88	0	0	0	10	18	40
89	0	0	0	10	18	40
90	0	0	0	0	0	0

^a Started in 1931, took over by Monterey Sand Co. in 1950 and ceased mining 1990.

^b Started in about 1949–1950 and ceased mining 1968 (pers. com. Cotchett, Granite Construction Co.).

^c Started in 1927, increased production in the late 40's and ceased mining 12/31/86.

^d Actual amounts based on pers. com Robinette, Monterey Sand Co., 1988.

^e U.S. Army Corps of Engineers permit maximum: Dec 1968–July 1988.

^f U.S. Army Corps of Engineers permit maximum: Dec 1968–July 1990.

^g Mined 1944–1986.

^h Mined 1957–1980?

alongshore to the south due to the predominant waves from the northwest. Griggs and Savoy (1985) suggest that sand mining reduced the shore-connected shoals that are prevalent along this shoreline, which protect the beach by dissipating the winter storm wave energy within the surf zone. The lack of shore-connected shoals would allow the wave energy to reach the shore more easily and erode the beach and dune face. In this manner, it is hypothesized that sand mining contributed to dune erosion.

Estimates of the amount of sand mined from the surf zone vary. The U.S. Army Corps of Engineers (1985) estimated that a total of 540,000 m³ were mined prior to 1959 and that about 60,000 m³ were mined in 1959. Dorman (1968) estimated 76,000 m³/yr, whereas Arnal et al. (1973) estimated 190,000–230,000 m³/yr. The amount of sand mined is difficult to accurately determine as the mining companies went to court and made the records proprietary, ostensibly to insure there was no price fixing. Information on the amounts of sand mined was provided for the Sand City operations through personal communication with the mine operators just prior to the closing of the mines (Robinette, 1987; Battalio, 1989), and this information is the basis for the estimates in Table 2. The estimates for the Marina operations are based on the values provided in Sand City, as the operations were similar. The maximum estimate is based on the maximum amount allowed in the U.S. Army Corps of Engineers lease of 76,000 m³/yr by Lone Star Industries in Sand City for the years from 1968 to 1988 and 115,000 m³/yr by the combined Monterey Sand Company operations at Sand City and Marina for the years 1968–1990. Sand mining leases were not renewed after 1988, as it was hypothesized that the mining contributed to erosion (Griggs and Jones, 1985). It is assumed in the lease request that the miners conservatively overestimated their needs. The minimum is assumed to be simply 50% of the best estimate. Based on the best estimate, the total yearly averaged sand mined during the intensive 1940–1984 mining period was 128,000 m³/yr, which is equivalent to almost 50% of the 270,000 m³/yr average dune loss.

The slopes of the recession plots are examined to determine if the rate of recession (slope) has changed since sand mining stopped. The dune top recessions are compared with the amount of sand mined at the combined Sand City operations in Fig. 11 and at the combined Marina operations in Fig. 12 (summarized in Table 1). The errors in the measurements (given earlier) are indicated by the dimensions of the symbols with a time uncertainty of ± 0.5 years. The uncertainty in slope is estimated as the difference in the minimum and

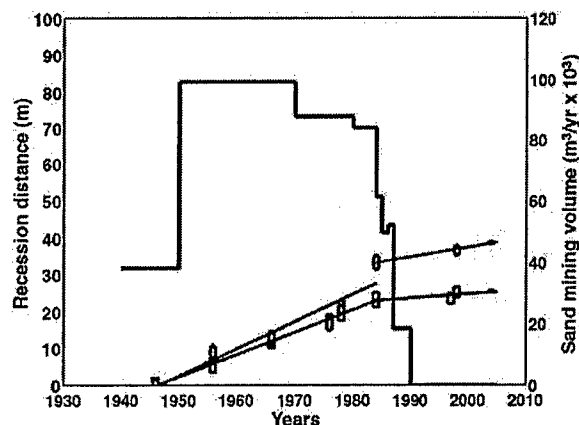


Fig. 11. Recession of dune top dune edge at locations 1 km (rectangles) and 3 km (ellipses), and the total amount of sand mined at Sand City operations at locations 4.8–5.6 km (see Table 2). Regression slopes have been calculated separately between 1940s–1984 during time of intensive sand mining and 1984–2004 after intensive mining (see Table 1). Uncertainties are indicated by dimensions of symbols.

maximum slopes calculated as a regression on the minimum and maximum measurement uncertainties. Examining the evolution of erosion rates, there appears to be at least a qualitative decrease in the regression slopes for 1984–2004 after sand mining stopped compared with the regression slopes of 1940s–1984, during the time of intensive sand mining. Hypothesis tests were applied to determine whether the regression slopes have changed using a two-sided *t*-distribution test (see for example, Bowker and Lieberman, 1961). The slopes and *t*-statistic values are given in Table 1. For locations between Monterey and Sand City at alongshore distances 3 km (Fig. 11) and 4 km, there are statistically significant decreases in the slopes. For locations between Sand City and Marina at alongshore distances 6 and 8 km (Fig. 12), there is a qualitative decrease in slopes, but they are not statistically significant. Therefore, it is concluded that sand mining increased erosion, at least south of Sand City mining operations.

Sand extraction can be viewed as “digging a hole” in the surf zone, and it would be expected that sand would be drawn from both upcoast and downcoast as well as onshore and offshore to fill the hole (Dean, 2004). However, since alongshore transport of sand is generally to the south along this shoreline, it would be expected the hole would be filled more by the upcoast drift. The southerly transport of sand intercepted by the mining would reduce available sand to the beaches to the south of the mining operations. Therefore, it would be expected that locations south of mining operations would be more affected.

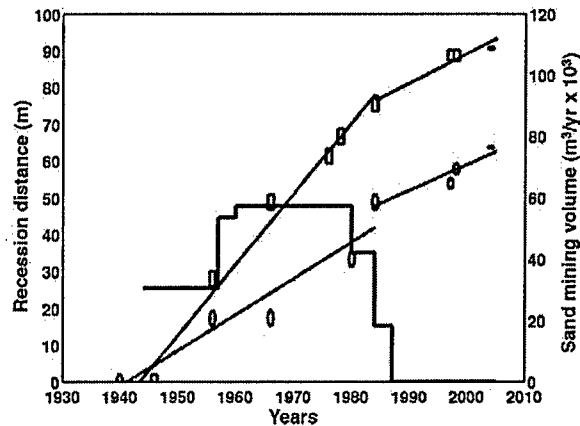


Fig. 12. Recession of dune top edge at locations 6 km (rectangles) and 8 km (ellipses), and total amount of sand mined at Marina operations at locations 14.7–15.3 km (solid line) (see Table 2). Regression slopes have been calculated separately between 1940s–1984 during time of intensive sand mining and 1984–2004 after intensive mining (see Table 1). Uncertainties are indicated by dimensions of symbols.

A possible reason that the rate of erosion has decreased between Monterey and Sand City is because the average 81,000 m³/yr of sand mined at Sand City during the intensive mining years of 1940–1984 was nearly twice the average amount of 47,000 m³/yr mined at Marina during the same time period. While during this same time, the average rate of recession for locations south of the Sand City mines (averaged over locations 1, 3, and 4 km) was 0.85 m/yr compared with the average rate of recession for locations south of the Marina mines (averaged over locations 6 and 8 km) of 1.43 m/yr (see Tables 1 and 2). The expected impact of stopping sand mining would be greater south of Sand City where the erosion rate was lower, but the volume of sand mining was greater, compared with the larger erosion rates and lower amounts of sand mined south of the Marina area. Therefore, it is concluded that sand mining increased the mean recession rates, and also affected the alongshore variation in recession owing to the different amounts of sand extracted at the two sites.

It was pointed out earlier that erosion is not spatially or temporally constant. At most sites, there was an increase in recession between the measurements just prior to 1984 and again between 1997 and 1998, which coincide with the 1982–83 and 1997–98 El Niños. There are only four data points between 1984 and 2004, resulting in only two degrees of freedom on the *t*-statistic. Therefore, a large change in slope is required to have a statistically significant change, even though the erosion rate qualitatively appears to have decreased

everywhere. The highly episodic wave climate complicates relating the volume of sand extracted by mining operations with volumes of sand eroded along the coast.

6. Summary and conclusions

Long-term erosion rates were measured along 18 km of shoreline in Southern Monterey Bay from 1940 to 2004. Erosion is defined here as a recession of the top edge of the dune. Dune erosion occurs when storm waves and high tides coincide to undercut the base of the sand dune causing the dune to slump onto the beach. This results in permanent recession. Dune erosion varied spatially alongshore for both the long-term mean, over kilometer scales, and for the short-term seasonal variation over scales O(200 m). Erosion occurred along the entire 18 km shoreline and varied alongshore at long-term rates that increase from about 0.5 m/yr at Monterey to 1.5 m/yr near Fort Ord and then decrease further north. Causes examined to explain the spatial variation in erosion are: concentration of wave energy, fluctuations in mean sea level, changes in rainfall, and the amount of historical sand mining. It is concluded that the primary reason for alongshore variation in recession rates is the gradient in mean wave energy going from small waves at Monterey, which is sheltered by Point Piños, to larger waves northward.

Erosion is highly episodic. Erosion events are enhanced during stormy winters and particularly during El Niño periods, when prolonged storm waves coinciding with high tides and elevated sea level erode the protective beach and berm, exposing the dune to wave run-up and undercutting. Dune recession appears to be correlated with variations in mean sea level. Mean sea level is increased during El Niño winters. The calculated volume loss of the dune in southern Monterey Bay during the 1997–98 El Niño winter was 1,820,000 m³, which is almost seven times the historical mean annual dune loss of 270,000 m³/yr. Although during an El Niño winter an increase in the erosion rate can be observed, the preceding and following non-El Niño years compensate for this increase with lower erosion rates, keeping the overall historical trend consistent.

The Southern Monterey Bay surf zone was intensively sand mined starting in the early 1900s and continuing until 1990. It was hypothesized that sand mining was a primary cause of erosion in southern Monterey Bay during this time. The best estimate of total average yearly mined sand during the intensive mining years 1940–1984 is 128,000 m³/yr, which is equivalent to approximately 50% of the yearly averaged

dune volume loss during this period. Since sand mining stopped, the erosion rates qualitatively decreased with a significant (at 95% confidence) decrease south of the sand mining operations in Sand City but not significant change at Marina to the north. The alongshore changes in erosion since the cessation of sand mining are partly due to almost twice as much sand being mined at Sand City as compared with Marina. Attempts to determine average recession rates since the cessation of sand mining are complicated by severe erosion occurring during the 1997–98 El Niño winter. Although erosion rates may have slowed as the result of cessation of sand mining, significant recession continues to occur, particularly during times of El Niño winters.

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Rip currents, mega-cusps, and eroding dunes

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Abstract

Dune erosion is shown to occur at the embayment of beach mega-cusps O(200 m alongshore) that are associated with rip currents. The beach is the narrowest at the embayment of the mega-cusps allowing the swash of large storm waves coincident with high tides to reach the toe of the dune, to undercut the dune and to cause dune erosion. Field measurements of dune, beach, and rip current morphology are acquired along an 18 km shoreline in southern Monterey Bay, California. This section of the bay consists of a sandy shoreline backed by extensive dunes, rising to heights exceeding 40 m. There is a large increase in wave height going from small wave heights in the shadow of a headland, to the center of the bay where convergence of waves owing to refraction over the Monterey Bay submarine canyon results in larger wave heights. The large alongshore gradient in wave height results in a concomitant alongshore gradient in morphodynamic scale. The strongly refracted waves and narrow bay aperture result in near normal wave incidence, resulting in well-developed, persistent rip currents along the entire shoreline.

The alongshore variations of the cusped shoreline are found significantly correlated with the alongshore variations in rip spacing at 95% confidence. The alongshore variations of the volume of dune erosion are found significantly correlated with alongshore variations of the cusped shoreline at 95% confidence. Therefore, it is concluded the mega-cusps are associated with rip currents and that the location of dune erosion is associated with the embayment of the mega-cusp.

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1. Introduction

The shoreline of southern Monterey Bay is one of the world's best examples of a quasi-stable rip current system owing to abundant sand supply and near normal wave incidence. Rip channels are persistent morphologic features, which are evident in the photograph (Fig. 1) taken atop a 35 m high dune along the shoreline in southern Monterey Bay. Large beach cusps, termed mega-cusps, with alongshore lengths O(200 m) are also evident.

A convenient morphodynamic framework is provided by Wright and Short (1984), who characterize beach states using a dimensionless fall velocity ($W = H_b / Tw_s$, where H_b is breaking wave height, T is wave period and w_s is sediment fall velocity) starting with high energy dissipative beaches ($W > 6$), to intermediate ($5 > W > 2$), and lower energy reflective beaches ($W < 1$). Given the nominal range of H_b (1–4 m), T (8–16 s) and grain size (0.2–1.0 mm), the most common beach state is intermediate, which is further subdivided into alongshore bar–trough beach, rhythmic bar and beach, transverse bar and beach, and low-tide terrace beach. The values of W range from 0.5 to 5 for southern Monterey Bay,

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Fig. 1. View looking north from a dune crest at Fort Ord showing large scale O(200 m) cusate shoreline with rip currents (indicated by arrows) at the center of their embayment backed by high dunes (exceeding 40 m) vegetated by ice plant.

which increase from south to north as do the wave height and grain size, so that the various beach states tend to be distributed alongshore. The dominant beach morphologies are: 1) low-tide terrace incised by rip channels, 2) transverse bars with associated rip channels, and 3) crescentic, or rhythmic, bar and beach.

Wright (1980), Short and Hesp (1982) and others observed that erosion of intermediate beaches are dominated by the presence of rip currents, with the maximum erosion occurring in the lee of the rip current creating a mega-cusp embayment. If mega-cusps are erosion features of rip currents, this suggests rip currents initiate the morphology and determine the alongshore length scale. Therefore, to understand the alongshore length scale of the mega-cusps, it is essential to understand the mechanism(s) that form rip currents.

Quasi-periodic spacing of rip currents/channels has been observed at numerous locations around the world. Short and Brander (1999) combined observation of rip spacing from a wide variety of sites in Australia, Europe, the United States, Japan, South Africa, and New Zealand. They found the mean number of rips per kilometer ranged from 2 to 13 with the number generally decreasing with increasing wave height and wave period.

Breaking wave patterns in aerial photographs and video time-lapse images can be used to identify rip channels. Wave breaking is a function of depth (Thornton and Guza, 1981). Waves break continuously across shoals owing to shallower water depths, and shows up as white in aerial photos or video images owing to foam and

bubbles generated during breaking. Wave breaking is delayed in deeper rip channels, which shows up as darker regions owing to a lack of wave breaking. Long-term monitoring of nearshore morphology with high spatial and temporal resolution has become possible with the application of video imaging (Lippmann and Holman, 1990). Video “time stacks” have proven a useful means of examining the evolution of nearshore morphology and rip channels (e.g., Holland et al., 1997; Van Ekenvort et al., 2004). Symonds and Ranasinghe (2000) used an alongshore line of time-averaged pixel intensity within the surf zone to identify rip channels as troughs in the intensity. Holman et al. (2006) examined 4 yr of daily time-averaged images. Of particular interest were the events when the rip channels were destroyed and their subsequent regeneration (termed “resets”). The average lifetime of individual rip channels for this pocket beach was 46 days. Resets were hypothesized to be due to filling in of channels during storm events by alongshore sediment transport.

A comprehensive rip current experiment in southern Monterey Bay, RIPEX, was conducted to measure their dynamics and kinematics (MacMahan et al., 2004, 2005, 2006). It became obvious in the course of the investigations on rip currents that observed cusate shoreline and dune erosion had similar alongshore length scales with the rip channels, and that they behaved in similar manners in response to the wave climate. An aerial photograph mosaic of the 18 km shoreline from Monterey to the Salinas River shows rip channels all along the

shore with increasing alongshore spacing toward the north (Fig. 2). A detailed aerial photograph (Fig. 3) shows that the shoreline is cusped, and that a rip channel is located at the center of the embayment of all the mega-cusps.

Based on these qualitative observations, it is hypothesized that dune erosion occurs at the embayment of O (200 m) mega-cusps (Short, 1979; Short and Hesp, 1982; Shih and Komar, 1994; Revell et al., 2002) that are erosion features of rip currents (Bowen and Inman,

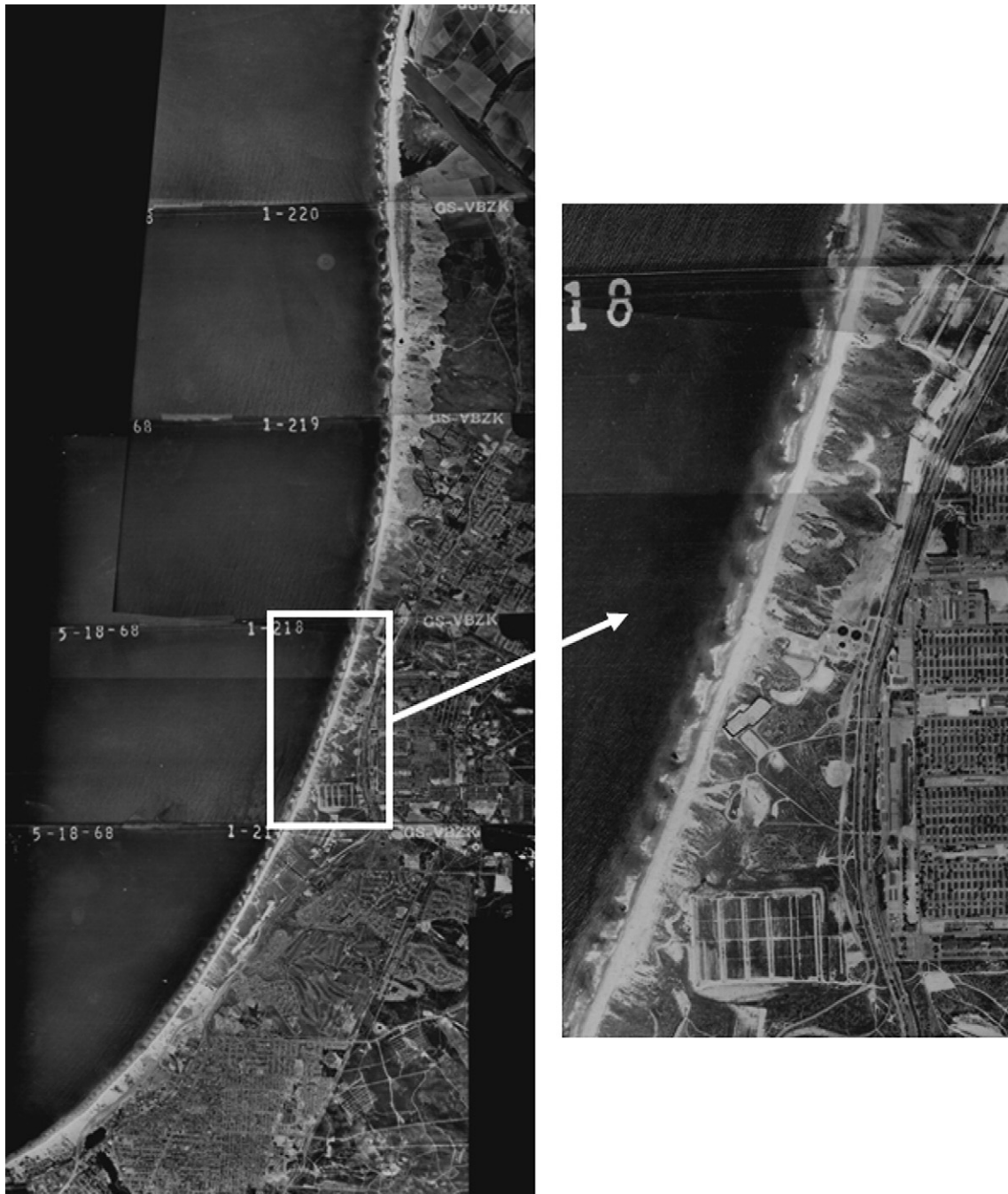


Fig. 2. 15 km aerial photo mosaic of southern Monterey Bay shoreline, which shows rip channels (dark region between white of breaking waves) with spacing increasing from north to south.

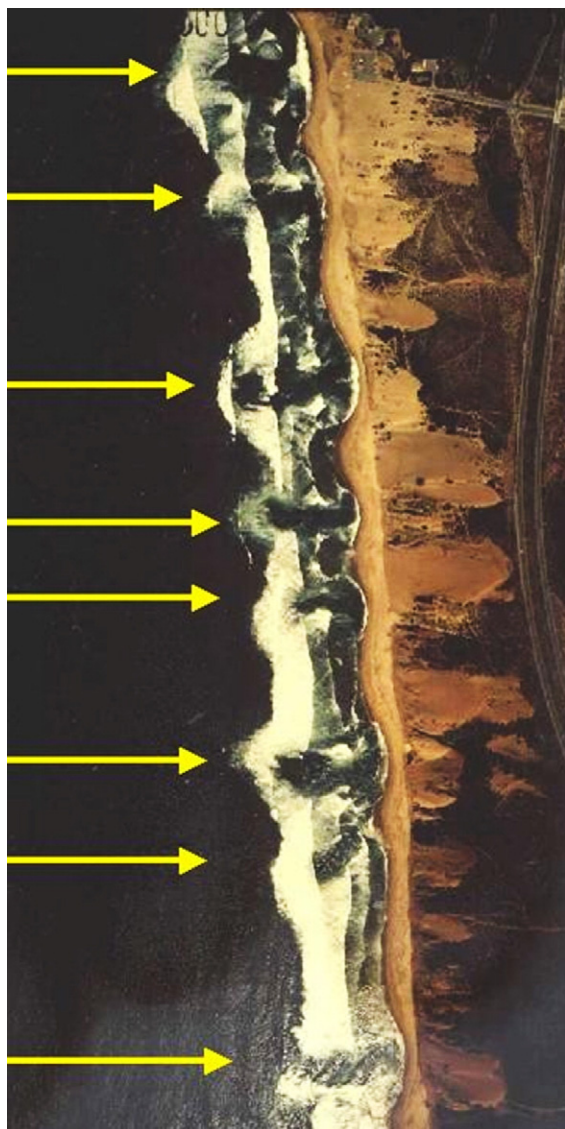


Fig. 3. Cusped shoreline (wave lengths 100–400 m) with rip currents (dark areas in surf zone indicated by arrows where waves do not break in the deep rip channels) at the center of each mega-cusp embayment.

1969; Komar, 1971; Short and Hesp, 1982). The beach is the narrowest at the embayment of the mega-cusps where the natural buffer by the beach to erosion is decreased. This allows the swash and the additional set-up by large storm waves during coincident high tides to more easily reach the toe of the dune and undercut it, causing the dune to slump onto the beach. These hypotheses are tested by analyzing field measurements of rip channels, beaches and dunes acquired using a variety of surveying techniques, and of directional wave data acquired during the same time.

2. Setting

Monterey Bay is a 48 km long bay extending from Point Santa Cruz in the north to Point Piños in the south. Dominant bathymetric features within the bay are the Monterey Bay submarine canyon, the largest in the western hemisphere, and the ancient delta offshore the Salinas River (Fig. 4). The predominant deepwater wave directions are from west to northwest. The waves approach at near normal incidence all along the shore because of the narrowing of the aperture by the headlands to the north and south, the strong refraction across the canyon, and the historical (geologic time-scale) re-orientation of the shoreline in response to the wave climate. The near-normal incidence of waves to the shoreline is conducive to rip current development, maintenance and relative stationarity.

The bay is partitioned into north and south littoral cells by the submarine canyon, which extends to the mouth of Elkhorn Slough at Moss Landing. The submarine canyon intercepts the dominant littoral drift from the north and diverts it down the canyon. Wave refraction analysis by the U.S. Army Corps of Engineers (1985) over the bulge in the bathymetric contours about the ancient delta of the Salinas River suggests that the littoral transport diverges to the north and south at the river. This further subdivides the southern littoral cell into two cells at the river mouth.

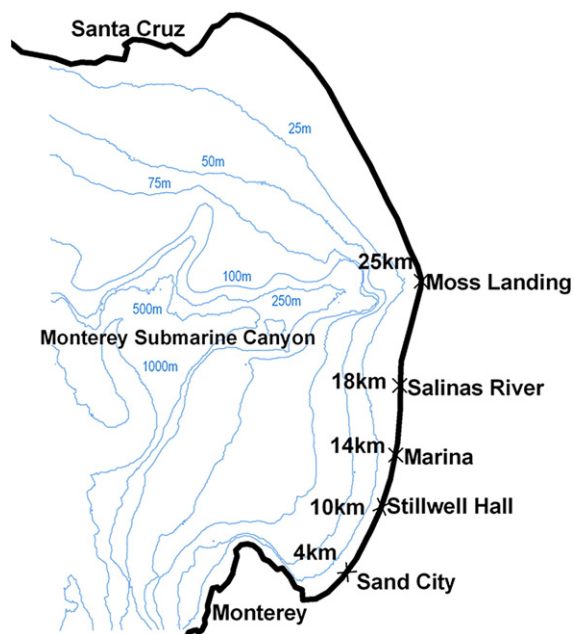


Fig. 4. Shoreline and bathymetry of Monterey Bay. The survey area is from Monterey to Salinas River (distances from Monterey are indicated in km).

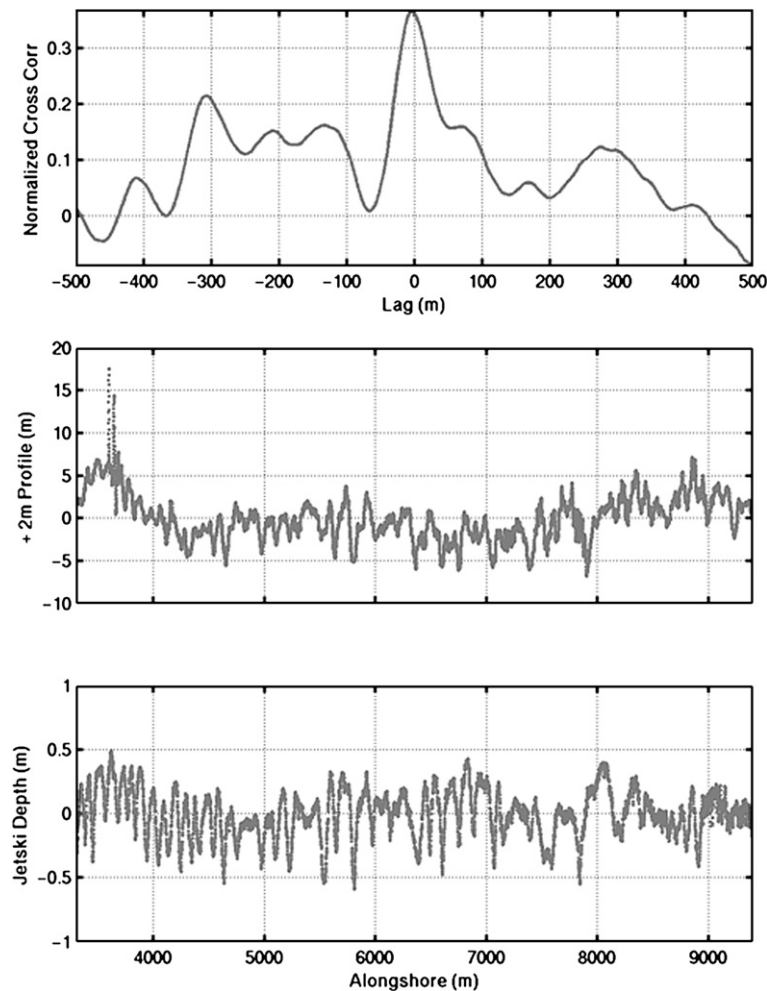


Fig. 5. The +2 m contour deviation from mean shoreline as a function of alongshore distance, 8 August 2003 (middle panel), shore parallel bathymetry showing shoals and rip channels alongshore on 18 July 2003 (bottom panel), and the cross-correlation between the two (upper panel).

The focus of this study is the littoral cell encompassing the 18 km shoreline from Monterey (0 km) to the Salinas River (18 km) (Fig. 4). The sandy shoreline is backed by extensive dunes, which between Sand City and Marina rise to heights exceeding 40 m. The shoreline and dunes are in a general state of erosion with average recession rates varying from 0.5 to 2 m/yr (Thornton et al., 2006). Erosion is episodic, and only occurs during coincident high tides and sustained storm waves. The tides are semi-diurnal with a mean range of 1.6 m. Sand size varies alongshore, dependent on wave height. The largest median grain size on the beach face ranges from 0.6 to 1 mm between the Salinas River and Fort Ord where the wave energy is the largest, and then decreases towards Monterey (Dingler and Reiss, 2001). Grain size and petrology evidence suggest that the sediment contribution by the Salinas River to the south

even during times of major floods is small and limited to within 7 km of the river mouth (Clark and Osborne, 1982). Therefore, sand slumping onto the beach due to erosion of the dunes is the primary source of sediments to the southern littoral cell. Alongshore variation in long-term (averaged over ~40 yr) erosion appears correlated with the alongshore variation in mean wave energy (Thornton et al., 2006).

3. Field measurements

3.1. Morphology

The rip channel/shoal morphology, cusped shoreline and dune erosion are measured using a variety of survey techniques. Bathymetry is measured by a sonar mounted on a personal watercraft (PWC) navigated using

Kinematic Differential GPS (KDGPS) with an ~ 5 cm rms accuracy in all three directions sampling at 10 Hz (MacMahan, 2000). On a low wave day ($< \sim 50$ cm wave height), the personal watercraft was piloted along a line maintaining a constant distance of approximately 25 m from shore. The resulting measurements resolve bar shoals and rip channels continuously alongshore (Fig. 5, bottom panel), from which rip channel spacing can be determined.

The cusped shoreline is determined by measuring the +2 m contour using an all-terrain vehicle (ATV) navigated with KDGPS. The ATV drives the beach at low tide close to the water line and returns higher on the beach. The 2 m contour is interpolated from the location information of the two lines. The 2 m contour is chosen as it includes the classic ($O(30$ m)) beach cusps, which are not present below mean sea level (MSL) and are not generated on the back beach. The +2 m contour is

higher than the mean high-high water (MHHW) elevation of +0.8 m relative to MSL. The curvature of the mean shoreline is subtracted from the surveys. A mean shoreline of the measured 18 km shoreline on 7 January 2004 was obtained by fitting six contiguous least-square-fit quadratic sections that are joined by matching intersections and slopes. This mean shoreline is subtracted off all measured beach surveys (e.g., Fig. 5, middle panel). The beach surveys were started in July 2003, but only measured sporadically until February 2004, after which surveys have been conducted (every 2 weeks) to obtain a time history of the mega- and beach cusp evolution.

The shoreline of Monterey Bay was surveyed using airborne Light Detection and Ranging (LIDAR) before (October) and after (April) the 1997–1998 El Niños winter, during which time significant erosion of the beaches and dunes occurred (up to 15 m dune recession).

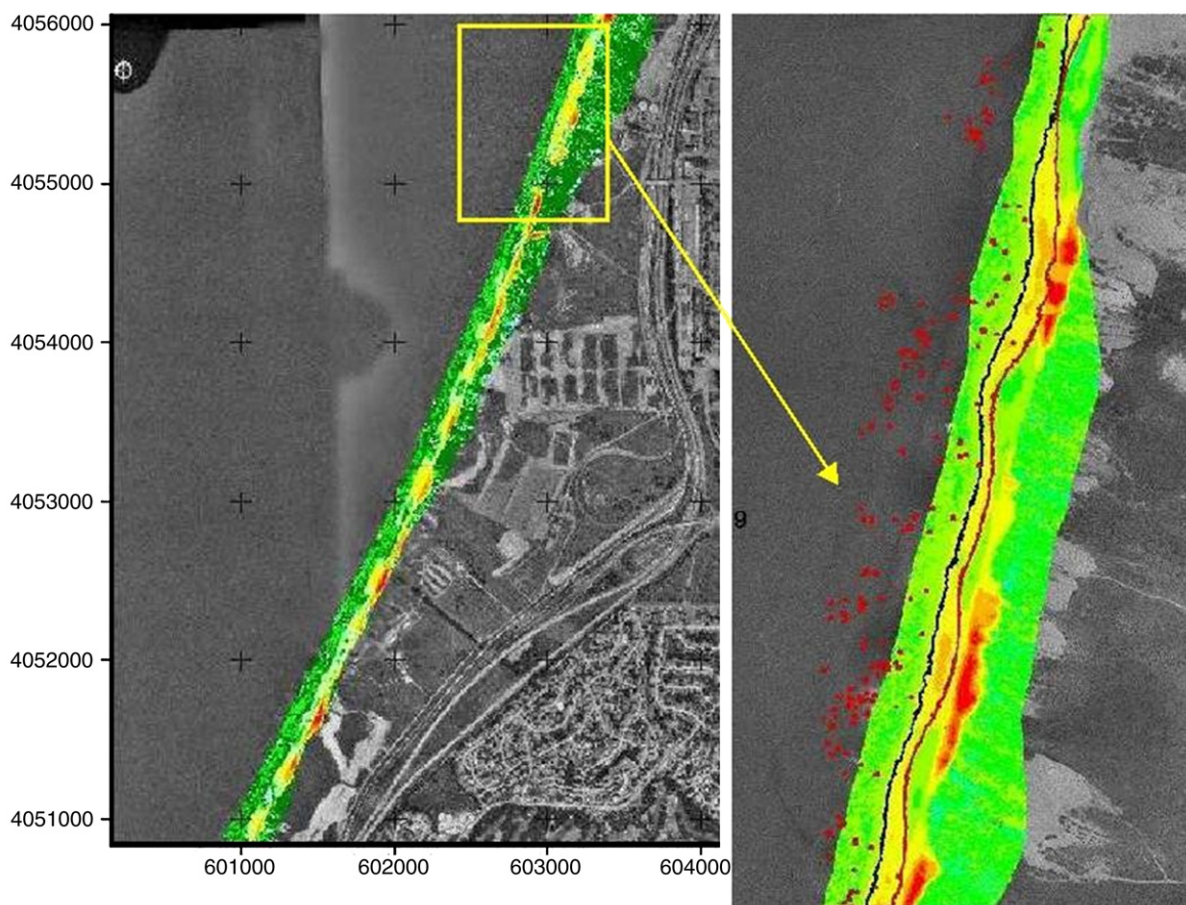


Fig. 6. Elevation differences between LIDAR surveys obtained October 1997 and April 1998 along 4 km of shoreline showing “hot spots” of erosion (red) spaced 100–400 m alongshore. Inset blow-up shows +2 m beach contours for October 1997 (black) and April 1998 (red). Hot spots occur at embayment of mega-beach cusps.

The LIDAR measures the subaerial topography of the exposed beach and dunes with 1–2 m horizontal resolution with better than 15 cm vertical accuracy (Sallenger et al., 2003). Erosion is determined from the difference of the two surveys. Large alongshore variations of the dune erosion were measured (Fig. 6), which shows up as “hot spots” with length scales of 200–500 m. The +2 m beach contour measured by LIDAR for both pre- and post-El Niño is indicated in the Fig. 6 inset, which shows large cusped features having the same 200–500 m length scale as the dune hot spots. The dune erosion most commonly occurs in back of the mega-cusp embayments where the beach width is the narrowest.

To quantify the randomly sampled LIDAR data, the measurements were converted to a regular grid in rectangular coordinates using a Delany triangulation interpolation. Cross-shore profiles were computed every 25 m alongshore. Beach and dune erosion are determined by subtracting the cross-shore profiles of April from that of October (Fig. 7). The dune toe height, determined from where there is a large change in profile slope, divides the beach from the dune profile.

The magnitude of the beach and dune erosion variability is examined by comparing four cross-shore LIDAR profiles for 1997 and 1998 spaced ~100 m apart, starting at alongshore location 11.5 km and proceeding north (Fig. 8). The first panel shows beach profiles with no dune erosion, 100 m north both beach and dune

erosion occur with 14 m of dune recession, 100 m farther north there is again beach erosion with no dune erosion, and 100 m farther north there is 11 m of dune recession with no beach erosion. As will be shown, this large alongshore variation in dune erosion is related to the cusped shoreline, which is related to the rip currents.

3.2. Waves

Directional wave spectra are measured routinely at NOAA 46042 buoy located 40 km offshore of Monterey Bay and are refracted shoreward (Fig. 9) to provide wave heights throughout the bay every 4 h (<http://cdip.ucsd.edu/models/monterey>). Nearshore directional wave spectra are measured by acoustic Doppler current profilers cabled to shore located in 12 m offshore of Monterey and Sand City, and by a Wave Rider directional buoy in 17 m offshore Marina. There is a large gradient in wave height over km scales going from small waves in the shadow of the southern headland, to the middle of the bay at Fort Ord and Marina where convergence of waves owing to refraction over the Monterey Bay submarine canyon results in increased wave heights.

Frequency-directional spectra of the incident waves at the shallow water locations are calculated from the time series of pressure and velocity, and slope and heave using a Maximum Entropy Method (Lygre and Krogstad, 1986) every 2 h. The significant wave height

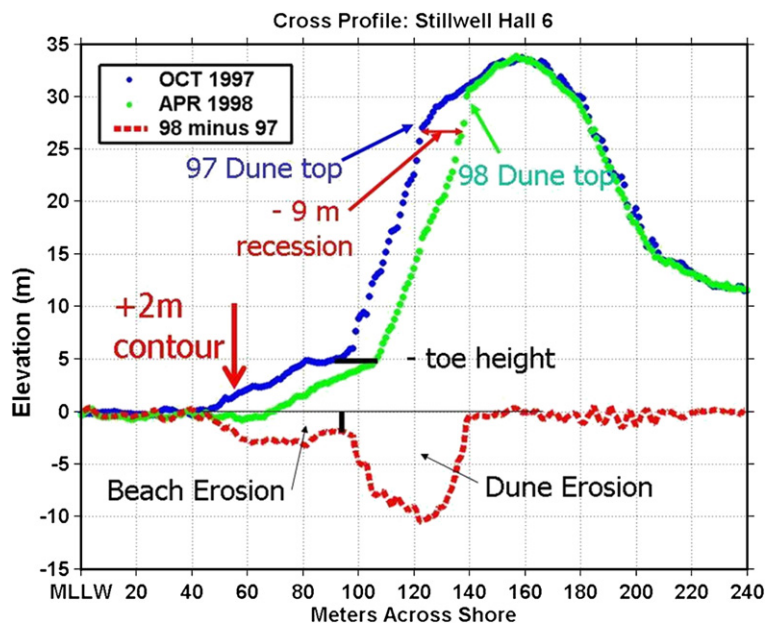


Fig. 7. Cross-shore profiles as measured by the LIDAR surveys for October 1997 and April 1998. Beach and dune erosion separated by the toe height are determined from the difference of the two profiles. The 2 m contour is determined from the profile.

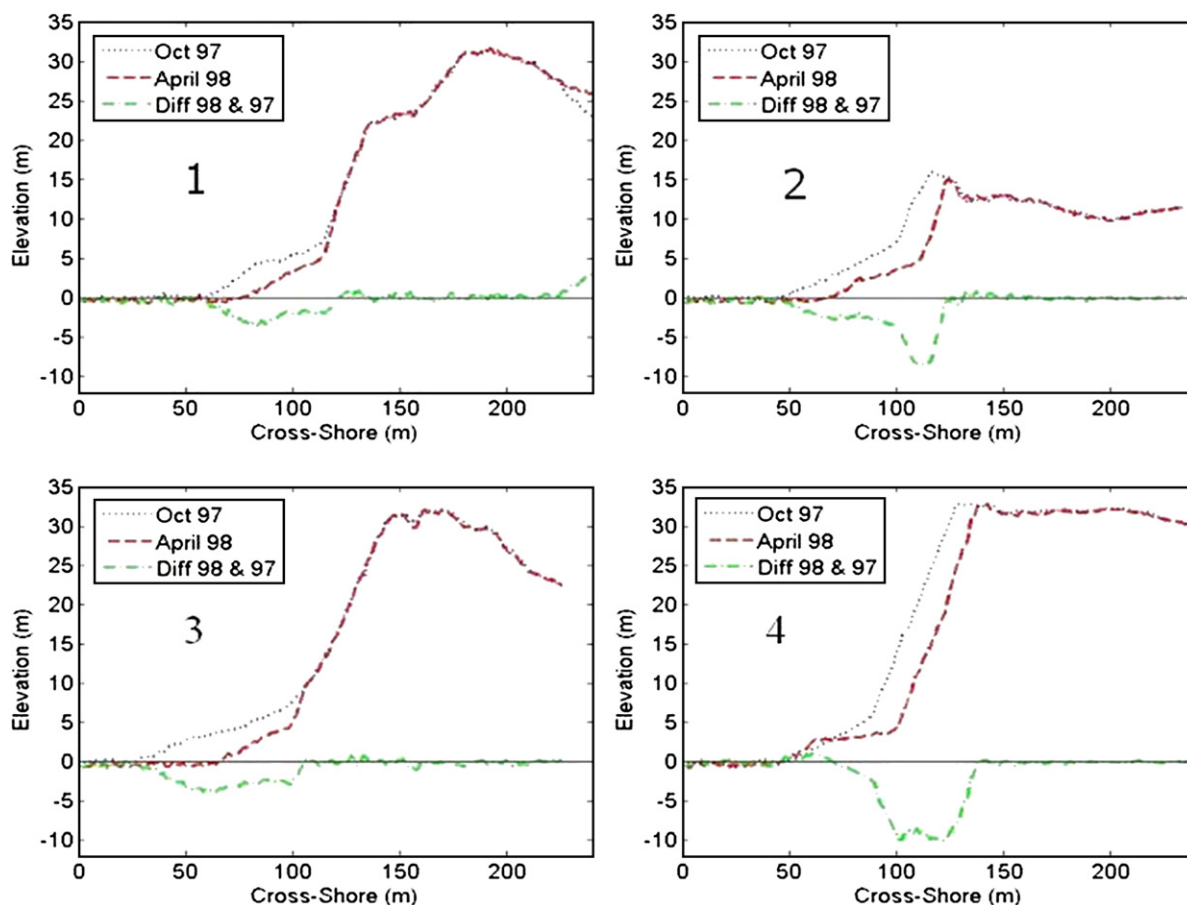


Fig. 8. Cross-shore profiles spaced approximately 100 m in the alongshore as determined from the LIDAR surveys showing large alongshore variations in beach and dune erosion.

(H_s), peak period (T_p), and mean wave direction of peak period (D_p) at Sand City in 12 m water depth are compared with data from the offshore buoy for January–April 2004 in Fig. 10. H_s at 12 m depth reflects the offshore H_s in time with diminished heights. The D_p during this time was primarily from the west-northwest to south (the shoreline orientation of 313° has been subtracted). Owing to wave refraction, the mean wave approach direction in shallow water is near normal incidence. The peak periods of waves measured in shallow water are longer than measured offshore at the buoy (not shown). The wave energy inside the bay represents the swell component of the wave spectrum as refraction and the narrower aperture of the headlands filter the higher frequencies associated with diurnal sea breezes.

4. Analysis of data

The alongshore spatial and temporal variations of rip channel, mega-cusp, and dune recession spacings are

cross-correlated with each other to test hypotheses. It was not possible to acquire synoptic data on rip channels, cusped shorelines and dune erosion owing to the episodic occurrences of the dune erosion. Many years there is no dune erosion. Dune erosion is enhanced during El Niños winters when storm waves occur more frequently with greater intensity on average. El Niños winters occur on average about every 7 yr, and one has not occurred since starting the beach surveys. Therefore, the rip channel variations obtained from an opportunistic PWC survey obtained when the waves were low are compared with the cusped shoreline surveyed with GPS-equipped ATV, and then the cusped shoreline and dune erosion measured with LIDAR are compared for different times.

The hypothesis that the mega-cusps are associated with rip currents is examined first by cross-correlation of the shore-parallel PWC survey of bathymetry conducted on 8 August with the +2 m contour determined by an ATV survey on 18 July 2003 (Fig. 5). The

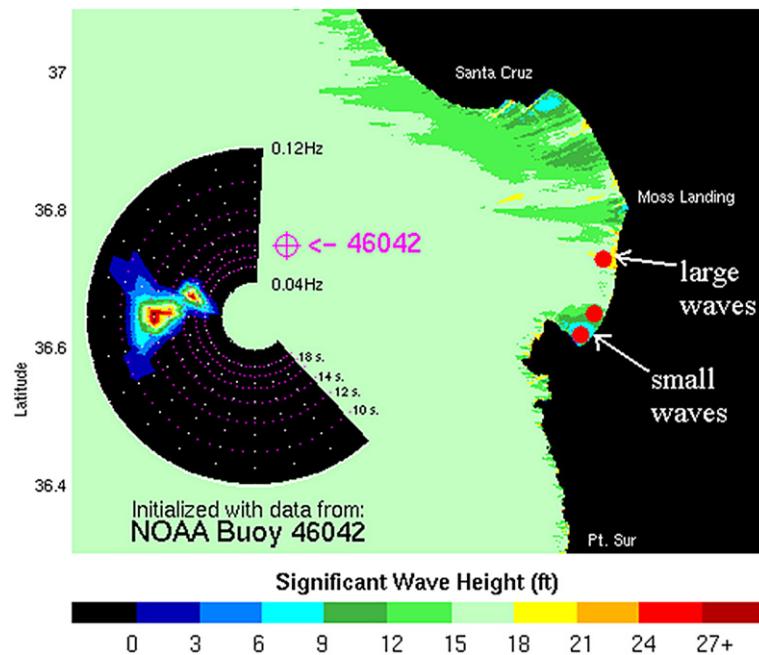


Fig. 9. Directional wave spectrum measured at NOAA buoy 46042, 40 km offshore, refracted into Monterey Bay. Large variations of wave height occur alongshore owing to wave refraction over the Monterey Bay submarine canyon and sheltering by headlands. Locations of nearshore directional wave sensors are indicated by dots.

spacing of the rip channel locations and mega-cusps of the shoreline varied between 200 and 300 m over the approximate 6 km of shoreline. The maximum cross-correlation value between the rip channel morphology and shoreline is 0.35, which is significant at the 95% confidence level with near zero spatial lag.

The lack of correlation (value < 1) between the two records occurs primarily because of the 21-day separation time between surveys. This is demonstrated by calculating de-correlation times and migration rates from cross-correlations of the shoreline spatial series. The shoreline spatial series for February–April 2004 when surveys were taken regularly is used. A reference +2 m contour shoreline at the start of the series on yearday 51 (20 Feb 05) is cross-correlated with subsequent shoreline surveys. In addition, a single shoreline survey taken 44 days previous (on yearday 10) to the reference survey is cross-correlated (Fig. 11). Since the shoreline series is inhomogeneous (scale varies alongshore owing to wave height gradient), the cross-correlations are done for sections of shoreline. As an example, cross-correlations for the shoreline between 4 and 10 km show the peak correlation decreases with time and the location of the maximum correlation shifts alongshore indicating the cusps are migrating alongshore (Fig. 12). The peak correlation as a function of

time since the initial survey is fitted with an exponential curve in a least-square sense (Fig. 12, left panel). A measure of the de-correlation time is the e-folding time. Both the previous (indicated by a circle) and subsequent shoreline surveys (stars) are consistent. The e-folding time during “normal” winter/spring waves exceeded 50 days.

The de-correlation with time is used to explain the lack of correlation between the mega-cusps and rip channels shown in Fig. 5. If the rip channel morphology and shoreline act in the same temporal manner (i.e., correlated), then the expected cross-correlation with a 21-day separation in time using the de-correlation with time measured above would be 0.65. If it is assumed the rip channel morphology and shoreline act independently with time, then the expected cross-correlation with a 21-day separation in time using the de-correlation with time of 0.65 would be the square of that value to give 0.4, which is consistent with the measurements.

Mean migration rates of the mega-cusps for sections of shoreline are determined by the displacement of the peak correlation with time (Fig. 12, right panel). For the 4–10 km section of beach, the mega-cusp system migrated at 3.4 m/day to the north for 70 days from 7 January to 18 March. Since the shoreline and rip channel bathymetry are correlated and it is assumed the cusps

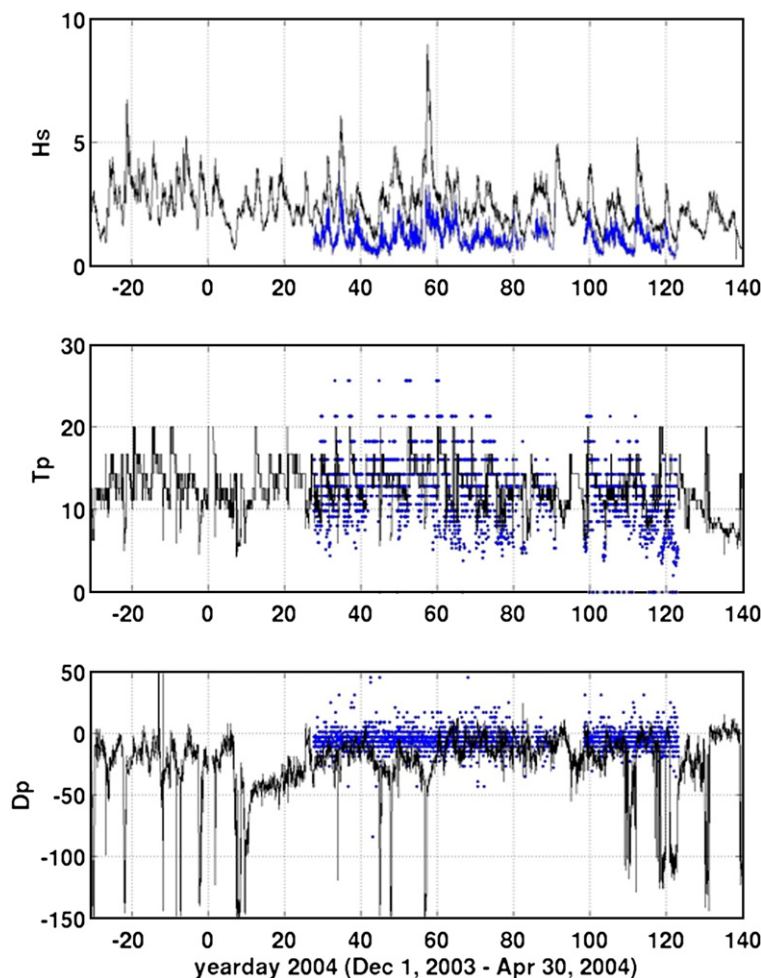


Fig. 10. Significant wave heights, H_s , at offshore buoy and at 12 m depth at Sand City, California, peak wave period at 12 m depth, T_p , mean wave direction at peak period, and D_p , at the offshore buoy (solid black line) and at 12 m depth (blue dots) relative to shore normal.

shoreline is an erosion feature of the rip currents, it would be expected that the rip channels migrate at the same mean rate. Therefore, it would be expected that the spatial lag for their cross-correlation would be near zero as they migrated together at approximately the same rate as is found in Fig. 5.

For the 10–15 km section of shoreline, the de-correlation e-folding time is approximately 40 days (Fig. 13, left panel). This section of beach is more exposed to higher waves, and this may account for the faster de-correlation time compared with the section of shoreline between 4 and 10 km. The mega-cusps migrated at 3.7 m/day to the north for 70 days from 7 January to 18 March, and then were stationary (Fig. 13, right panel), similar to the migration of the mega-cusps between 4 and 10 km.

The 40–70-day de-correlation times imply that bi-monthly surveys are sufficient to avoid aliasing the time

series and for describing the processes. However, between shoreline surveys on 9 December 2003 to 7 January 2004, a major storm occurred (7 m significant wave height offshore on 10 December during time of spring tides, see Fig. 10) and the de-correlation time was less than the time between surveys (Fig. 14). It is noted that the largest waves of the winter (>8 m) occurred on 1 March during a time of neap tides such that little or no erosion occurred, and the shoreline correlation did not change between surveys (Fig. 13, left panel). The ATV surveying system was not operational from the last survey in April until the next survey in October, a 190-day time period. However, the two surveys were still correlated, indicating that the de-correlation time during the summer months when the waves were lower exceeded 200 days (Fig. 14).

The hypothesis that dune erosion occurs at the embayment of the mega-cusps is examined by cross-correlating the alongshore variation of dune erosion

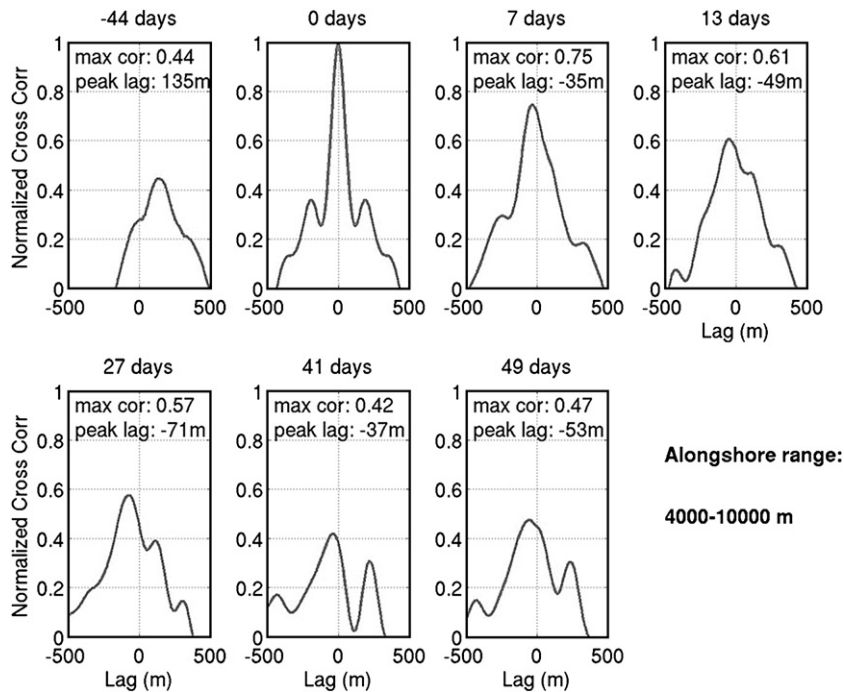


Fig. 11. Cross-correlations between shoreline survey of +2 m contour for 4–10 km on 20 February 2004 and subsequent surveys. Days between survey and survey on 20 February 2004 is noted at top of each plot.

with the +2 m beach contour. The volume of dune erosion was determined by the difference between cross-shore profiles every 25 m for the 1997 and 1998 LIDAR surveys. The cusped shoreline was determined from the 2 m contour measured from the cross-shore profiles every 25 m for the 1998 LIDAR survey. The dune erosion and the alongshore variations in the shoreline 2 m contour are significantly correlated at 95% confidence (Fig. 15, upper panel).

Since dune erosion is found significantly correlated with beach width, which is narrowest at the embayment of mega-cusps, it is expected that the dune erosion

would be in-phase with the shoreline, *i.e.* zero spatial lag. However, a significant spatial lag of about 75 m is noted between the volume of dune erosion and the mega-cusps, which is discussed in the next section.

Both the cross-shore width of the mega-cusps (measured as the difference between the cross-shore locations of the horn and embayment) and the alongshore mega-cusp length varied alongshore. For example during the April 1998 LIDAR survey, widths of the cusps increased from 10 m to more than 40 m and lengths increased from 180 m to over 400 m proceeding from south to north (Fig. 15, middle panel). The volume of dune erosion also

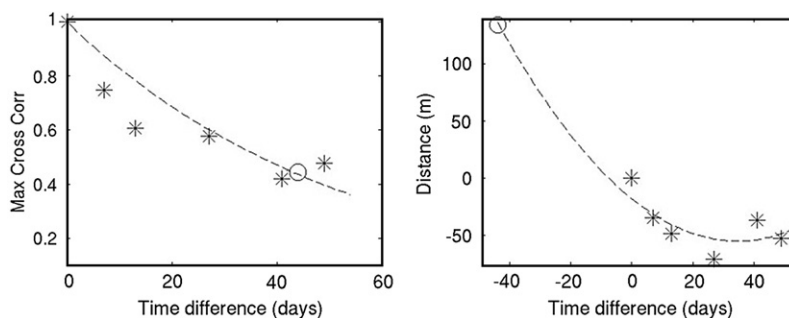


Fig. 12. Maximum cross-correlation between 20 February 2004 and subsequent (*) and previous (○) surveys (left panel), and the displacement of the maximum cross-correlation between subsequent surveys describing migration of shoreline (right panel) for 4–10 km.

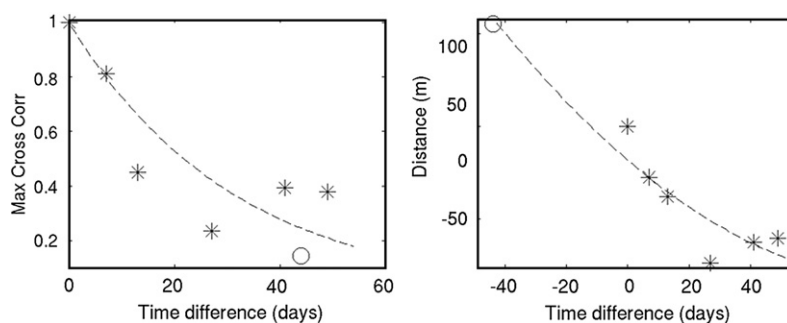


Fig. 13. Maximum cross-correlation between 20 February 2004 and subsequent (*) and previous (O) surveys (left panel), and the displacement of the maximum cross-correlation between subsequent surveys describing migration of shoreline for 10–15 km.

varies significantly alongshore (Fig. 15, lower panel) and is dependent on both recession rate and height of the dune.

5. Discussion

5.1. Spatial lag between dune erosion and mega-cusps

Since the enhanced dune erosion remained in the same locations after the 1997–1998 El Niño winter, the spatial lag that was measured between the dune erosion and 2 m contour is due to the migration of the cusps between the time(s) of the dune erosion and the April shoreline survey. Dune erosion is the culmination of storm events over the winter. A measure of erosion potential is when swash run-up exceeds the elevation of the toe of the dune, so that the swash can impact the dune. Following the method by Sallenger et al. (2000), the swash run-up height of the average highest 2%

waves (Holman and Sallenger, 1985; Holman, 1986) is calculated based on wave height and period of waves measured every 4 h at NOAA deep water direction wave buoys:

$$R_u = H_0 \left(\frac{0.83 \tan \beta}{\sqrt{H_0/L_0}} + 0.2 \right) + \eta_{\text{tide}}$$

where H_0 is significant wave height in deep water, L_0 is deep water wave length calculated from the period using linear wave theory, $\tan \beta$ is the beach slope and η_{tide} is the tide elevation measured in Monterey Bay at the time of the wave measurement.

The NOAA wave buoy 46042 offshore Monterey Bay failed on 27 October 1997 owing to large waves and was not restored until June 1998, so these data were not available during the time of interest. Instead, the waves measured by the NOAA wave buoy 46026 off San Francisco 110 km to the north were used during 1997 and when it also failed in early January 1998, the NOAA wave buoy 46014 off Mendocino 310 km to the north was used. The wave heights and periods measured by the northern buoys were “adjusted” to correspond to the Monterey buoy data by using linear regression curves between buoys calculated for a 130-day period (19 June–26 October 1997). The waves at Monterey during this time period were 1.14 times greater than off San Francisco, but 0.94 times less than off Mendocino. The mean peak wave period at Monterey was 2% greater than off San Francisco and 8% greater than off Mendocino. The wave heights and periods in deep water off Monterey Bay and calculated run-up during the interval of LIDAR surveys are shown in Fig. 16. The horizontal dashed line is the mean elevation of the dune toe. The vertical solid lines are days when the LIDAR surveys were conducted. During the time between LIDAR surveys, the calculated run-up exceeded the dune toe for an extended time 40 to 90 days prior to the

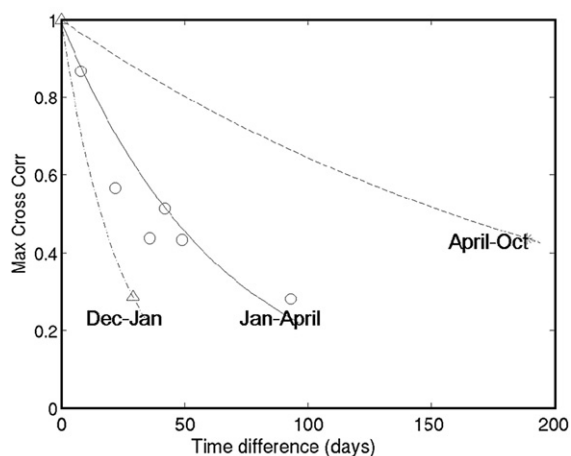


Fig. 14. De-correlation between surveys of +2 m contour for 10–15 km alongshore.

survey in April, when significant erosion would be expected. Given that the average cusp migration rates measured during the 2004 surveys ranged 0 to 3.5 m/day, the mega-cusps could easily be expected to have migrated 75 m between when the erosion occurred and the April LIDAR survey of the 2 m shoreline contour.

The lack of correlation (<1) between alongshore variations in dune erosion and the 2 m contour is assumed due primarily to the approximate 45-day time difference between the cumulative occurrence of dune erosion (latest time of when the persistent run-up exceeded the toe of the dune, Fig. 16) and when the 2 m contour survey was performed. Assuming that the shoreline migration acted independently after the occurrence of dune erosion, and using the measured correlation function between rip channel locations and 2 m contour as an analog (Figs. 12 and 13, right panels), the expected maximum correlation would be approximately 0.4, which is comparable to the measured value (Fig. 15, upper panel).

5.2. Hot spots

It has become apparent that erosion does not occur uniformly, but is highly variable with recognizable “hot spots” of erosion. Hot spots are sections of coast with substantially higher rates of erosion than adjacent areas. There are a number of processes responsible for hot spots, only some of which are understood (such as those associated with wave focusing around offshore holes or shoals). List and Farris (1999) used a GPS-equipped ATV to measure changes of mean high water shoreline position along a 70 km section of coastline on the Outer Banks of North Carolina and 45 km of Cape Cod, Massachusetts. They found “reversing storm hot spots”, which are areas of significant storm erosion that alternate, on a spatial scale of 2–10 km, with sections of coast that experience little or no erosion. During post-storm fair weather, storm hotspot erosion is rapidly reversed by a similar magnitude of accretion, while the intervening areas remain unchanged. The cause of these hot spots is not understood.

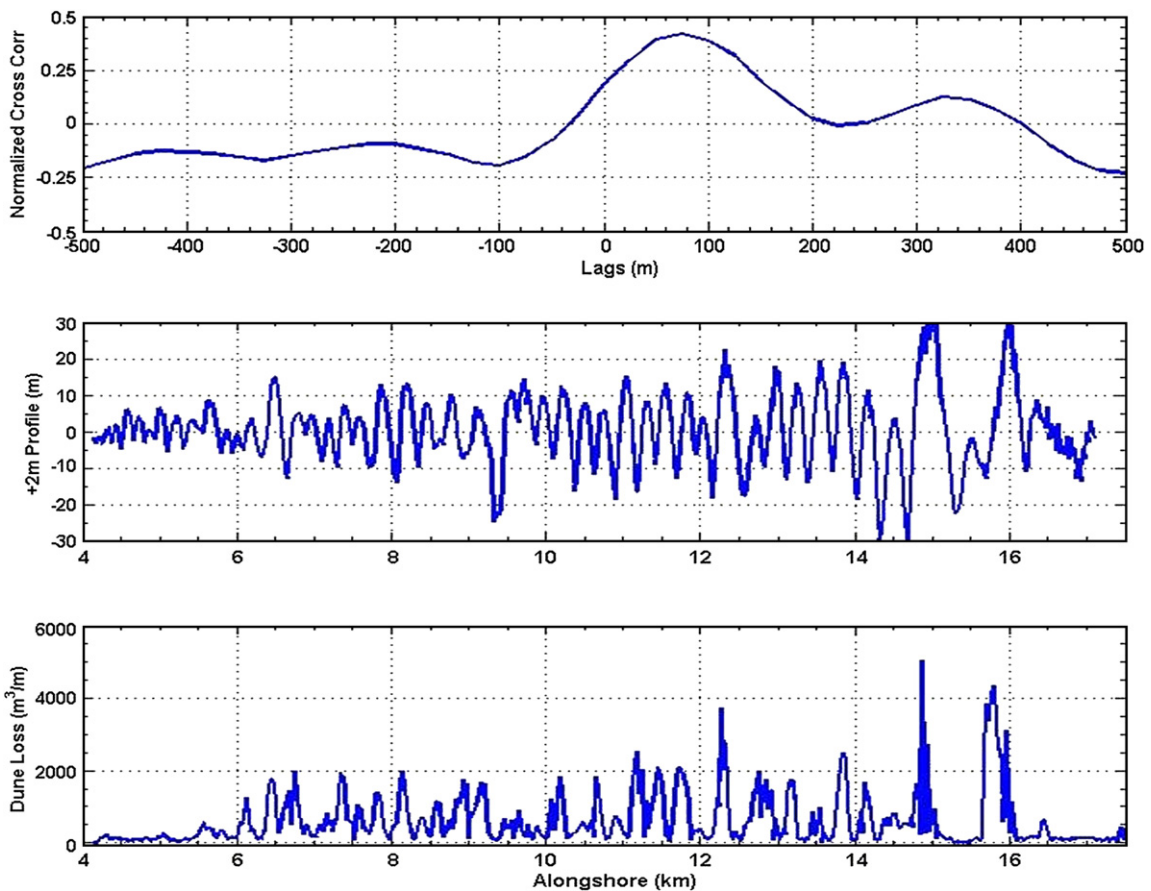


Fig. 15. Cross-correlation (top panel) between +2 m contour on April 1998 (middle panel) and volume of alongshore dune erosion between October 1997 and April 1998 (bottom panel) obtained from LIDAR surveys.

Hot spots observed in southern Monterey Bay are irreversible. Dune recession is permanent, because there is no present-day natural mechanism for the restoration of the dune face. Based on the analysis here, we feel that the hot spots are due to the narrowing of the beach at the mega-cusp embayments associated with rip currents making the dunes at these locations more vulnerable to undercutting by swash during coincident high tides and storm waves.

The spatially variable erosion created by these hot spots enhances the erosion rate as compared with a uniform shoreline with the same average beach width. For the uniform beach, a smaller percent of swash events would be able to reach to dune toe because of the greater beach width compared with the narrower beach in the embayment. Hence, fewer erosion events would occur with decreased overall erosion.

The location of these hot spots cannot persist, as eventually there would be substantial holes in the dune. The dunes are observed to recess quasi-uniformly over

the long term. Therefore, the location of the rip channels and associated mega-cusps and dune erosion either migrate, or are “reset” and regenerated at random alongshore locations. The primary sediment supply to the littoral cell of southern Monterey Bay is the slumping of the sand onto the beach by the eroding dune. The dune slumping onto the beach can act as a negative feedback by providing a supply of sand to fill the cusped shoreline and rip channel in the absence of alongshore currents.

It is important to remember that dune erosion occurs episodically and does not even occur every winter. Severe erosion occurred during the 1997–1998 El Niños owing to the large storm waves that persisted for extended periods of time (Fig. 16). The 1997–1998 El Niños along with that in 1982–1983 were the most extreme storms of the 20th century (Seymour, 1998), and the 1997–1998 El Niño caused the more severe erosion in southern Monterey Bay. Persistent, or repeated, storms cut back the beach, making the dunes more vulnerable to future storms. The total calculated

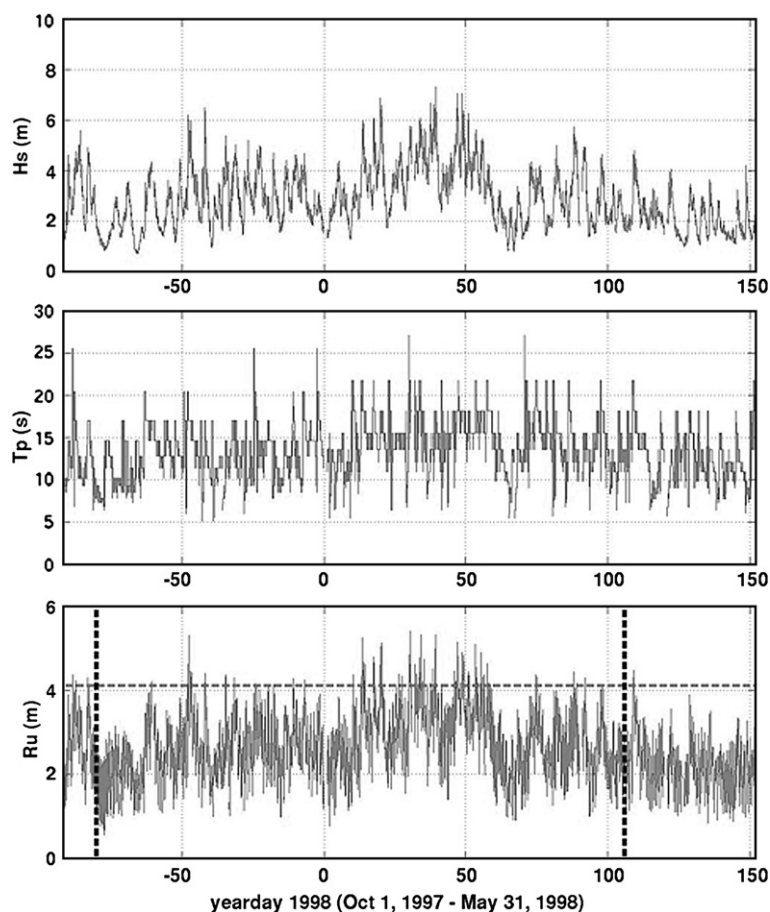


Fig. 16. Significant wave height, H_s , and peak wave period, T_p , at offshore buoys, and calculated run-up plus tide elevation (dotted line is mean elevation of dune toe). The vertical lines in the run-up plot are the times of the LIDAR surveys.

volume of dune erosion over the 18 km of shoreline during the 1997–1998 El Niño was 1,820,000 m³, which is almost seven times the historical annual mean dune erosion of 270,000 m³/yr (Thornton et al., 2006).

Hot spots are important to take into account in coastal management decisions. In the consideration of setbacks, it is important to recognize that there is a significant variation, both in space and time, in the mean erosion rate associated with potential hot spots. Hot spots often cause property owners to panic, and seek to armor their property. In the case of southern Monterey Bay, the hot spot are not expected to return at the same location the next year.

Interestingly, reversing hot spots have only been recorded on the eastern shoreline of the U.S., while cusped shorelines associated with rip currents are most commonly observed on the west and gulf coasts. This is presumably associated with the differences in wave climate.

5.3. Morphodynamics

Migration of rip channels and their time-scales are not understood. Obviously at some locations alongshore currents and associated littoral sand transport cause rip currents to migrate, but at the same time they act to destroy the rip channels by filling them. Alongshore currents are weak in southern Monterey Bay because of the near normal wave incidence (hence, the persistent rip fields). Local surfers observe (complain) that rip channels tend to be filled during large storms (therefore, diminishing their wave crest surfing edge). On the other hand, Dingle (pers. comm.), in the course of 17 yr of repeated beach profiles in Monterey Bay (Dingle and Reiss, 2001), visually observed that the rip channels tended to be filled by low, long-period summer waves transporting sand shoreward, which was also observed in a short-term field experiment by Brander and Short (2001). This process is not understood, and hopefully long-term video data will provide the necessary answers to this question.

Swash generated by incident and infragravity storm waves is responsible for undercutting the dunes at high tide. Swash is a function of the incident breaking waves. The interaction of the incident waves and outgoing rip current can cause waves to break, which would diminish the swash. Wave set-up (the mean of swash) in rip channels was measured in the laboratory by Haller et al. (2002). They found that set-up was dependent on how the waves broke within the rip channel. Higher set-up occurred when the waves did not break in the rip channel, but broke closer to the shoreline. No field data exists

on swash in back of rip currents and only limited lab data is available. Therefore, the mechanism responsible for dune erosion in back of rip currents and in mega-cusp embayments is not well understood.

Haller et al. (2002) and MacMahan et al. (2006) found a counter circulation in back of the rip current near the beach that was created by an adverse pressure gradient as the waves broke closer to shore. The counter current may be important in eroding the embayment of the cusp in back of the rip current.

Classical beach cusps (wavelengths O(30 m)) were often observed to be well-developed with amplitudes increasing in the direction of increasing wave energy. Short (1999) suggests the beach cusps tend to occur on the mega-cusp horns, with a steeper eroded beach face in the embayment.

A deficiency in this study is that the data were not obtained synoptically. Dune erosion and a cusped shoreline were measured using LIDAR and appear correlated. Unfortunately there were no aerial photos or time-averaged video images available during the time of the LIDAR surveys to establish a direct relationship between dune erosion, mega-cusps and rip channels. Four video camera systems have since been installed along the shoreline between Monterey and Marina, and future studies will address the temporal evolution of rip currents, cusps and dune erosion.

6. Summary and conclusions

Monterey Bay affords a natural laboratory to study rip currents, cusped shorelines and eroding dunes. This study encompasses 18 km of shoreline in Monterey Bay, California. The bay consists of a sandy shoreline backed by extensive dunes, rising to heights exceeding 40 m. The shoreline and dunes are in a general state of erosion with average erosion rates varying from 0.5 to 2 m/yr. There is an increase in wave height going from small wave heights at the southern most part of the bay in the shadow of a headland, to larger waves in the center of the bay owing to convergence of waves by refraction over Monterey Bay submarine canyon. The waves approach at near normal incidence all along the shore, because of the narrowing of the aperture by the headlands to the north and south, the strong refraction across the canyon, and the historical (geologic time-scale) reorientation of the shoreline in response to the wave climate, resulting in well-developed rip currents and associated mega-cusps O(200 m) along the entire shoreline. The large alongshore gradient in wave climate results in a concomitant alongshore gradient in morphodynamic scale.

Dune erosion and shoreline morphology were measured using LIDAR during a time of high erosion (October 1997, April 1998). Temporal monitoring of the beach-face was performed (every 2 weeks) by driving the beach with an ATV mounted with KGPS to determine the 2 m shoreline contour. Rip channels were surveyed by personal-water-craft equipped with sonar and KGPS. Directional wave spectra are measured in deep water and at three locations within southern Monterey Bay.

Enhanced dune erosion is shown to occur at the embayment of mega-cusps that are associated with rip channels. The beach is the narrowest at the embayment of the mega-cusps. This allows the swash of large storm waves during high tides to reach the toe of the dune, and undercut the dune causing it to slump onto the beach resulting in recession of the dune. The alongshore variations of the volume of dune erosion are correlated with alongshore variations of the cusped shoreline at 95% confidence. Therefore, it is concluded the location of dune erosion is associated with the embayment of mega-cusps.

Rip currents are located at the center of mega-cusps. Rip current spacing and mega-cusps dimensions are the same. The alongshore variations of the cusped shoreline are correlated with the alongshore variations in rip spacing at 95% confidence. Therefore, it is concluded the mega-cusps are associated with rip currents. The cusped shoreline tends to be erased (straightened) by storms through both erosion of the horns and filling of the embayment. The slumping of the receding dune is the primary source of sand to the beaches. This source of sand is then available to build new mega-cusps.

Acknowledgements

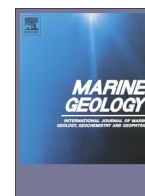
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Temporal and spatial variations in sand budgets with application to southern Monterey Bay, California

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ABSTRACT

Often in calculating a sediment budget there is an unknown contribution, which is ascribed to the residual of the balance, and the budget cannot be fulfilled. The temporal and spatial variations and sediment size within a littoral cell provide additional information to define sediment budgets. The approach here is to consider only medium to coarse sand (grain size > 0.25 mm) over a long time period during significant changes of natural and anthropogenic inputs and losses that allow calculating several budgets to isolate the unknown inputs and outputs to close the system. Considering only medium to coarse sand eliminates including the cross-shore transport of fine sand by waves, which is poorly quantified. To demonstrate these concepts, shoreline recession rates measured over a 101-year time period are used to calculate sediment budgets for southern Monterey Bay, California, littoral cells. The coarse sandy shoreline is backed by extensive bluffs and dunes that reach 44 m in elevation. Intensive sand mining of coarse sand derived directly from the beach and surfzone started in 1927 and continues today. A contribution of about $100 \text{ k m}^3/\text{year}$ of medium to coarse sand from the Salinas River is calculated from measured shoreline accretion for the period 1910–1945 starting when the river first flowed into the littoral cell, prior to damming of the river and significant losses owing to sand mining. Sediment budgets are calculated for 1940–1989 and 1989–2011 to spatially identify the loss of about $200 \text{ k m}^3/\text{year}$ attributed to different mining operations that captured the littoral transport. The primary contributions of medium to coarse sand to the littoral system is approximately $180 \text{ k m}^3/\text{year}$ from the eroding dunes and beaches. Only a quarter of the dune sand is found to be compatible with the coarser beach sand with the finer fraction carried offshore. A conclusion is that sand mining is the cause of the observed high recession rates.

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1. Introduction

Sediment budgets have been shown to be useful tools in understanding regional sediment processes (e.g. Rosati, 2005; Patsch and Griggs, 2007; Limber et al., 2008). The approach is to quantify the inputs, losses and storage for a littoral region, or littoral cell, with well-defined lateral boundaries. The most useful boundaries are located where there is a well-defined input or sink, such as a river mouth or submarine canyon. Sediment inputs to a cell include rivers, bluff and dune erosion, beach nourishment, littoral alongshore transport entering the cell and shoreward transport by waves. Losses include littoral alongshore transport leaving the cell, sand mining, submarine canyons, cross-shore transport by waves and wind. The off-shore transport by waves is not well quantified. For example, assessing the amount of seaward moving sand by waves requires estimating an ill-defined closure depth where the bottom profile does not change with time (Hallermeier, 1981). This cross-shore transport value is often treated as an unknown and appear as a residual, leaving less confidence in the budget.

Three approaches are proposed for solving this problem. The first approach is to simplify the budget by defining a littoral cutoff diameter that determines the minimum grain-size diameter of the sediments to be considered (Limber et al., 2008). Only medium to coarse sand (grain size > 0.25 mm, herein referred to as beach sand) will be considered. Second, by considering separate, but connected littoral cells, the boundary condition of the adjoining cells may be solved independently (e.g. Patsch and Griggs, 2008). Third, if a long enough time series of the inputs and losses are available during which significant natural and anthropogenic changes occur, it may be possible to isolate an unknown input or output to close the system.

To demonstrate these concepts, beach sand budgets in southern Monterey Bay, California, (hereafter referred to as SMB) are calculated for a littoral cell from Sand City to the Salinas River (Fig. 1). Several sediment budgets have been calculated for SMB, but considerable variations exist in the estimates (Dorman, 1968; Patsch and Griggs, 2007; PWA et al., 2008; amongst others). The sediment budgets are complicated by both spatial and temporal changes to the inputs and losses to the littoral cell over the last century. A large natural change to the littoral cell occurred when the discharge location for the Salinas River changed from discharging through Elkhorn Slough to north of the head of the

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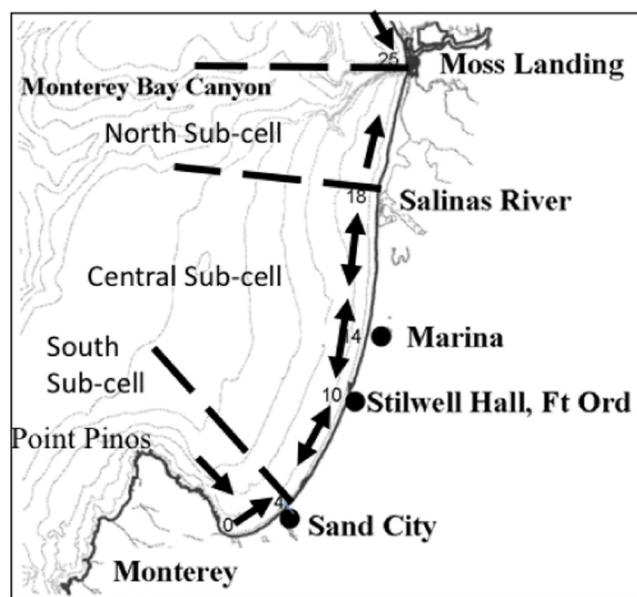


Fig. 1. Map of southern Monterey Bay. Dominant features are the Monterey Bay Submarine Canyon, bulge of sand at the Salinas River, and Point Pinos headland at the southern end. Littoral cells are delineated. The distances in km relative to Wharf II (0) in Monterey are shown. The arrows indicate the direction of sediment transport. The dark circles are the locations of video stations.

Monterey Submarine Canyon, which blocks sand from reaching SMB, to its present location 6 km south in 1910 (Chin et al., 1988). The current Salinas River location added a sediment source to the SMB littoral cell. The Salinas River was subsequently dammed by the small Salinas dam in 1941 and the larger San Antonio and Nacimiento dams in 1956 and 1965, decreasing and modifying its input (Willis and Griggs, 2003). A second, more important, anthropogenic change has been the large volumes of coarse sand selectively mined directly from the surf zone and beach in SMB starting in 1927, with the volumes and locations mined changing with time.

An impetus for the sediment budget studies started in the 1970s with an attempt to determine whether or not sand mining was responsible for the observed high recession rates in SMB, with recession rates as much as 2 m/year at Fort Ord (Fig. 1). SMB was identified as the most erosive shoreline on average along the entire California coast over the period 1945 to 1998 with an average erosion rate of 0.8 m/year (Hapke et al., 2006). The mined sand is economically valuable owing to high silica content, hardness, grain roundness, amber color and wide range of usable sizes. Uses include filtration, sandblasting, foundry purposes, packing for water wells, and surface finishing (Combellick and Osborne, 1977).

The study objectives are 1) to demonstrate techniques for calculating sediment budgets by only considering the coarser fraction of the sediments, considering spatially connected littoral cells to solve the boundary condition of littoral transport between them, and examining a long enough time period during significant changes to calculate several budgets, and 2) to provide new data on dune recession and to refine the sediment budget estimates in southern Monterey Bay based on an accumulation of knowledge from recent studies. The timelines of significant events are summarized in Table 1. Taking advantage of temporal changes, the contribution by the Salinas River is isolated and measured between when it first started flowing into SMB in 1910, before significant sand mining in 1945. Beach sand budgets are calculated for two time periods to examine the impact of sand mining. The first budget is calculated from 1940 to 1989 during the time of intensive drag-line sand mining of the surf zone focused on the south end of the littoral cell. The second budget is calculated from 1989 to 2011 after all the

Table 1
Time lines.

1909	Sand mining started at Lapis site in Marina
1910	Salinas River changes discharge from north of Moss Landing to present location
1941	Salinas Dam built on Salinas River
1940–1989	Intensive drag-line sand mining directly from ocean
1956	Nacimiento Dam built on Salinas River
1965	San Antonio Dam built on Salinas River
~1965	Hydraulic sand mining by dredge boat on pond at Lapis mined started
~1985	Larger dredge boat started mining pond at Lapis mine
1986	Sand mining by drag-lines stopped in Marina
1989	Sand mining by drag-lines stopped in Sand City

drag-line mines were closed leaving only a dredge pond mining operation at the north end of the littoral cell.

2. Geology setting

Monterey Bay is the largest open embayment along the central California coast. SMB shoreline is characterized by sandy beaches backed by dunes and pervasive sea cliffs composed of Quaternary dune deposits, which will be referred to in the text as dunes. The arcuate shape of the bay suggests that the bay has an equilibrium form. The entire shoreline morphology is characterized as a transverse- bar and rip-beach, or alternatively, low-tide terrace-bar incised by rip channels (Short, 1999).

Prominent morphologic features in SMB are the Monterey Submarine Canyon, the sediment lobe offshore of the Salinas River, and the Point Pinos headland at the south end of the bay (Fig. 1), all features that significantly modify the incident wave field. SMB forms a closed littoral cell bounded at the north by the Monterey Submarine Canyon, which extends almost to the shoreline at Moss Landing and intercepts the predominant drift from the north (Wolf, 1970; Smith et al., 2007). The effectiveness of the Monterey Submarine Canyon as a barrier to littoral transport is substantiated by the change in heavy mineral provinces across the canyon (Sayles, 1966) and textural and petrographic differences of sand samples north and south of Moss Landing (Clark and Osborne, 1982).

The southern end of Monterey Bay is bounded by the rocky Point Pinos headland around which no sand appears to enters the bay (Storlazzi and Field, 2000). Within the southern bight is the impermeable concrete wall at Wharf II built in 1950 defining the eastern side of Monterey harbor located on an east-west oriented shoreline (Fig. 1). The wall forms an effective barrier to littoral transport from the east, and therefore forms the southern end of the littoral cell. Locations on the map and in the text are referenced by distance from Wharf II.

2.1. Shelf sediments

Considerable information regarding the sediment budget is provided by examining the distribution of sediment size and sand characteristics. The surface sediments on the shelf based on mean grain size reveal: 1) a mid-shelf mud belt (not important to this study), 2) a lobe of sediments offshore the Salinas River composed of sediments < 0.25 mm, 3) coarse sand deposits referred to as rippled scour depressions in 10–60 m water depths, and 4) a near-shore sand corridor (Eittreim et al., 2002).

The bulge of sediments off the Salinas River extends to water depths of 10 to 90 m. The lobe has a maximum thickness of 35 m located 2.5 km seaward of the river mouth and thins in all directions. The adjacent shelf areas are characterized by a thin (2 to 5 m thick) and uniform veneer of fine sediments. Acoustic stratigraphy of the bulge is characterized by at least three uniformity-bounded depositional sequences of marine deposits formed during interglacial highstands and/or during early stages

of falling sea level (Chin et al., 1988). Therefore, the bulge is relict, and not the result of the modern relocation of the Salinas River.

Coarse sand occurs on the inner shelf of SMB as irregularly shaped, rippled scour depressions out to depths of 60 m (Davis et al., 2013). This geometry is explained by Eittreim et al. (2002) as a layer of 1 m thick fine-sand/mud overlying a widespread coarse-sand layer in the subsurface that is exposed in some places by high-energy wave velocities that act to ripple the coarse sediment bottom. The source of the coarse sand may be a Pleistocene transgressive lag deposit underlying much of the shelf. These coarse sands do not move onshore.

2.2. Beach and dune sand

Beach and dune sand grain-size statistics have been measured by a number of authors, which are summarized in Fig. 2. Beach mean grain-size starts out at about 0.2 mm at Wharf II and increases northward with a significant increase at Sand City to a maximum of approximately 0.8 mm at Marina, followed by a decrease towards the Salinas River (Fig. 2). Some of the alongshore variability appears related to the sampling procedures and seasonal variations, as the samples were taken both in winter and summer. Based on grain-size distributions, 99% of the beach sand between Sand City and the Salinas River exceeds 0.25 mm in diameter (Combellick and Osborne, 1977), which defines the beach sand cutoff diameter for SMB. This compares with the definition by Limber et al. (2008) where 95–98% of the all littoral sediments exceeded the littoral cutoff diameter of 0.125 mm for the study location at Ocean Beach, California.

Fourier grain-shape analysis was used by Porter et al. (1979) and Clark and Osborne (1982) to discriminate the more angular river sands from the dune and beach sands, which are more rounded owing to originating from aeolian dune sands and ongoing surf zone abrasion. They concluded that the Salinas River does not contribute a significant amount of sand to the southern beaches as river sand was only detectable within 2.5 km south of the river mouth. However, the beaches to the north of the river contained numerous irregular shaped grains, strongly suggesting a fluvial source. They concluded that the primary source of beach sand in SMB south of the Salinas River is dune sand based on textural and petrographic analysis.

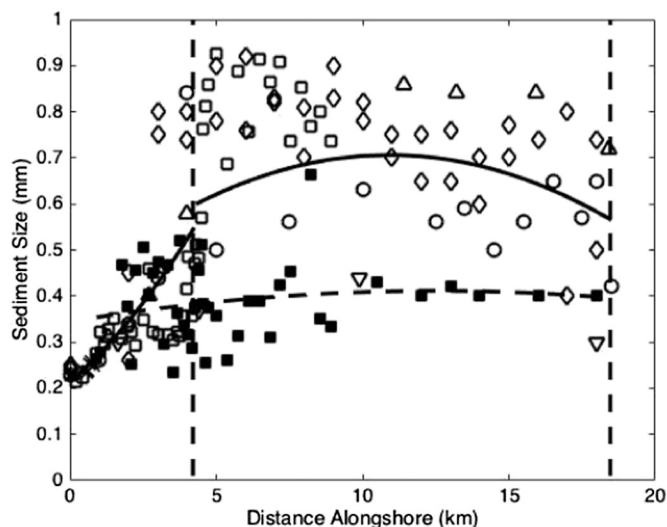


Fig. 2. Alongshore distribution of mean sediment size (mm) of beach and dune sands. Beach sand (open symbols) collected at mean tide level by Sayles (1966) triangles; Dorman (1968) squares; Combellick and Osborne (1977) diamonds; Dingler and Reiss (2001) inverted triangles; and collected at +1 m MSL by Combellick and Osborne (1977) and Clark and Osborne (1982) circles. Dune samples (closed symbols) collected by Dorman (1968), Combellick and Osborne (1977) and the author. Polynomial regression fits indicated by solid line for beach sand and dashed line for dune sand. The central sub-cell is delineated as between the vertical dashed lines.

A change in mean grain-size and composition of beach sands occurs at Sand City at about 4.3 km from Wharf II (Fig. 2). At approximately the same location Sayles (1966) found a change in heavy-mineral composition from a predominantly hornblende suite to the south to a hornblende-garnet suite to the north. He concluded that the beach sand between Wharf II and Sand City is derived from the granitic rock outcropping on the Monterey Peninsula. Dorman (1968) found a lobe of medium size sand offshore of Sand City and concluded that this is an area of convergence (Fig. 3). Clark and Osborne (1982) further concluded on basis of grain-shape that the medium size sand offshore and on the beach in this area are similar and have the same source. However, Johnson et al. (2016) found that the sediments form only a thin veneer suggesting that this is more a null point than a strong convergence. Therefore, based on these sedimentological features, a littoral sub-cell boundary is defined at Sand City at 4.3 ± 0.5 km alongshore (Figs. 1, 3).

3. Wave climate and littoral transport

3.1. Wave climate

During the winter (November to March), northern hemisphere waves are typically generated by cyclones in the north Pacific with deep water significant wave heights offshore of Monterey Bay up to 11 m, and with wave directions from north-west to west-south-west (Wyland and Thornton, 1991). Local wind driven seas typically develop rapidly when low pressure systems track offshore in the winter months.

The summer months (July to August) are a time of the most persistent winds and swell waves that come from the northwest owing to a persistent high pressure system offshore. Low, long period swell waves arrive from the south generated by storms in the Southern Ocean during summer months, but are generally not important in SMB as they are blocked by Point Pinos. In addition, strong sea breezes and associated waves are typically generated during the summer months as the result of heating of the interior land of the Salinas valley located inland of Monterey Bay. In summary, the larger winter storm waves tend to arrive from the west or southwest with the waves predominantly from the northwest the rest of the year.

Long-term variations in wave climate are primarily associated with El Niño years when the eastern Pacific water is warmer. The warmer water results in thermal expansion raising the surface elevation along the coast order 30 cm, and at the same time, more intense storms tend to occur. The combination of the super-elevation of the water surface and more intense storms results in increased beach erosion. In addition, El Niño storms tend to occur later in the winter when the beach has already been narrowed by winter waves, making the dunes more vulnerable to erosion.

3.2. Alongshore sediment transport

Averaged breaking wave heights for the winter months November 2007 to April 2008 (Fig. 4) were calculated by refracting directional wave spectra measured every six hours by the NOAA direction wave buoy 46,042 offshore Monterey Bay (Orzech et al., 2010). Wave energy focuses on Fort Ord and Marina as the waves are refracted over the Monterey Submarine Canyon. The shoreline in the southern bight is sheltered by Point Pinos for waves from the south and west quadrants, resulting in reduced wave energy at Monterey and Sand City. The waves approach at near normal incidence all along the shore owing to the narrow aperture formed by the headlands to the north and south, refraction across the canyon, and historical (geological time-scale) reorientation of the shoreline in response to the wave climate. The near-normal wave incidence results in well-developed rip currents and associated mega-cusps with alongshore length scale ranging 200 to 1000 m along the entire shoreline (Thornton et al., 2007).

Alongshore sediment transport in SMB has been calculated by a number of authors (Dorman, 1968; Orzech et al., 2010, amongst others)

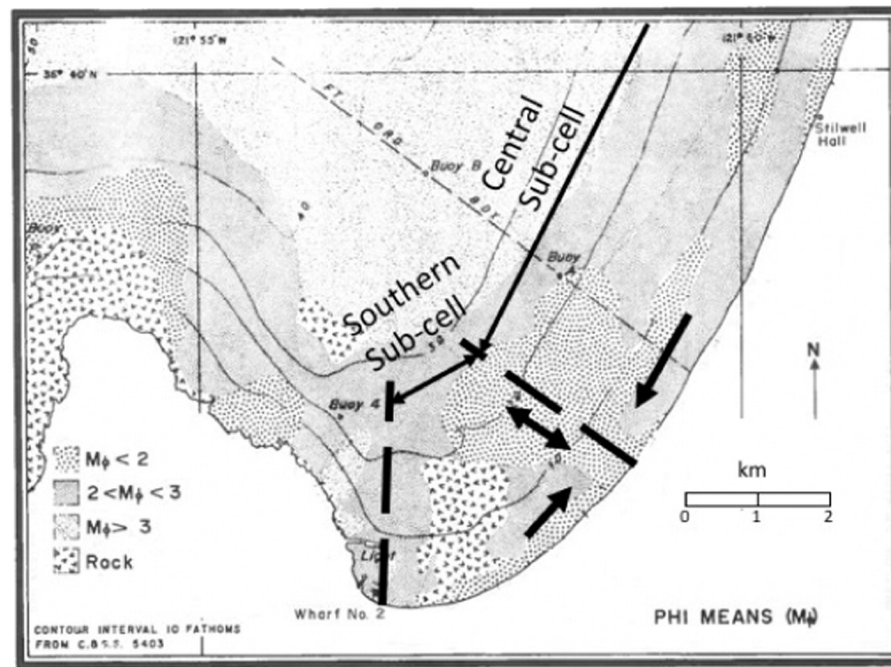


Fig. 3. Mean-grain-size (phi units) in the southern bight of Monterey Bay showing confluence of sediments at Sand City (modified from Dorman, 1968). Arrows indicate direction of sediment transport. The littoral sub-cells are indicated.

with a large variation in estimates. The littoral transport estimates generally agree in direction, but vary considerably in magnitude. A problem is that the transport magnitude is sensitive to wave direction relative to the shoreline, where the shoreline varies from east-west at Wharf II to north-south at the Salinas River (Fig. 1). Since the waves approach the shoreline at near normal incidence owing to refraction, small errors in choosing shoreline orientation can result in substantial error in the transport magnitude.

Orzech et al. (2010) calculated daily net sediment transport rates over a three-year period (2005 to 2008) using measured wave spectra

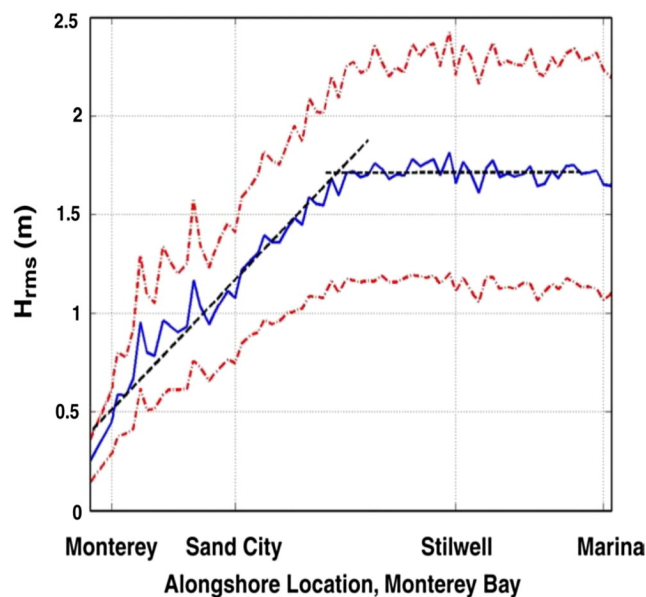


Fig. 4. Model-predicted rms wave heights at breaking along the shoreline of southern Monterey Bay, averaged over October 2007 to April 2008. Data spread ($\pm$ one standard deviation) is shown by dash-dot lines. Dashed lines on top of main curve indicate mean alongshore slopes of wave heights on southern and northern sections of the shoreline between Monterey and Marina. (After Orzech et al., 2010).

refracted from the offshore NOAA wave directional buoy as input and applied the U.S. Army Coastal Engineer Research Center (CERC) (2002) formulation. Orientation of the shoreline was based on recent surveys. Over the same time period, Orzech et al. (2010) measured the daily migration of rip current channels using time-lapse video images taken at Sand City, Fort Ord and Marina (Fig. 1), and hypothesized that the migration was due to alongshore sediment transport. They found correlation coefficients ranged 0.76 to 0.94 between cumulative net transport and daily rip channel migration distance giving confidence in the calculated sediment transport values. Sediment transport at Fort Ord and Marina was seasonally variable with transport to the south most of the year but with a sharp reversal to the north during the winter. The calculated net transport rates were 100,000 and 50,000 m³/year to the south at Marina and Fort Ord respectively. At Sand City, the wave directionality relative to the shoreline has a more north-easterly orientation that drives a potential transport consistently to the north at 33,000 m³/year (Orzech et al., 2010). Owing to the continuous curvature of the shoreline, a null point where the transport is near zero occurs somewhere between the northward transport at Sand City and the net southerly transport at Fort Ord.

The littoral transport studies show that the lobe offshore the Salinas River significantly modifies wave refraction and the resulting direction of sediment transport. The mean transport just south of the river and at the river mouth was found to be both north and south, but north of the river the transport was found to be to the north (Fig. 1). Therefore, SMB is additionally divided with a northern sub-cell from the Salinas River mouth to the head of the Monterey Submarine Canyon at Moss Landing, and a central sub-cell to the south of the Salinas River.

4. Sand budgets

In this study, three sub-cells in SMB are identified as Wharf II to Sand City (south sub-cell), Sand City to the Salinas River (central sub-cell) and the Salinas River to the Monterey Submarine Canyon (north sub-cell) (Fig. 1). The sand budget analysis focuses on the 15.1 km central sub-cell ranging from Sand City at 4.3 km alongshore to the Salinas River at 19.4 km alongshore (Fig. 1). Only beach sand is considered in the budgets.

4.1. Inputs

Sediment inputs are derived from dune sand slumping onto the beach and the beach sand transported alongshore, and contribution by the Salinas River. These inputs are described in the following.

4.1.1. Contribution from dune erosion

A primary contribution to the sediment budget is from sand slumping onto the beach during dune erosion caused by the swash of storm waves coincident with high tide (maximum high tide $\sim +1$ m relative MSL) undercutting the dune. The dune sand is comprised of fine to coarse size fractions. The fine sands are sorted and carried offshore by waves. The medium to coarse sand stays on the beach and is then transported alongshore. Two different recession data sets are used in the sediment budgets. The first data set is for the period 1940 to 2011 during the time of intensive sand mining. For this data set, dune erosion is defined using the recession of the dune-top edge, which was measured by Thornton et al. (2006) using a combination of stereo-photogrammetry, LIDAR and GPS walking surveys over the period 1940–2005. These measurements are extended here to include an additional GPS walking survey in 2011, and are referred to in the figures as NPS for Naval Postgraduate School. The recession is averaged in the alongshore over at least 500 m as there is considerable variation alongshore owing to the mega-cusate shoreline. The horizontal accuracies are estimated to be at least ± 2 m for stereo-photogrammetry, ± 1.4 m for the LIDAR and ± 0.3 m for the walking GPS surveys. The details of these measurement techniques are discussed in Thornton et al. (2006).

The dune height above the dune toe elevation and beach height (dune toe elevation relative to MSL) are based on a 1998 LIDAR survey augmented by a walking GPS survey in 2004. Dune height is highly variable with a maximum of 39 m at Fort Ord (Fig. 5a).

The average recession rate is calculated as the slope of the linear regression line of the recession values as a function of time. Recession rates are calculated for two time periods, first, during sand mining including drag-line operations from 1940 to 1989, and second, after the drag-line mines were closed with only the dredge mine operating in Marina from 1989 to 2011 (Fig. 6). All linear regression fits had R^2 values exceeding 0.85 except for the recession at 13.5 km alongshore

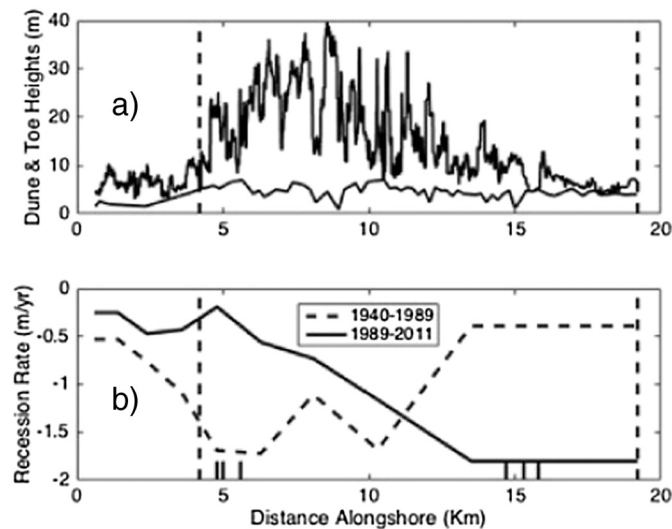


Fig. 5. a) Alongshore variation of dune height and dune toe elevation relative to MSL. The central littoral sub-cell is delineated as between the vertical dashed lines; b) alongshore variation of dune recession rates during time of intensive dragline mining (1940–1989) and after dragline mining ceased with only the dredge-pond sand mine in Marina operating (1989–2011). The location of the five drag-line sand mines plus the dredge-pond sand mine (most north) are indicated by the short vertical lines on the horizontal axis.

between 1940 and 1989, which had a value of 0.22. The error in the recession rate is the uncertainty in the regression slope estimated as the difference of the minimum and maximum measurement uncertainties giving a maximum error of ± 0.2 m and a time uncertainty of ± 0.5 years. The recession rates alongshore are shown in Fig. 5b for the two time periods.

4.1.2. Contribution from beach sand

Sand grains are sorted in the cross-shore and alongshore with each grain-size fraction seeking an equilibrium location where gravity force and stirring by turbulent wave energy balance. In the cross-shore, grain-size is a maximum near the breaker line location where the turbulence levels are the highest (Dean and Dalrymple, 2002) and on top of the berm carried there by the maximum wave uprush (e.g., Wiegand, 1964). The finer sand tends to go offshore where wave energy is less. Medium and coarse sands tend to be moved onshore by the action of swell waves owing to the inherent skewness of the wave-induced velocities with the onshore velocity magnitude exceeding the offshore velocity magnitude (e.g., Komar, 1998). In the case of SMB, the beach sediments are also sorted alongshore with the coarse sand beaches in the central part of the bay where wave energy is greatest and with medium to fine sands progressing towards Wharf II (Fig. 2).

Beach width variations throughout Monterey Bay were examined over a 71-year period between 1930 and 2001 by Ried (2004). He found the beach widths to be in a steady state configuration from the Salinas River south to Monterey. Since the dune face is at near angle of repose all along the shoreline owing to active erosion, the dune-top and dune-toe maintain an approximate constant spatial relationship. Therefore, as recession occurs, the dune-top and dune-toe recess back at the same rate as the beach in order to maintain a constant width as observed by Ried (2004), which is a basic concept of this analysis.

The cross-sectional area of beach sand is schematically represented by trapezoids with the same recession widths as the dune recession width (Fig. 7). Beach height is equal to the difference between the elevation of the dune toe and the maximum depth of medium sand (grain-size > 0.25 mm), h_{ms} . The beach profiles of SMB typically have a steep beach face order 1:10 to approximate MSL followed offshore by a flat, low-tide terrace bar and then more steeply descending offshore. The width of the low-tide terrace bar varies from about 130 m to 80 m at the rip channels at Sand City. The maximum width of the low-tide terrace bar increases to over 200 m at Marina. Waves tend to

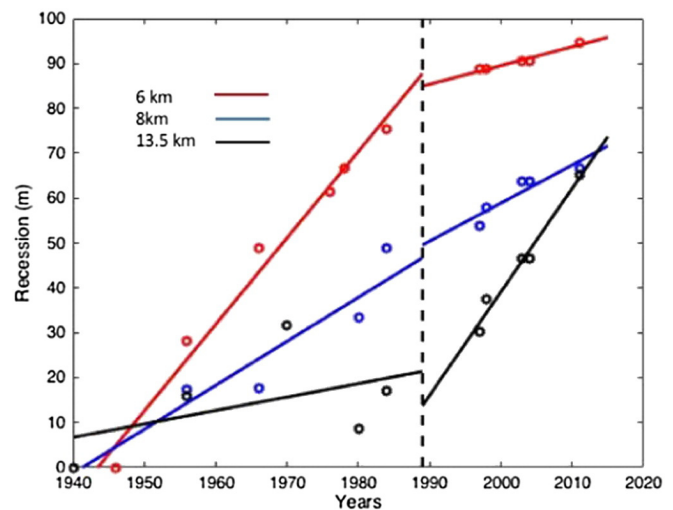


Fig. 6. Recession as a function of time at various alongshore locations relative to Wharf II with linear regression fit to periods 1940 to 1989 during the time of significant drag-line sand mining and 1989–2011 after the drag mines were closed. The vertical dashed line indicates 1989.

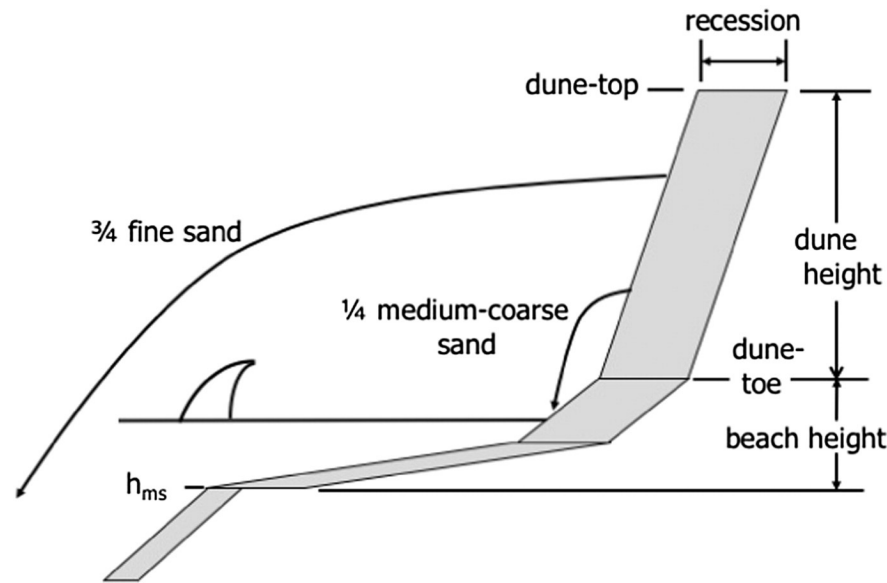


Fig. 7. Cross-section schematic of dune transitioning to a steep beach and then to a low-tide terrace bar all recessing at the same rate. One-fourth of the recessing dune volume is composed of medium to coarse sand which is transferred to the beach. The remaining fine sand is transferred offshore. The dune height is the difference in elevations between the dune-top edge and dune toe. The beach height is the difference in elevations between the dune toe and the offshore limit of medium sand (grain size > 0.25 mm), h_{ms} .

break at the change in slope at the seaward extent of the low-tide terrace bar, or at higher tides, to break at the toe of the steep beach slope (Reniers et al., 2013). It is noted that the cross-sectional area of the beach sand described by trapezoids is independent of beach slope and only a function of the recession width (i.e., not the width of the beach) and combined heights of the trapezoids.

The cross-shore distribution of surficial sediment grain-size was examined in comprehensive nearshore experiments at Sand City (MacMahan et al., 2005; Reniers et al., 2013). It was found that the offshore extent of medium sand (>0.25 mm diameter) was limited to inside the low-tide terraced bar, which extends to depth $h_{ms} \sim -1.8 \pm 0.2$ m relative MSL. The elevation of h_{ms} would be expected to depend on wave height. A simple first approximation is to assume that h_{ms} is proportional to wave height calibrated to the wave height at Sand City. Using the alongshore distribution of breaker wave height in the winter months by Orzech et al. (2010) shown in Fig. 4, $h_{ms} = -2.2$ m for most of the shoreline in the central sub-cell.

Dune erosion rate per unit alongshore is calculated as the dune recession rate (Fig. 5b) times the dune height (Fig. 5a). The beach erosion rate per unit alongshore is similarly calculated as dune recession rate times the beach height (schematically shown in Fig. 7). The total dune and beach erosion volume rates are calculated by spatially integrating the dune and beach erosion rates per unit alongshore for the two time

periods within the central sub-cell between Sand City and the Salinas River (Table 2).

4.1.3. Contribution of dune sand to beaches

In the central sub-cell, the mean grain-size of the dune sand is 0.35 mm with only 22% being >0.5 mm, whereas the mean grain-size of the beach sand is 0.65 mm with 60% being >0.5 mm. Not all dune sand is compatible with the sand on the beach. The dune sand slumping onto the beach is sorted such that only the coarser fraction of the dune sand is retained on the beach with the finer sands going offshore. The amount of dune sand that remains on the beach is calculated based on sediment distributions (Dean, 1974). The observed skewness of the beach sand is near zero in phi units (Combellick and Osborne, 1977), indicating that the sediment distributions in phi units are log-normal. Hence, the distributions are completely described by mean and standard deviations in phi units, ϕ , (see Table in Fig. 8). The number of units of dune sand, K , required to equal one unit of beach sand is calculated such that their distributions have the same mean grain-size, where the fine fraction of dune sand is lost. This requires that the 0 and 1st moments of the truncated dune sand distribution multiplied by K , be equal to the same moments of the beach sand distribution, as given by

$$\int_{-\infty}^{\infty} \phi^n f_{beach}(\phi) d\phi = \frac{K}{\sigma_b \sqrt{2\pi}} \int_{-\infty}^{\phi_*} \phi^n f_{dune}(\phi) d\phi \quad n = 0, 1 \quad (1)$$

where $f_{beach}(\phi)$ and $f_{dune}(\phi)$ are the log-normal sediment distributions of the beach and dune, n is the order of the moments, σ_b is the standard deviation of the beach sand, and ϕ_* is the truncation limit. These result in two equations with two unknowns, K and the limit ϕ_* , that are solved iteratively. For the areas and means of $f_{beach}(\phi)$ and the partial $Kf_{dune}(\phi)$ (shaded area in Fig. 8) to be equal, 4 units of dune sand are required to replace each unit of beach sand owing to the dune sand not only having a smaller mean grain-size (smaller is larger in phi units), but is better sorted (smaller standard deviation). The ratio $1/K$ is defined here as the compatibility factor. Therefore, for each volume of dune sand eroded, approximately only 1/4 volume is compatible with the beach sand with 3/4 of the volume of fine sand transported offshore, which is included in the sand budgets (Table 2).

Table 2

Sand budget for SMB central sub-cell. Values in $m^3/\text{year} \times 10^3$. Uncertainties are presented with the values.

	1940–1989	1989–2011
Mean recession (m)	−1.0	−1.3
Dune erosion	190	155
Dune erosion × compatibility factor, 0.25	48 ± 5	39 ± 4
Beach erosion	105 ± 9	127 ± 11
River input	56 ± 6	34 ± 3
Littoral transport in from south	20 ± 4	10 ± 2
Littoral transport in from south × 0.29	6 ± 2	3 ± 1
Sand mining	−174 ± 43	−205 ± 50
Residuals	41 ± 69	−2 ± 71

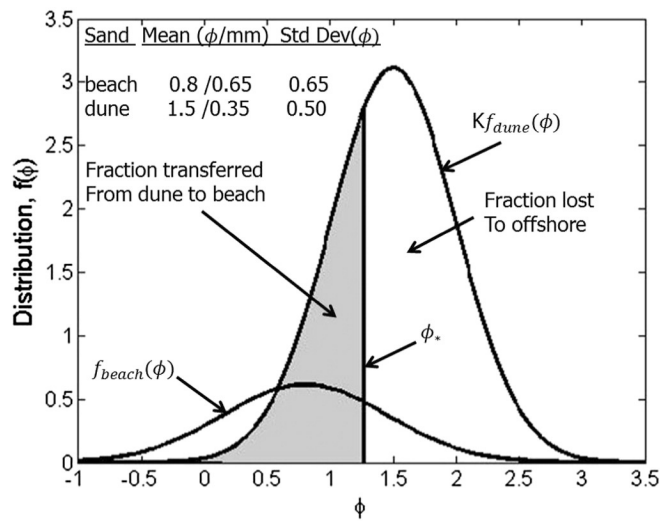


Fig. 8. Distributions of dune $f_{dune}(\phi)$ and beach $f_{beach}(\phi)$ sand size (phi units) demonstrating how the overfill ratio is calculated. The truncated distribution of the fraction of sand transferred from the dune to the beach (shaded area) must equal the area and have the same mean grain-size as $f_{beach}(\phi)$. K is the number of units of dune sand required to match the beach sand. Compatibility factor is defined equal to $1/K$. Average alongshore mean grain-size and standard deviation values (phi units) for SMB are given.

4.1.4. River input

The original source of sand building the beaches and extensive dunes backing SMB was discharge by the Salinas River at a lower stand in sea level when the river gradient was much steeper and the sediment carrying capacity of the river much greater (Chin et al., 1988). As was pointed out, the discharge location of the river has changed over time with the most recent change resulting in the river discharging at its present location south of the Monterey Submarine Canyon starting in 1910. The Salinas River is ephemeral flowing seasonally during the winter wet season. About ninety-percent of the sediment is discharged between December and March during the months of peak precipitation. The suspended sediment discharge is calculated using rating curves based on measured suspended load as a function of measured stream flow from 1970 to 1979 at a gaging station 27 km from the mouth of the Salinas River. The rating curves are then applied to the entire time series of measured stream flow (Willis and Griggs, 2003; Gray et al., 2014; amongst others). Each study found the total average suspended sediment flux to be on the order of 10^6 m³/year, which includes all sediment size fractions.

Willis and Griggs (2003) calculated annual discharge of the sand size fraction (grain size > 0.063 mm) from 1929 to 1999. Suspended sand was estimated to be 15% of the total suspended sediment flux. They estimated the overall uncertainty for annual suspended sediment discharge to be a maximum of $\pm 37\%$. Bedload was assumed to be 10% of the total suspended sediment flux, and that all the bedload is sand size or coarser. To complete the time series for this study, additional annual sand (grain size > 0.063 mm) discharge from 2000 to 2011 are provided in Gray et al. (2014). The interest here is the contribution of medium to coarse sand. Including only grain sizes > 0.25 mm based on the sediment size distributions of river discharge given in Brownlie and Taylor (1981), the suspended sediment contribution is reduced by 33% and the bedload by 42%. Therefore, the average annual discharge of beach-size sand from the Salinas River from 1929 to 1945 is estimated at 373,000 m³/year (Table 3). Upon reaching the ocean, the sand is transported both north and south in unknown proportions.

The amount of sand moving south from the Salinas River into the SMB central sub-cell is determined by using a second shoreline recession rate data set by Hapke et al. (2006). They calculated recession

Table 3

Average annual discharge of beach sand (>0.25 mm) by the Salinas River and the 0.27 contribution to SMB.

Period	Total discharge ($\times 10^3$ m ³ /year)	SMB contribution ($\times 10^3$ m ³ /year)
1910–1945	373 ^a	101 ^b
1940–1989	209	56
1989–2011	126	34

^a River discharge of beach sand based on measurements between 1929 and 1945.

^b Beach sand accretion measured using shoreline surveys.

rates for the time periods 1854 to 1998, 1910 to 1998 and 1945 to 1998 (Fig. 9). The Hapke et al. (2006) recession rates from 1945 to 1998 are compared with recession rates by Thornton et al. (2006) for the same time period (Fig. 9). The results are consistent, giving confidence in using estimates from both methods in the calculations for recession rates, at least for application to SMB. The objective is to isolate the beach accretion owing to the Salinas River beach sand discharge that occurred between 1910 and 1945 when the river first started contributing to the SMB littoral cell and before significant sand mining. Shoreline recession rates for 1910 to 1945 are calculated by subtracting pro-rata recession from 1945 to 1998 from pro-rata recession for 1910 to 1998 to obtain recession rates from 1910 to 1945 (Fig. 10). See Appendix A for details of the calculation. Examination of the 1910 to 1945 shoreline accretion rates indicates that the contribution by the Salinas River appears to stop at about 15 km alongshore. Therefore, an estimate of the average annual volume of beach size sand contributed to the SMB littoral cell by the Salinas River is obtained by multiplying the shoreline accretion by the beach height (see Fig. 7) and integrating alongshore from 15 km to the Salinas River to give 101,000 m³/year (Table 2). This value represents contribution of beach sand by the river from 1910 to 1945. Assuming that the average annual discharge of beach sand from the Salinas River was constant from 1910 to 1945, the proportion of the annual beach sand discharge directed south into SMB is 0.27 of the average total annual Salinas River beach sand discharge of 373,000 m³/year. This proportion is then applied to the measured annual river beach sand discharge to determine the Salinas River

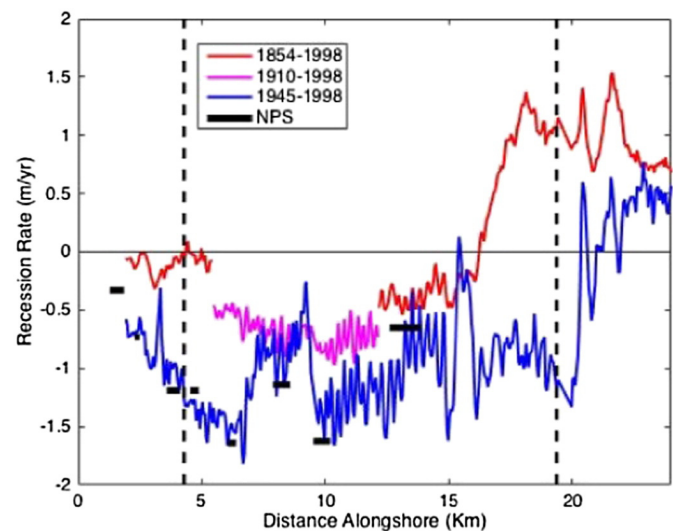


Fig. 9. Long-term shoreline recession rates composed of shorelines from 1854 to 1998 (red), a section from 1910 to 1998 (magenta) and short-term from 1945 to 1998 shoreline recession rates (m/year) calculated by the USGS (Hapke et al., 2006). The dune-top recession rates by NPS are shown for comparison (broad solid lines). The central littoral sub-cell is delineated as between the vertical dashed lines. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

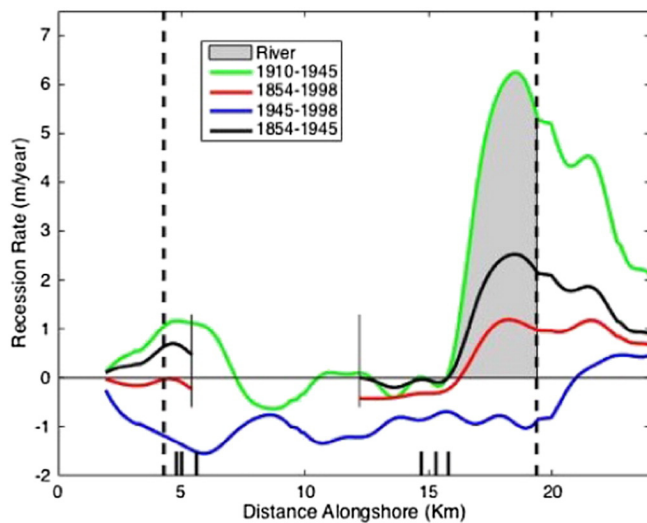


Fig. 10. Filtered long-term (1854–1998; red line) and short-term (1945–1998; blue line) shoreline recession rates (m/year) calculated by the USGS (Hapke et al., 2006). Prorated shoreline recession rates are shown for 1854–1945 (black line), 1910–1945 (green line) and the southerly discharge of sand from the Salinas River (1910–1945; fill area). The central littoral sub-cell is delineated as between the vertical dashed lines. The thin vertical lines delineate the 1910 to 1998 section between 5.4 and 12.2 km alongshore. The location of the five drag-line sand mines plus the dredge-pond sand mine (most north) are indicated by the short vertical lines on the horizontal axis. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

input to the central littoral sub-cell for the time periods of the sediment budgets (Table 3).

4.1.5. Littoral transport from the south sub-cell

The contribution by littoral transport into the central sub-cell from the south is determined by calculating sediment budgets for the southern sub-cell (Fig. 1). Two budgets are calculated for the time periods 1940 to 1989 and 1989 to 2011. The inputs are by dune and beach sands and some possible run-off from urban areas that is not considered. Losses are due to sand transported offshore and littoral transport out of the sub-cell into the central sub-cell. The littoral cutoff diameter for the southern sub-cell is based on cumulative sediment grain-size distributions in Dorman (1968), where 99% of the sand exceeded 0.14 mm in diameter. The contribution of sand is calculated as the recession rate times the height of the beach and dunes (Fig. 7) and integrated alongshore as before. The height of the beach, h_{ms} , varies as the wave height in Fig. 4 as before. A compatibility factor for dune sand of 0.8 is calculated alongshore based on the alongshore mean grain-size regression model for the beach and dune sands (Fig. 2) to obtain the contribution by the dune (Table 4). Only a small portion of the dune sand differs in grain-size from the beach sand, which is assumed to be lost offshore. Evidence that little sand is transported offshore is confirmed by the observation that much of the shelf bottom at the southern end of SMB is barren of sand (Fig. 3).

Table 4

Sand budget for SMB southern sub-cell. Values in $\text{m}^3/\text{year} \times 10^3$. Uncertainties are presented with the values.

	1940–1989	1989–2011
Dune erosion	11	6
Dune erosion $\times$ compatibility factor, 0.8	9 ± 2	5 ± 1
Beach erosion	12 ± 2	5 ± 1
Littoral transport out	-20 ± 4	-10 ± 4
Residuals	0 ± 8	0 ± 6

The input of sand by the beach and dune is balanced by the loss of sand transported out of the sub-cell to the north (Table 4). It is noted that the amounts of available sand for transport are much less than the calculated potential transport of $33,000 \text{ m}^3/\text{year}$ by Orzech et al. (2010). The mean grain-size of the beach sand transported to the north is calculated as a weighted average of the volume of beach sand alongshore times the alongshore grain-size distribution (regression line in Fig. 2). The calculated weighted mean grain-size is 0.37 mm, which is the same for both budget periods. This grain-size is significantly smaller than the beach mean grain-size immediately upcoast in the central sub-cell (Fig. 2). A compatibility factor equal to 0.29 is calculated using Equation 1 based on the mean sand size (0.37 mm) and standard deviation (0.5) of the incoming sand from the southern sub-cell and the mean grain-size of the beach sand (0.65 mm) of the central sub-cell to determine how much of the incoming sand contributes to the beach, with the remainder being transported offshore and lost. Transport of medium size sand offshore at the boundary of the two sub-cells is in accord with the sediment data presented earlier that the sand size is similar to the sand size of the southern sub-cell. The alongshore transport of beach sand from the south is added to the sand budget for the central sub-cell (Table 2).

4.2. Losses

Losses of beach sand are due to sand mining, offshore transport, and reveted shoreline. The loss by onshore wind is neglected because the shoreline morphology of steep bluffs and dunes, except for a short length of shoreline near the Salinas River, does not allow up-dune ramps for the sand to escape the beach. The transport of fine sand offshore by waves is excluded in the analysis. It is assumed the beach sand is welded to the shoreline by the skewness of the waves. Reveted (e.g. seawalls) shoreline is counted as a loss as it prevents dune sand from slumping onto the beaches and contributing to the system. However, there was <200 m of reveted shoreline in the central sub-cell fronting Stillwell Hall at Fort Ord between 1978 and 2004 representing a negligible loss. Therefore, the only loss accounted for is due to sand mining.

4.2.1. Sand mining

Southern Monterey Bay has been the most intensively mined shoreline for sand in the U.S. (Magoon et al., 1972) with six commercial sites between Marina and Sand City (Fig. 5b). Five drag-line mines historically took coarse sand directly from the ocean at Sand City and Marina starting in 1927 (Table 1). A sixth mine started in about 1965 in Marina approximately 4 km south of the Salinas River, where the sand is hydraulically mined just landward of the berm by a dredge floating on a self-made pond that acts to extract sand from the littoral zone as explained below.

Sand mining was not regulated until 1960, when the State Lands Commission asserted jurisdiction over extractions from land below MHW, which by law belongs to the State of California, and began licensing the operations through issuance of leases and charging royalties. The State Lands Commission imposed minimum mining amounts ranging $20,000$ – $40,000 \text{ m}^3/\text{year}$ on each company. The amount of mined sand is proprietary, ostensibly to prevent price-fixing. Hence, the precise amount of sand mined was unknown to the public. The U.S. Army Corps of Engineers in 1974 also required leases under the Rivers and Harbors Act of 1899, which regulates activities below MHW. They, however, attached maximum mining amounts to the various leases ranging $76,000$ – $115,000 \text{ m}^3/\text{year}$ to protect the environment. After ten-years, the Corps of Engineers concluded that the sand mining caused coastal erosion, and the permits were not renewed. All mines were shut down by 1989 except the operation at Marina on the back beach above the MHW line.

Thornton et al. (2006) examined the impact of sand mining on the erosion of the dunes by comparing the dune recession rates before

and after drag-line sand mining ceased, but did not include the mining operation on the back beach at Marina. They based their estimates of the amount of sand mined on scant personal communication with a mine operator for the years 1984–86 and the maximum amounts allowed by the Corps of Engineers permits. They concluded that the primary cause of erosion was due to sand mining, and that there was a statistically significant decrease in recession rates south of Sand City after drag-line sand mining ceased in 1989.

Since the Thornton et al. (2006) study, the actual volumes mined using drag-lines as reported to the California State Lands Commission were obtained through a Freedom of Information request. The volume of sand mined by year at Marina, Sand City and Total is shown in Fig. 11. The amounts reported were audited by the State Lands Commission based on sales receipts and are deemed accurate. Some files were missing, which resulted in gaps in the records. A ten-year moving average filter was used to fill the gaps. The amount of sand mined shows significant year-to-year variation. The variation is due in part to mining operations being interrupted by equipment damaged during winter storms that took several months to repair.

The biggest change in the amount of sand mined was the introduction of the dredging operation on the beach at Marina starting in about 1965, referred to as the Lapis mine. This mining operation efficiently takes advantage of the natural cross-shore sorting of sediments where coarse sediments are selectively washed over the top of the berm during times of high waves and high tide filling the pond with coarse sand. The berm elevation is approximately 4 m. The pond is effectively refilled in this manner as documented by aerial photos (Fig. 12).

Since this mine is still in operation, the volume of sand mined is proprietary. Estimates of the amount of sand mined are based on initial mining volumes reported to the State Lands Commission for 1965 to 1970, and the annual amount reported by the new owners, CEMEX, in 2000 of at least 300,000 tons (Coast Weekly, 2006), which equates to 205,000 m³/year using the conversions in Slagel and Griggs (2008). It is assumed that this was the constant amount of mining starting with introduction of a new dredge boat in 1985 until the present with linear interpolations in-between (Fig. 11). This mining operation captures the alongshore transport of from both the north and south resulting in loss of sand from the littoral budget. The sand mining losses are obtained by integrating the mining curves in Fig. 11 over the sand budget time



Fig. 12. Aerial photographs of dredge pond during operation in April 2005. Copyright 2005 Kenneth and Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org (upper panel) and when dredge pond is filled with sediments in the winter (photo taken by Rob Wyland 15 January 2008) (lower panel).

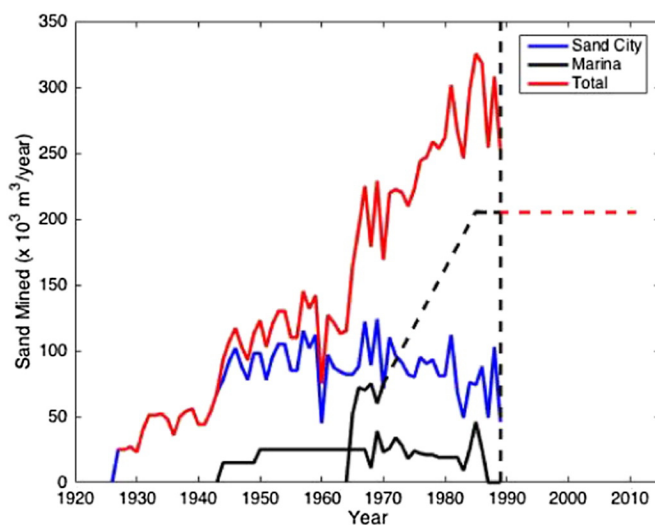


Fig. 11. Annual amounts of sand mining reported to State Lands Commission (solid lines) and estimated dredge pond annual amounts (dashed lines) at Sand City (blue line) at Marina (black line) and total (red line). Vertical dashed line indicates when the drag-line mines were all closed in 1989. Sand mined after 1985 is estimated based on reported amount in 2000. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

periods (Table 2). The biggest uncertainty in the sand budget analysis is the amount of dredge pond mining (Fig. 11, dashed lines).

5. Discussion

5.1. Assumptions of the sand budgets

The residuals of the sand budgets are the balances of the inputs and losses (Table 2) with the expectation that if all contributions are correctly calculated the residual would be zero. The residuals are non-zero, but within the margins of uncertainty of the calculations.

Assumptions made in the sand budget analysis include: 1) the depth of medium to coarse sand is limited to h_{ms} ; 2) the dredge pond sand mined since 1985 averaged 205,000 m³/year based on the reported amount in 2000 and assumed to remain constant; 3) river sand input to SMB is based on discharge from 1929 to 1945 that does not account for climate variations between 1910 and 1929. The first two assumptions are discussed in the following. Climate variation is discussed in the next section, 5.2.

The value of h_{ms} is important in determining the amount of beach erosion and the baseline contribution by the Salinas River, which is measured as the volume of the accretionary beach. The sensitivity of h_{ms} is examined by varying its value by $\pm 25\%$ (± 0.5 m), which result in a $\pm 8\%$ differences in beach erosion when integrated alongshore and $\pm 7\%$ differences in the baseline contribution of the Salinas River

for the 1989–2011 sediment budget. Similar percent changes are calculated for the 1940–1989 sediment budget (Table 2). Therefore, the calculated amounts of beach erosion and river input are not sensitive to error in h_{ms} .

An independent estimate of the volume of the dredge pond mined annually is obtained by assuming the pond is effectively filled every year and subsequently dredged to an area estimated from 13 aerial photos between 1998 and 2015, which range 7000 to 25,000 m² with an average of 14,500 m². The maximum depth of the dredge pond is based on the depth to which the dredge head can reach, which is estimated to be at least 11 m based on measurements of the dredge, plus at least a 3 m difference between the beach and pond elevations. Applying the average pond area (accounting for angle of repose of the side walls) and assuming the pond is dredged to a maximum depth of at least 14 m below the beach elevation, the potential amount of sand mined averages 203,000 m³/year. However, at the same time the pond is filling, it is being mined, so that the potential amount of sand mined might be expected to be greater. This volume is similar to the 205,000 m³/year reported by the mine owners.

The contribution to the sand budgets by the Salinas River has decreased significantly since the 1910 to 1945 baseline period (Table 3). The decrease is partially attributed to the building of dams on the Salinas River. Dams reduce sediment discharge by both impounding the sand behind the dams and by reducing the sediment carrying capacity by reducing flow in the river, particularly during times of floods. Willis and Griggs (2003) estimated that the impact of building the three dams on the Salinas River was a 32% reduction in the total annual sediment flux.

5.2. Climatic variations and El Niño

A basic assumption of the analysis is that the average annual river discharge measured between 1929 and 1945 is the same as during the baseline beach accretion measurement period between 1910 and 1945, which ignores climatic variations. Input of sand by the Salinas River is episodic with large infrequent flood events. California statewide rainfall records show a cyclic nature and tend to be associated with El Niño events when greater precipitation tends to occur. Although the definition of the occurrence of an El Niño varies considerably, there have been approximately 8 from 1910 to 1940, 8 from 1940 to 1989, and 7 from 1989 to the present. Wet periods occurred during 1905–1915, 1931–1944 and 1978–2010. A significant 34-year dry period occurred 1944–1978 (Hoell et al., 2016). The baseline river input was for the period 1910–1945, which included both wet and dry periods. Unfortunately, the discharge measurements of the Salinas River that would allow definitive measures of the baseline input did not start until 1929, which does not include the wet period between 1910 and 1915. This would indicate that the baseline river discharge in Table 3 may be underestimated, which would result in the proportion of sand contribution to SMB being smaller. Therefore, sand input by the Salinas River may be overestimated for the subsequent sediment budget periods.

Dune and beach erosion related to wave action is highly episodic and often associated with El Niño events. The strongest El Niño associated large waves since 1900 occurred in 1982–83 and 1997–98 (Seymour, 1998). Thornton et al. (2006) estimated that the total volume loss during the 1997–1998 winter was 2,593,000 m³, obtained by integrating the erosion alongshore, of which 1,820,000 m³ is dune loss and 773,000 m³ is beach loss. The dune volume loss during this El Niño winter was almost seven times the historical average annual rate. This emphasizes that erosion can be highly episodic in time. Surprisingly, large erosion episodes are not reflected in the recession curves, not even the extreme 1982–83 and 1997–98 El Niño events are evident (Fig. 6). The reasons may be that input by episodic erosion events and by floods resulting in greater river input tend to occur at the same time and may counter balance each other, and that loss by sand mining tends to be steady.

5.3. Alongshore variation of erosion with time and impact of sand mining

Examination of the shoreline recession rates (Figs. 5, 6, 9 and 10) suggests significant alongshore variation over time. An obvious change alongshore is the shift from high to lower erosion rates in the south end of the littoral cell after the closing of the mines in Sand City and from lower to high erosion rates in the north end of the littoral cell with the increased mining rates in Marina (Fig. 5b). The recession curves shown in Fig. 6 provide further evidence of the temporal and spatial changes. Qualitatively the change in the recession slopes at 6 km and 13.5 km alongshore suggest that there have been changes in erosion rates between the 1940s–1989 and 1989–2011. Hypothesis tests were applied to determine whether the regression slopes changed between these two time periods using a two-sided student-t distribution test with a 95% level of confidence (e.g., Bowker and Lieberman, 1959). It was previously shown that erosion had statistically decreased south of 4 km alongshore (Thornton et al., 2006). At the north end of the littoral cell at 13.5 km alongshore there has been a statistically significant increase in erosion between these two time periods with the caveat that the earlier regression line, although representative, has a low R² value. It could not be statistically concluded that the recession rates have changed in the middle sections from 6 to 10 km alongshore during these same time periods.

The interpretation of the spatial and temporal changes in erosion volume rates is complicated by the differences in dune elevation alongshore. For example, even though the average shoreline recession increased in the north end of the central sub-cell between 1989 and 2011, the total volume contribution by dune erosion decreased because of the lower dune heights in the north end.

The largest temporal change was from accretion to erosion about the Salinas River that is seen when comparing the 1945–1998 with 1910–1998 shoreline recession rates (Fig. 9). The erosion coincides with the start-up and continued sand mining near the river mouth. It also closely followed the damming of the Salinas River in 1956 and 1965. Evidence that the erosion is more associated with the mining is that the change from accretion to erosion only occurs south of the river, whereas the shoreline accretion rate remains essentially unchanged to the north. Further evidence suggesting that the mines intercepted the river sand is that river sand was not found south of the mine (Clark and Osborne, 1982).

6. Summary and conclusions

The sediment budgets of medium and coarse sand for SMB central sub-cell are the sum of the input of dune and beach sands, river discharge, plus littoral transport of sand from the south (Table 2). Simplification is obtained by only considering medium to coarse sand that focuses on the loss of sand to the budgets owing to mining of coarse sand and eliminates the not well-estimated off-shore transport of fine sand by waves. The medium and coarse sand are assumed trapped along the shoreline by the velocity skewness of waves. The largest inputs to the budgets are the dune sand slumping onto the beach and the alongshore transport of the beach sand. It is demonstrated that only about a quarter of the dune sand is of sufficient size to be compatible with the beach sand, with the remainder of the fine grain sand lost to the offshore. The input of medium and coarse beach sand transported alongshore is lost when it is intercepted and mined.

Sand budgets for the southern sub-cell were calculated to determine the littoral transport input from the south into the central sub-cell. The sediment size of the southern sub-cell sand is smaller and mostly incompatible with the beach sand of the central sub-cell. Hence, the littoral transport from the south provides only a small contribution.

Examination of the dune and shoreline recession/accretion over a long time period starting in 1910 to the present time provided the ability to calculate several sand budgets to separate the natural input by the Salinas River and anthropogenic losses by sand mining that were unique

to certain time periods. Important changes to the SMB littoral cell were the Salinas River input starting in 1910 followed by significant sand mining starting in the 1940s. Examination of the 1910–1945 shoreline recession rates allow calculating a baseline contribution of beach sand by the Salinas River south to the SMB littoral cells of approximately 100,000 m³/year, which was 27% of the total river discharge. The shoreline during this period was on average accreting. The subsequent calculated river input account for dams built on the Salinas River, which diminished the input by about 32% (Willis and Griggs, 2003).

With increasingly significant sand mining, starting in the 1940s, the shoreline became recessive. Two beach sand budgets are calculated to assess sand mining. The first time period is from 1940 to 1989 when five drag-line sand mines taking sand directly from the ocean operated in addition to a dredge-pond mine on the beach starting in about 1965. The second time period is from 1989 to 2011 that corresponds to after the drag-line mines were shut down with only the dredge-pond mine operating in Marina. The dredge-pond operation mines approximately 205,000 m³/year today, and appears to intercept most all the beach size sand transported south from the Salinas River and sand transported north from the beaches of the central littoral sub-cell. The impact of sand mining is evidenced not only by the high overall recession rates, but also by spatial changes in the rates over time. High recession rates occurred in the southern portion of SMB from 1940 to 1989, after which there was a decrease when the mines in the south were closed. A shift to higher recession rates starting in 1989 in the north portion of SMB is attributed to increased dredge pond sand mining. It is concluded that sand mining is the cause of the high shoreline recession rates observed in SMB, which continues today.

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Appendix A. Salinas river beach sand input to the central sub-cell

The percent of the total discharge of Salinas River beach sand that moves south into the SMB central sub-cell is determined by examining the shoreline recession rates by Hapke et al. (2006) for the period of time from 1910 to 1945 when the Salinas River first started to discharge into SMB and before significant sand mining. For Monterey Bay, Hapke et al. (2006) used surveys of the observed high-waterline (HWL) as measured as the rack line from T-sheets for 1852, 1854, 1910, 1933, and 1945 combined with measured MHWL obtained from a LIDAR survey in 1998. Uncertainties in measurements are due to using the qualitatively observed HWL measurement and not being able to account for seasonal variations since the date of the earlier surveys are unknown. Composite long-term recession rates were calculated using linear regression applied to shoreline positions from 1852 to 1998 for positions between 4.2 km and 5.2 km alongshore, fortuitously from 1910 to 1998 for positions between 5.2 and 12.3 km alongshore, and from 1854 to 1998 for positions between 12.3 and 25 km alongshore. The 1852 to 1998 and 1854 to 1998 recession shoreline rates are both simply referred to as 1854 to 1998 (Fig. 9). Short-term recession rates were calculated based on the end points of the 1945 and 1998 surveys (Fig. 9). The wavy shoreline recession rates are the result of well-developed mega-

cusps captured in the 1998 survey with an alongshore averaged rms excursion value of 0.4 m. Error analysis found a long-term error of ± 0.1 m/year and a short-term error of ± 0.4 m/year (Hapke et al., 2006). The wavy shorelines are not indicative of long-term shorelines. Therefore, the shorelines were spatially filtered using a Fourier low-pass filter with a cut-off of $1/2 \text{ km}^{-1}$ (Fig. 10).

Starting with the section of beach between 5.2 and 12.3 km alongshore, a shoreline recession rate for 1910 to 1945 is calculated by subtracting the total shoreline recession for 1945 to 1998 obtained by multiplying the shoreline recession rate by 53 years (the years of recession) from the total shoreline recession for 1910 to 1998 obtained by multiplying the shoreline recession rate by 88 years, and then dividing the difference in recession by 35 years, the interval between 1910 and 1945 (Fig. 10, green line between thin vertical lines). Additional prorated shoreline recession rates are calculated in a similar manner for the section from 4.2 to 5.2 km alongshore for between 1852 and 1945 (Fig. 10, black line) and for the section 12.3 to 25 km alongshore between 1854 and 1945 (Fig. 10, black line). The analysis shows that there was significant accretion south of the Salinas River.

It is observed that the prorated shoreline recession rates are almost the same for 1854 to 1945 and 1910 to 1945 where they meet at 12.3 km alongshore suggesting the shoreline recession rate from 1854 to 1910 prior to the Salinas River flowing into SMB and any sand mining was small (near zero). Therefore, it is assumed that shoreline recession rate prior to 1910 was negligible between 1854 and 1910. Approximate shoreline recession (accretion) rates for 1910 to 1945 are then obtained by dividing the total shoreline recession between 1854 and 1945 (1854 to 1945 shoreline recession rate multiplied by 91 years) by 35 years, the interval between 1910 and 1945. Combining the three alongshore sections results in shoreline recession (accretion) rates from 1910 to 1945 for the entire SMB shoreline (Fig. 10, green line).

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Reductions in Fluvial Sediment Discharge by Coastal Dams in California and Implications for Beach Sustainability

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ABSTRACT

The long-term sustainability of California's beaches depends on periodic deliveries of sand and gravel from coastal rivers and streams. To assess the long-term health of California's beaches, this study characterized the current state of fluvial sediment delivery and quantified, on a littoral cell basis, the cumulative impacts of dams in decreasing annual discharge. Presently, more than 500 dams impound more than 42,000 km² (or 38%) of California's coastal watershed area. Flow modeling suggests that by diminishing flood hydrographs, these dams have reduced the average annual sand and gravel flux to 20 major littoral cells by 2.8 million m³/yr (or 25%). In 70% of the streams considered in this study, suspended sediment loads during equivalent discharge events have declined over the past three decades, which indicates that dams have also significantly reduced downstream sediment supplies. Approximately 23% (or 274 km) of the 1193 km of beaches in California are downcoast from rivers that have had sediment supplies diminished by one-third or more. Moreover, 192 km (or 70%) of these threatened beaches are located in southern California, where most of the state's beach recreation and tourism activities are concentrated. Although past large-scale nourishment activities associated with coastal construction and harbor dredging have offset fluvial sediment supply reductions, particularly in southern California, many of these threatened beaches can be expected to undergo long-term erosion in the future.

Introduction

During the 1982–1983 and 1997–1998 El Niño winter storms, high wave energy coupled with elevated sea levels caused extensive beach and cliff erosion in California, while coastal structures experienced more than \$200 million in damages from wave impacts and flooding ([Griggs and Johnson 1983](#); [Storlazzi et al. 2000](#)). Policy makers and coastal-advocacy groups responded by lobbying the state for public funds directed toward beach restoration and nourishment projects. In 1999, these lobbying efforts were successful in securing \$10 million for beach restoration projects and research through California State Assembly Bill 64, the California Public Beach Restoration Act. The state legislature mandated that research first be conducted to describe the current condition of major sediment

sources, including coastal bluffs and rivers, and to investigate methods of increasing natural sediment supplies to the coast before embarking on an expensive, long-term beach nourishment program for California (Coyne and Sterrett 2002).

Littoral sediment budgets developed for California have estimated that, on average, rivers and streams provide 75%–90% of sand-sized material (>0.062 mm) and bluff and gully erosion provides the remaining 10%–25% (Bowen and Inman 1966; [Best and Griggs 1991](#)). However, the rates and magnitudes of fluvial sediment delivery have been significantly altered from long-term natural rates by (1) land use changes that have modified watershed erosion rates (i.e., sediment production), (2) the alteration of stream hydrographs (reduction of peak discharges), and (3) the construction of barriers to sediment transport. As early as 1938, researchers recognized the implications of the proliferation of dams in California's coastal watersheds on beach sand supply (Grant 1938). Not until the latter half

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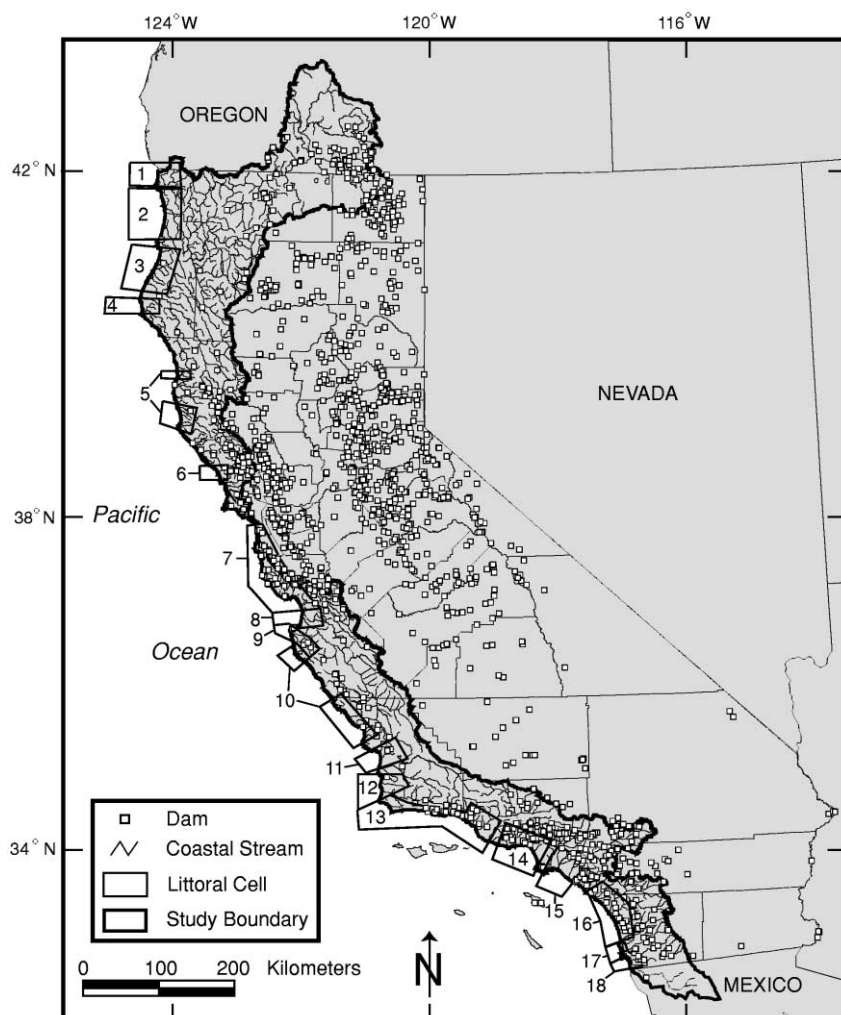


Figure 1. Map of the study area showing the locations of more than 1400 dams over 7.5 m in height or impounding more than 0.06 hm³ that have been constructed in California's coastal watersheds that drain directly to the Pacific Ocean and 20 major littoral cells along the California coast. Numbered littoral cells correspond to table 1.

of the century, however, did researchers attempt to quantify the volumes of sediment impounded by dams (Norris 1963; Department of Navigation and Ocean Development 1977; Brownlie and Taylor 1981; Griggs 1987; Flick 1993). Brownlie and Taylor (1981) completed the most rigorous estimation of the impacts of dams in reducing average annual sand discharge from southern California watersheds through the 1978 water year. Since 1978, California's climate has been dominated by El Niño events that have generated above-average precipitation and river discharges. Both the shift in California's climate and the significant expansion of sediment discharge records warrant a revision of existing estimates of long-term fluvial sediment discharges and the role of dams in reducing coastal

sediment supplies. Thus, the purpose of this study was to characterize the present state of fluvial sediment supplies to 20 California littoral cells (fig. 1) and to quantify, on a littoral cell basis, the cumulative impacts of dams in decreasing fluvial sediment discharge. The results of this study provide fundamental information for current research on strategies for increasing sediment supplies to the coast through dam removal, dam retrofitting, or the removal and transport of impounded sediment to the coast (Coyne and Sterrett 2002).

General Characteristics of the Coastal Fluvial Environment

California's coastal watersheds receive 82% of their annual precipitation between November and

March (National Climate Data Center 2001). As a result, almost all sediment is brought to the coast during storms throughout those winter months. This seasonal pattern of rainfall and streamflow is heightened by infrequent, exceptionally wet years when large floods flush enormous quantities of sediment out of coastal watersheds. A study of major rivers in central and southern California has shown that sediment discharge during flood years such as 1969, 1983, and 1998 averaged 27 times greater than during drier years (Inman and Jenkins 1999). For example, in 1969, more than 100 million tons of sediment were flushed out of the Santa Ynez Mountains, which was more than during the previous 25 yr combined (Inman and Jenkins 1999). Similarly, 63% of all the suspended sediment transported between 1936 and 1998 on the San Lorenzo River near Santa Cruz, California, occurred over just 62 d, less than 0.3% of the time over the 52-yr period. These infrequent, severe floods that take place every 10–20 yr are therefore responsible for delivering the majority of sediment to the coast.

California's coastal rivers have exceptionally high sediment loads as a result of the steep topography, the geologically young and tectonically active terrain, and, in central and southern California, the relatively sparse vegetative cover. California's coastal watersheds are of two general types: (1) the steep, erodible, conifer-forested Coast Range basins north of Monterey Bay, which are characterized by high seasonal rainfall and perennial streams, and (2) the more arid basins of central and southern California, which often drain chaparral- or grassland-covered headwaters but may cross broad alluvial valleys in their lower reaches (Griggs 1987). Sediment yield, the volume of sediment delivered per square kilometer of watershed, is typically very high in California relative to other major hydrographic regions of the United States. In fact, the Eel River in northern California has the highest sediment yield of any river its size in the United States (Brown and Ritter 1971) and discharges, on average, more sediment per year than any river in the lower 48 states after the Mississippi River (Meade and Parker 1984).

Quantifying Long-Term Fluvial Sediment Discharge

Methodology. Long-term average annual sediment discharge was estimated for 31 gaged coastal rivers using sediment transport data and sediment-rating curves to fill gaps in sediment discharge measurements. In the absence of sediment transport data, sediment accumulation records or sediment

yield estimates of adjacent basins were used. All published water discharge, suspended sediment, and bed load data for USGS coastal stream gaging stations through the 1999 water year were compiled to develop suspended sediment and bed load rating curves (Freeman et al. 1999; Rockwell et al. 1999).

Suspended sediment transport was estimated using a standard rating curve technique (e.g., Riggs 1968; Glysson 1987) in which suspended sediment measurements are correlated with water discharge by a power function of the form $Q_s = a \times (Q_w)^b$, where Q_s is the mean daily suspended sediment flux (tons/d), Q_w is the mean daily water discharge in m^3/s , and a and b are empirical constants for individual streams (in this study, a ranged from 10^{-5} to 10^3 , and b ranged from 0.6 to 3.5). Of the 4.9×10^5 d of water discharge data compiled for this study, mean daily suspended sediment discharge was measured on 1.0×10^5 d, while suspended sediment-rating curves were used to estimate suspended sediment flux for the remaining 79% of the days. All of the suspended sediment-rating curves were significant at the 0.01% level (r^2 values ranged from 0.5 to 0.96 and averaged 0.76). Daily measured and estimated suspended sediment fluxes for individual streams were summed by water year. Because this study is concerned with beach sediment supplies, only suspended sediment sizes coarser than 0.062 mm are relevant. The average percent of suspended sediment coarser than 0.062 mm was calculated from suspended sediment grain size distributions, and this average value was used to reduce the annual total suspended sediment flux to just the amount of sand-sized sediment discharged in that year.

Errors in estimating suspended sediment flux arise from measurement errors of suspended sediment in the field and statistical errors in rating curve calculations (Inman and Jenkins 1999). USGS sampling techniques are designed to ensure measurement errors are no more than $\pm 15\%$ (Edwards and Glysson 1999). To assess rating curve errors, we compared annual suspended sediment discharges calculated from sediment-rating curves with measured suspended sediment discharges. On average, our calculated annual discharges differed from measured annual discharges by $\pm 22\%$. Therefore, we estimate the overall uncertainty for annual suspended sediment discharge to be a maximum of $\pm 37\%$.

Bed load rating curves were developed when data were available, and grain size information from the bed surface was used to assess the sand and gravel fraction of the bed load. However, bed load mea-

Table 1. Impacts of Dams on Sand and Gravel Discharge (Q_L) from California Coastal Streams

Littoral cell and major rivers	Drainage area (km ²)	Controlled drainage area (km ²)	Percent controlled	Average annual sand and gravel flux (Q_L) (m ³ /yr)		Present Q_L reduction (%)
				Natural (no dams)	Actual (with dams)	
1. Smith River:						
Smith River	1823	0	0	136,475	136,475 ^a	0
2. Klamath River:						
Klamath River	40,601	18,761	46	2,025,000 ^c	1,275,371 ^a	37
Redwood Creek	761	0	0	256,283	256,283 ^a	0
Total	41,363	18,761	45	2,281,283	1,531,653	33
3. Eel River:						
Little River	121	0	0	40,680	40,680 ^b	0
Mad River	1308	311	24	575,000 ^d	525,509 ^a	9
Eel River	9538	792	8	2,900,000 ^d	2,869,455 ^a	1
Total	10,967	1103	10	3,515,680	3,435,645	2
4. Matolle River:						
Matolle River	966	0	0	177,602	177,602 ^b	0
5. Ten Mile and Navarro River:						
Noyo River	430	6	1	76,774	76,774 ^b	0
Navarro River	818	0	0	159,691	159,691 ^a	0
Total	1248	6	0	236,465	236,465	0
6. Russian River:						
Russian River	3845	747	19	168,500 ^d	139,994 ^a	17
7. Santa Cruz:						
San Gregorio–Pescadero	667	32	5	19,205	19,205 ^{a,f}	0
San Lorenzo–Soquel	950	50	5	81,410 ^c	79,608 ^a	2
Pajaro	3393	495	15	49,000 ^c	46,236 ^a	6
Total	5010	577	12	149,615	145,050	3
8. Southern Monterey Bay:						
Salinas River	10,952	2077	19	555,000 ^d	373,664 ^a	33
9. Carmel River:						
Carmel River	808	324	40	59,500 ^c	24,668 ^a	59
10. Point Sur and Morro Bay:						
Little and Big Sur Rivers	1905	62	3	137,152	137,152 ^{a,g}	0
11. Santa Maria:						
Arroyo Grande	396	183	46	85,500 ^d	28,537 ^a	67
Santa Maria River	4815	2939	61	620,000 ^d	199,368 ^a	68
San Antonio Creek	549	1	0	46,095	46,095 ^b	0
Total	5760	3123	54	751,595	274,000	64
12. Santa Ynez:						
Santa Ynez River	2327	1100	47	545,000 ^c	265,360 ^c	51
13. Santa Barbara:						
Santa Ynez Mountain streams	974	16	2	149,171	149,171 ^{b,h}	0
Ventura River	703	262	37	165,000 ^d	78,177 ^a	53
Santa Clara River	4178	1537	37	1,249,310 ^d	912,192 ^a	27
Calleguas Creek	982	56	6	49,644	49,644 ^a	0
Total	6837	1871	27	1,613,126	1,189,185	26
14. Santa Monica:						
Malibu Creek	285	176	62	40,600 ^{c,i}	18,200 ^{c,i}	55
Santa Monica Mountain streams	331	1	1	33,130	33,130 ^{b,h}	0
Ballona Creek	232	16	7	2209	2,209 ^{a,h}	0
Total	848	193	23	75,939	53,539	29
15. San Pedro:						67
L.A. River	2163	1166	54	178,000 ^{c,j}	59,014 ^a	
San Gabriel	1837	1558	85	139,000 ^{c,j}	45,297 ^b	67
Santa Ana River	4381	4095	93	290,000 ^{c,j}	95,811 ^a	67
San Diego Creek	334	25.2	8	12,392	12,392 ^a	0
Total	8715	6844	79	619,392	212,513	66

Table 1. (Continued)

Littoral cell and major rivers	Drainage area (km ²)	Controlled drainage area (km ²)	Percent controlled	Average annual sand and gravel flux (Q_L) (m ³ /yr)		Present Q_L reduction (%)
				Natural (no dams)	Actual (with dams)	
16. Oceanside:						
San Juan–Aliso Creek	1120	64	5	30,486	30,486 ^a	0
Santa Margarita River	1916	972	51	44,500 ^{d,i}	30,488 ^a	31
San Luis Rey River	1450	564	39	100,000 ^d	30,511 ^a	69
San Dieguito River	896	793	89	45,000 ^{d,i}	9,563 ^{a,i}	79
Total	5382	2393	44	219,986	101,048	54
17. Mission Bay:						
San Diego River	1111	698	63	55,000 ^{d,i}	5,031 ^{a,i}	91
18. Silver Strand:						
Tijuana River	4483	2880	64	63,500 ^{d,i}	32,188 ^{a,i}	49
Total	109,539	42,011	38	11,360,812	8,471,233	25

Note. Methods used to estimate sediment flux.

Source. Data derived in this study if not noted.

^a Sediment rating curves.

^b Sediment yield of adjacent basin.

^c Sediment accumulation records.

^d Flow modeling.

^e Watershed sediment modeling.

^f San Gregorio Creek from Best and Griggs (1991).

^g Department of Navigation and Ocean Development 1977.

^h Inman and Jenkins 1999.

ⁱ Knur 2001.

^j Brownlie and Taylor 1981.

surements have not been made at coastal gages on 85% of the rivers considered in this study. Therefore, bed load was assumed to be 10% of the total annual suspended sediment flux and 100% sand-sized or coarser, an estimate based on the small amount of bed load data at coastal gages that has been used frequently by previous researchers (Brownlie and Taylor 1981; Hadley et al. 1985; Inman and Jenkins 1999). Given the lack of bed load data, we cannot rigorously determine the accuracy of these bed load estimates.

The annual suspended sand and bed load sand and gravel fluxes were summed together to determine the total annual flux of beach material (Q_L). The mean annual sand and gravel discharge (Q_L) was calculated over the period of record to reflect the long-term average sand and gravel discharge for each river. No suspended transport data were available for six rivers, so assessments of Q_L were based on reservoir sediment accumulation rates within the basin or sediment yields of adjacent watersheds. Previously published estimates of sand and gravel discharge for 10 rivers are included in this study.

Results. Average annual sand and gravel discharges are summarized in figure 2 and table 1. The sand discharge includes all sand-sized material (0.062–2.0 mm), but sediment budget studies along the California coast have found that much of the fine sand (between 0.062 and 0.125 mm) is too

small to remain on the beach (Ritter 1972; Best and Griggs 1991). Therefore, the sand flux estimates provided should be considered maximum estimates of beach-quality material supplied from coastal streams. In general, the sand and gravel discharges from coastal watersheds decrease from north to south (fig. 2). The northern Coast Range and the Transverse Range are two distinct regions of high sediment discharge, while the Peninsular Range, on average, supplies the smallest quantity of sand and gravel. Precipitation and lithology are the primary sources of these regional differences in sand and gravel discharge. The northern Coast Range receives approximately twice the average annual rainfall (107 cm/yr) of the southern Coast Range (53 cm/yr) and the Transverse and Peninsular Ranges (43 cm/yr) (National Climate Data Center 2001). However, the frequency of precipitation events and antecedent conditions are more important than total annual precipitation for determining stream discharge. The northern Coast Range shares a climate more akin to the Pacific Northwest and receives a steady barrage of winter storms, so soils remain saturated and precipitation is translated directly into runoff. In contrast, the southern Coast, Transverse, and Peninsular Ranges experience more inconsistent storms that often arrive at intervals that are long enough for soils to dry out,

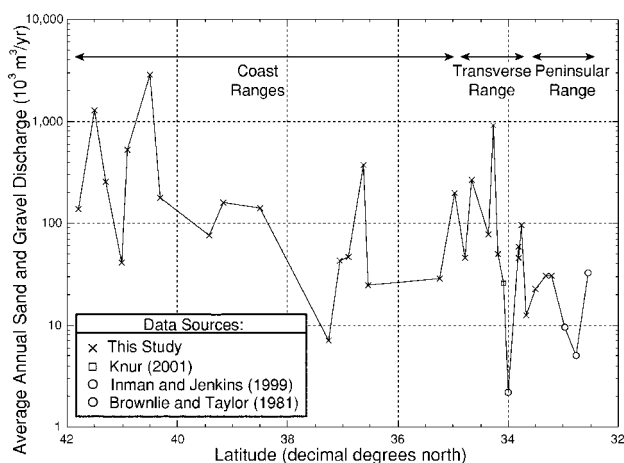


Figure 2. Latitudinal distribution of average annual sand and gravel discharge from 34 coastal rivers in California.

reducing the amount of runoff. The lithology of the Coast Range consists of a mixture of highly erodible Franciscan formation and younger sedimentary rocks as well as more resistant metamorphic and plutonic rocks. [Inman and Jenkins \(1999\)](#) attribute the high sediment yields of the Transverse Range to their composition—relatively young and unconsolidated Cenozoic sediments—and the region's structural complexity, which includes slip faults, thrust faults, and overturned beds. The Peninsular Range, in contrast, is principally composed of older and more resistant granitic rocks ([Inman and Jenkins 1999](#)). Despite the lithologic variations, streams draining the Coast, Transverse, and Peninsular Ranges transport suspended sediment that consistently averages 23%–25% sand with a median grain size of 0.15–0.19 mm.

Distribution of Coastal Dams

California suffers from an extreme mismatch between the distribution of its population centers and its surface water sources. Only 9% of California's population lives in northern California, where 73% of the state's surface water originates ([Bateni et al. 1998](#)). In contrast, 90% of Californians reside in central and southern California (primarily in the urban centers of San Diego, Los Angeles, and the San Francisco Bay Area), where the remaining 27% of the state's surface water is located ([Bateni et al. 1998](#)). Major centers of industrial-scale agriculture have also been established in central and southern California. The seasonal nature of California's precipitation further compounds this problem: 82% of

the state's precipitation falls between November and April (National Climate Data Center 2001), while water demands peak in the summer months. Groundwater sources were tapped in the early nineteenth century to offset surface water shortages in central and southern California, particularly in the Central Valley. However, as demand exceeded groundwater sources, a massive water engineering solution was developed—a complex network of dams, reservoirs, and aqueducts capable of storing 2 yr of California's average annual runoff (after losses through evapotranspiration) and transporting it from water-rich northern California to water-poor central and southern California ([Mount 1995](#)).

This study compiled a geographic information systems database of all regulated dams, watersheds, and digital elevations models for California to map the distribution of coastal dams and the watershed areas they impound. More than 1400 dams over 7.5 m high or impounding more than 0.06 hm³ (Division of the Safety of Dams 1998) have been constructed across California (fig. 1), with 539 of these dams located in the coastal watersheds that drain directly into the Pacific Ocean (59 dams are in watershed areas that extend into Oregon and Mexico). Since the construction of the first coastal dam in California in 1866, an average of 3.5 dams has been built each year (fig. 3). The period of the most rigorous construction of dams coincided with the post-World War II population expansion in California from 1945 to the mid-1970s (California Department of Finance 2000). Dam construction trends can be evaluated by either the number of individual dams built or the total design capacity established in a year. By both accounts, maximum activity occurred between 1945 and 1977, when 61% of the water storage capacity and 50% of the total number of dams in the study area were established. This time period also coincided with a prolonged period of below-average rainfall in southern California (below-average precipitation fell in 27 of the 33 yr; National Climate Data Center 2001). The majority of these coastal dams were built for water supply and irrigation (54%) or flood control (19%) ([Environmental Protection Agency 1998](#)) and are operated primarily by local governments and water districts (52%) or private entities (31%) ([Division of the Safety of Dams 1998](#)).

Downstream Impacts of Dams on Sediment Discharge

Dams affect sediment transport in two ways: (1) they alter the annual hydrograph and typically reduce peak discharges and sediment transport down-

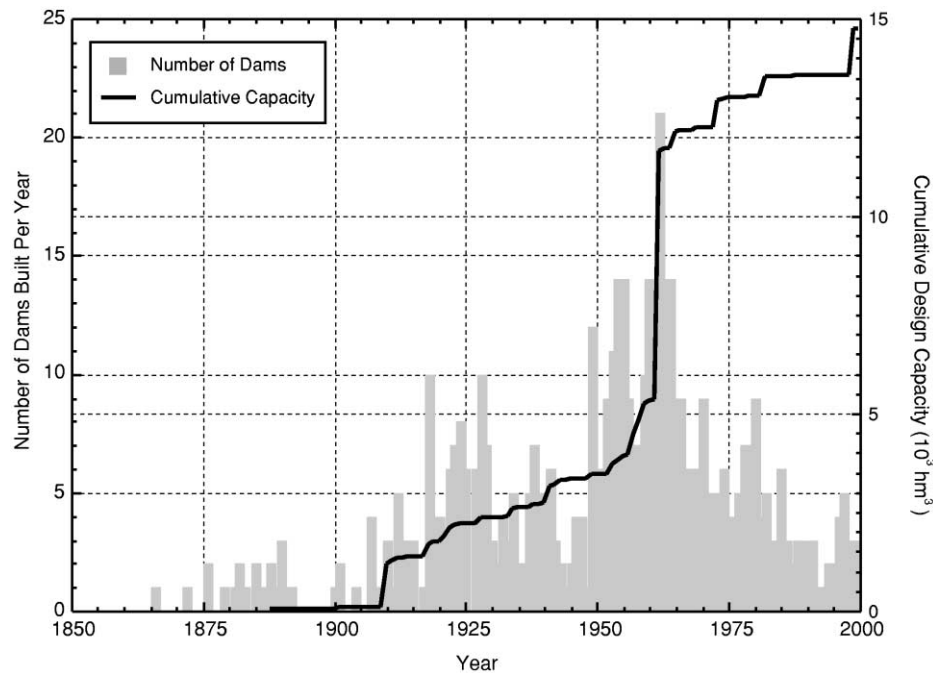


Figure 3. Number of coastal dams built per year in California and their cumulative design storage capacity

stream, and (2) dams trap sediment and reduce the amount of upstream sediment that reaches the downstream river network (fig. 4). The most obvious impacts of dams are on water flow downstream of the dam. Most of the large coastal dams in California impound reservoirs with capacities sufficient to absorb high flows while releasing little or no water downstream and dampening or completely eliminating the flood hydrograph from propagating downstream. With the decrease in peak discharges downstream, the rivers' competence and capacity are reduced. In addition, tributary discharges may become decoupled from flows on the main stem as the timing of flows is altered, causing problems for transporting tributary sediment inputs downstream (Kondolf and Matthews 1991; Topping et al. 2000). The downstream impacts of dams on sediment supply are less well understood. When rivers enter reservoirs, flow velocities rapidly decrease such that all bed load in transport is deposited at the head of the reservoir and all but the finest suspended sediment settles farther down the channel within the reservoir. Reservoir surveys of bed sediment typically show evidence of delta deposits at the entry points of rivers into reservoirs with gradients in grain size from gravel to sand to silt and clay (e.g., Scott et al. 1968). Various empirical relations have been developed to measure the degree of suspended sediment trapping, or

"trapping efficiency." Using the simplest of these empirical methods, Brune's (1953) watershed-reservoir size ratio, we found that California's major dams have an average trapping efficiency of 84%. Bed degradation, bed coarsening, and bank erosion have been widely documented just downstream of dams because of the release of "hungry water," water that has excess stream power as a result of low sediment loads (Williams and Wolman 1984; Kondolf and Matthews 1991). However, sediment loads hundreds of kilometers downstream have also been shown to decrease over time because

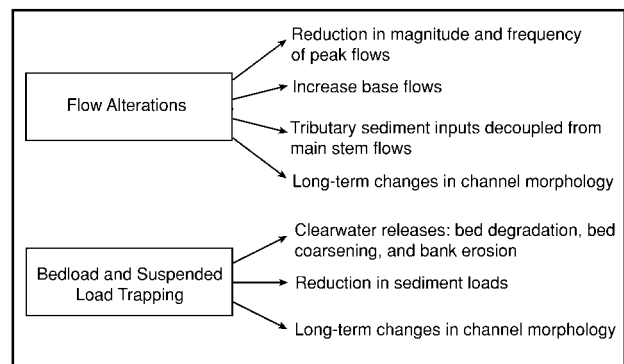


Figure 4. Schematic of the major downstream impacts of dams on water flow and sediment supply.

the downstream river network no longer has access to impounded upstream sediment sources (Andrews 1986; Topping et al. 2000). If sediment budgets are significantly disrupted, channel morphology adjustments will occur (Andrews 1986).

Quantifying the effects of dams on coastal sediment discharge in California is particularly challenging because of the lack of predam sediment transport data and the large annual variability in streamflow. We were not able to find any published suspended sediment or bed load data for coastal gages before dam construction. Most sediment records have been collected since the late 1960s; however, most rivers have been regulated by dams since the early to mid-1900s. In addition, California has an irregular climate and receives highly variable amounts of precipitation from year to year. Thus, flow frequency analysis is often not a viable technique for quantifying the impact of dams on downstream flows because it is difficult to distinguish between climatic variations and flow regulation. In regions where good pre- and postdam sediment transport data are available, the effects on sediment supply can be clearly documented. For example, after the completion of the Glenn Canyon Dam in 1963, suspended sand concentrations at the Grand Canyon gage on the Colorado River have declined, on average, by an order of magnitude over the entire range of measured discharge (Topping et al. 2000). Given the lack of data for California, this study attempted to tackle the problem in two steps: first addressing the effects on downstream flows to predict alterations to long-term sediment discharge at coastal stream gages and then investigating trends in historical suspended sand data to assess qualitatively the degree of sediment supply reductions.

Quantifying Reductions in Sediment Flux due to Flow Alterations

Methods. Using a methodology established by Brownlie and Taylor (1981), we estimated natural flows and sediment discharges for time periods when reservoir inflow and release data were available to quantify the impact of dams on average annual sediment discharge at coastal gaging stations. Inflow and release rates are typically recorded on a daily basis at major reservoirs in water discharge units of m^3/s or ft^3/s . Daily inflow and release data were gathered from dam operators for reservoirs on nine California rivers. The influence of a dam on mean daily flow downstream was estimated by subtracting the mean daily outflow (Q_{out}) from the mean daily inflow (Q_{in}). When a dam was releasing more water than was entering the reservoir, the

$\Delta Q = (Q_{\text{in}} - Q_{\text{out}})$ value would be negative, and natural flows would be predicted to be less than actual flows measured at the coastal gage. Alternatively, if a reservoir was receiving more water than was being released, the ΔQ value would be positive, and natural flows would be predicted to be greater than actual flows measured at the coastal gage. The natural mean daily discharge at a coastal gage was estimated by adding ΔQ from all reservoirs within the basin to the actual mean daily discharge measured at the coastal gage, after accounting for percolation losses using empirical data specific to each river. Once the natural mean daily discharge was estimated, the same suspended sediment and bed load rating curves described in "Methodology" were used to predict the natural daily sediment discharge. By using the same rating curves, we are assuming that the predam and postdam rating curves are equivalent. In the following section, we will present evidence that the rating curves have shifted over time and discuss the implications of our estimates of reductions in sediment discharge.

An example of the flow modeling for the Speckels gage on the Salinas River is shown in figure 5, in which we have plotted the predicted natural mean daily discharges subtracted from actual mean daily discharges. Actual mean daily discharges have

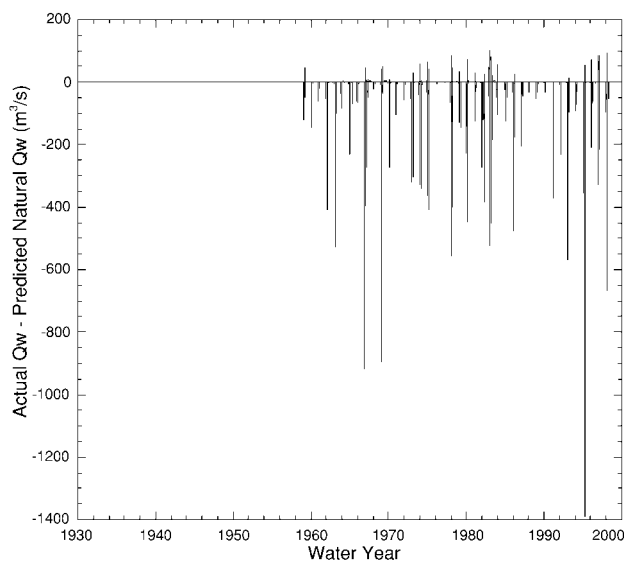


Figure 5. Predicted natural mean daily water discharges subtracted from the measured mean daily water discharges at the Speckels gage on the Salinas River, showing the influence of dams on flows since 1959. Actual mean daily water discharge has been decreased by a maximum of nearly $1400 \text{ m}^3/\text{s}$ and increased by as much as $100 \text{ m}^3/\text{s}$ in the past 40 yr.

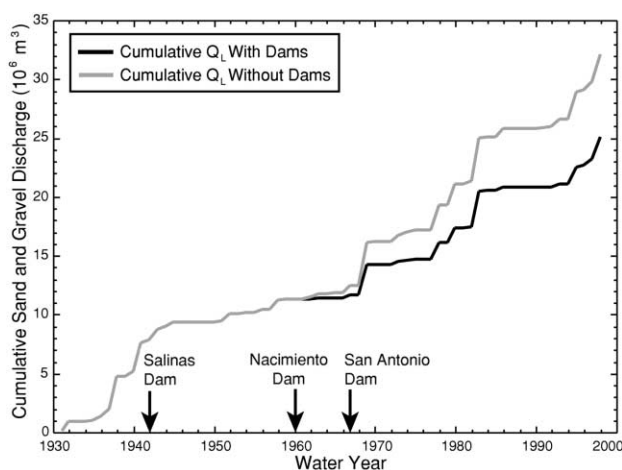


Figure 6. Actual (with dams) and natural (without dams) cumulative sand and gravel discharge for the Salinas River for water years 1930–1999. Average annual sand and gravel discharge has been reduced by 32%, or 7 million cubic meters.

been reduced by as much as 1400 m³/s since Nacimiento Dam began regulating flows significantly in 1959. Since completion of the third major dam on the Salinas River in 1965, the average annual sand and gravel discharge has been reduced by 32% (fig. 6). To check our flow modeling methodology, sediment transport estimates were made using the same rating curves but with natural daily flow estimates for the Spreckels gage provided by the Monterey County Water Resources Agency (MCWRA). The MCWRA's natural flow estimates were generated using a more robust hydrologic model, the U.S. Army Corps HEC-2 model (Montgomery Watson 1998). The MCWRA data suggest that the average annual sand and gravel discharge has been reduced by 35%. Although the simple modeling approach used in this study is not likely robust enough to predict daily flows accurately, the close agreement between the average annual sediment reductions bolsters the credibility of this technique for predicting long-term reductions in sediment discharge.

For seven watersheds for which dam inflow and outflow data were not available, reservoir sediment accumulation data were used to evaluate the decrease in sediment discharge to the coast. Long-term sediment yields for impounded watersheds were estimated from the volumes of reservoir sediment, the duration of deposition, and the basin areas above the reservoirs. Natural long-term sediment yields (i.e., without dams) were estimated from averages of the impounded basins' sediment

yields and the sediment yields of the basins below the reservoirs (determined previously by sediment-rating curves), weighted by the respective basin areas. There were relatively few new data for seven streams in southern California, so previously published estimates of reductions in sediment flux were included in this study.

Results. The cumulative impacts of dams on sediment delivery to the coast have been dramatic. Dams currently impound more than 42,000 km² (or 38%) of California's total coastal watershed area draining to the Pacific (fig. 7). The single largest impounded watershed (nearly 17,000 km², or 40% of the total impounded area) is the upper Klamath basin, an important region for hydroelectric power generation. Approximately 19,000 km² of watershed area is impounded in southern California, chiefly in the Santa Maria, Santa Ynez, Santa Clara, Los Angeles, San Gabriel, Santa Ana, and Tijuana basins. Smaller impounded areas are scattered across northern and central California on the Trin-

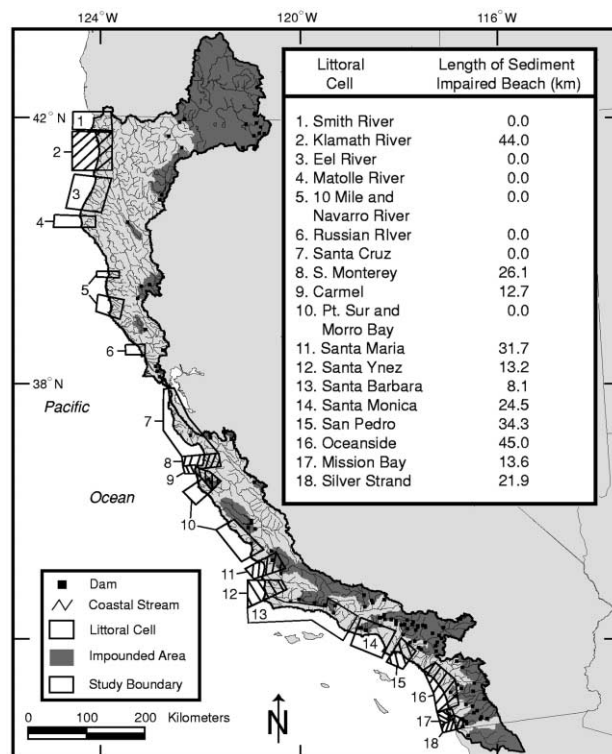


Figure 7. Map depicting the major watershed areas impounded by dams. The littoral cells with the hatched patterns indicate that fluvial sediment supplies have been diminished by 33% or more. Dams shown are the 70 dams that are responsible for 90% of the sediment discharge reductions. Numbered littoral cells correspond to table 1.

ity, Eel, Russian, and Salinas Rivers. By reducing downstream flows, these dams have decreased average annual sand and gravel discharges into the 20 littoral cells addressed in this study by 25%, or about 2.8 million m³/yr (table 1). Nearly half of the 41 rivers included in this study discharge less than 75% of an average annual volume of sand and gravel that would occur without these dams in place. More important, nine of 20 littoral cells have had average annual fluvial sediment supplies reduced by one-third or more (these cells are denoted by a hatched pattern in fig. 7). Six of the nine cells that have experienced significant declines in sediment supply bound the southern California coast. The length of beach that is in a net transport direction from rivers that have had sediment discharge reduced by one-third or more is tabulated for each cell in figure 7 (termed "sediment-impaired beach").

The flow modeling results from this study and Brownlie and Taylor (1981) indicate that a nearly 1 : 1 relationship exists between the percent of a basin area impounded by a dam and the percent reduction in the average annual sediment discharge (fig. 8). This relationship suggests that a balance exists in these coastal watersheds among the source areas for runoff, the distribution of the dams in relation to runoff source areas, and the degree to which the dams stop flows from propagating downstream. Most of the watersheds considered here have precipitation gradients that run parallel to the river channel (predominately flowing east to west), such that the highest precipitation falls in high-elevation headwaters and decreases down slope to the coast. The largest deviations from the least squares best-fit line occur when dams fully impound the high-relief, high-precipitation zones. For example, the average annual sand discharge on the Salinas River has decreased by 32%, while less than 20% of the basin is impounded by dams. The two largest dams impound two subbasins draining the eastern side of the Santa Lucia Mountains, best known for their dramatic expression along the Big Sur coastline of central California. The Santa Lucia Mountains have a strong rain shadow effect on the Salinas Valley to the east; the impounded basins receive, on average, 63 cm of precipitation per year, while the Salinas Valley receives only 38 cm/yr. Thus, the dams block an important source area for runoff and streamflow. In the absence of other data, the nearly 1 : 1 relationship in figure 8 between impounded basin area and average annual reduction in sediment flux provides a good, first-order predictor of the influence of dams on long-term sediment discharge.

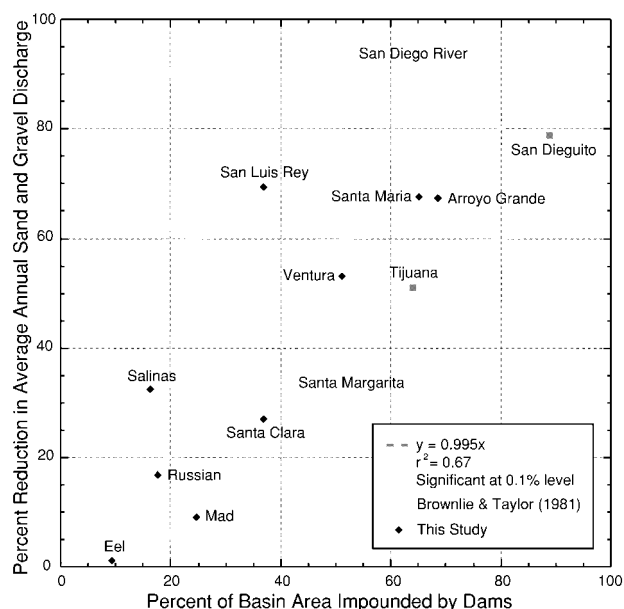


Figure 8. Flow modeling suggests a nearly 1 : 1 relationship between the watershed area impounded and the reduction in average annual sediment discharge.

Downstream Impacts of Sediment Trapping

Methods. As mentioned previously, researchers have shown with pre- and postdam suspended sediment measurements that suspended sediment loads for equivalent discharge events decrease after the construction of major dams upstream, in some cases hundreds of kilometers upstream (Williams and Wolman 1984; Andrews 1986; Topping et al. 2000). These decreased suspended sediment loads have been attributed to sediment trapping behind the dam and the resulting sediment-deprived environment that evolves downstream (Andrews 1986; Topping et al. 2000). In lieu of direct, predam suspended sediment measurements at coastal gages in California, temporal trends in suspended sand concentrations were investigated to detect consistent declines in suspended sand loads for equivalent discharge events that would be indicative of the gradual proliferation of dams within California watersheds and the evolution of a sediment-deficient river network. Our investigation was modeled after that of Dinchart (1997), who used similar techniques to document the decline in sediment loads in streams draining Mount St. Helens in the decade following the volcano's eruption in 1980. Fourteen coastal streams were identified as having suspended sampling records at coastal gages with grain size information over at least a 10-yr period. These watersheds had a minimum of 5% to a maximum

of 91% of upstream basin area affected by dams. For each station, the time series of suspended sand concentrations and water discharge were sorted into six discharge ranges that were based on flow frequency: (1) 2%–10% range: the highest flows that occur between 2% and 10% of the time; (2) 10%–20% range: the second-highest flows that occur between 10% and 20% of the time; (3) 20%–30% range; (4) 30%–50% range; (5) 50%–70% range; and (6) 70%–90% range. Trends in suspended sand concentrations over time were examined for all six discharge ranges both graphically and statistically. A graphical example for the Santa Ana River (91% of the upstream basin is impounded by dams) is shown in figure 9. A sharp decline in suspended sand concentrations since the late 1960s is clearly evident for the two highest discharge ranges (2%–10%: fig. 9A; 10%–20%: fig. 9B). The non-parametric Kendall's tau analysis was used to determine whether temporal trends were statistically significant (Dinehart 1997). Because California streamflow is extremely variable over time, a significantly wide range of discharge events often fell within each of our six discharge ranges. Therefore,

to avoid biasing the results, the Kendall's tau analysis was also performed to check for temporal trends in discharge for our six discharge ranges. If any trend in discharge was found to be significant at the 90% confidence level, the data were discarded; thus, all data reported in this study are statistically independent of discharge.

Results. We have focused our analysis on the temporal trends evident in just the two highest discharge ranges (2%–10% and 10%–20%) because the high-flow events transport the bulk of the sediment to the coast. Statistically significant temporal declines in suspended sand concentrations were present in 10 of 14 rivers (71.4%), as shown in figure 10. Four of these 10 rivers exhibited a sharp decline in sand concentrations of similar magnitude to the trends present in figure 9. Significant increases in suspended sand concentrations through time were present in two rivers (or 14.3%), and no positive or negative trend was present for another two rivers (or 14.3%). Although none of the 14 streams investigated here is completely free from the influence of dams, three of the rivers have 8% or less of their watershed impounded by dams. Yet two of

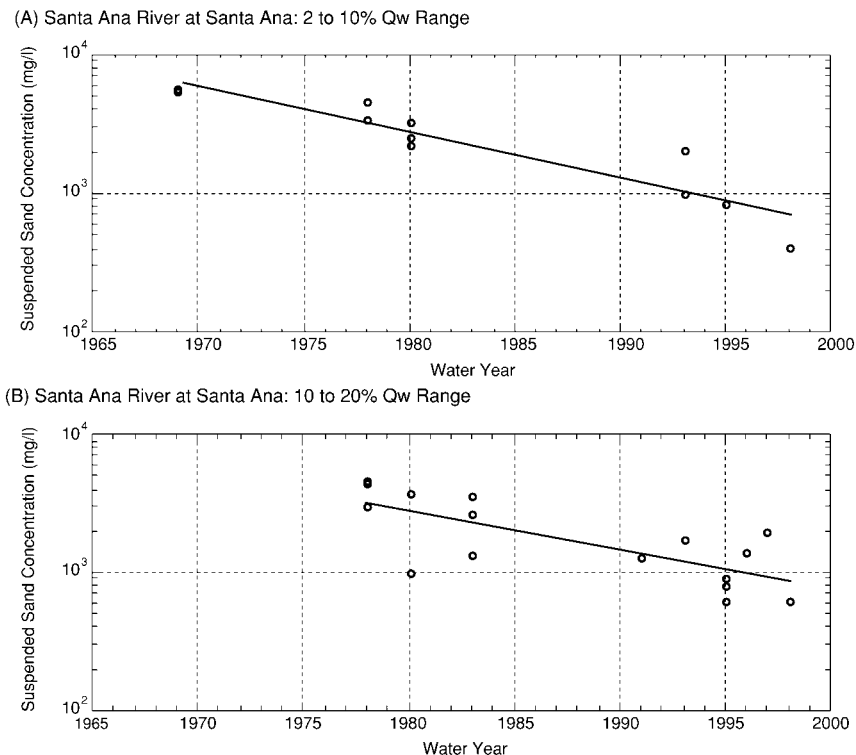


Figure 9. Measured suspended sand concentrations over time on the Santa Ana River at Santa Ana, California, for the discharge events that occur between (A) 2% and 10% and (B) 10% and 20% of the time. Suspended sand concentrations have declined exponentially over the past three decades.

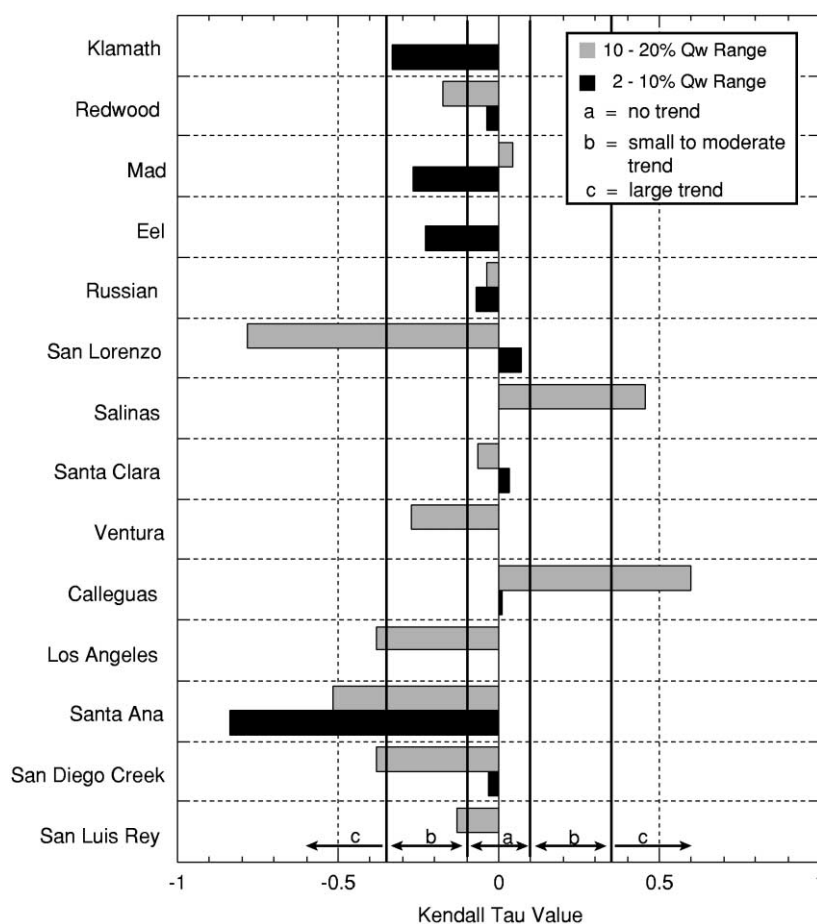


Figure 10. Significant trends in suspended sand concentrations for 14 coastal rivers since 1960. Here, Kendall's tau value indicates the strength and direction of the trend in suspended sand concentrations through time.

those rivers still showed evidence of declining suspended sand loads. More difficult to explain is the strong trend of increasing suspended sand concentrations on the Salinas River, where dams impound approximately 20% of the basin. Clearly, there are other watershed modifications—including urbanization, agricultural practices, in-stream sand mining, and timber harvesting—that can also influence suspended sand concentrations through time. At present, it is not possible to attribute temporal changes in sand concentrations to specific land-use changes in individual watersheds. However, these results confirm that many California rivers are experiencing supply limitations and decreasing sediment loads for equivalent discharge events. Therefore, the cumulative impacts of coastal dams, presented in "Results" in the section "Quantifying Reductions in Sediment Flux due to Flow Alterations," should be considered conservative estimates because they do not fully account for

decreasing sediment loads and shifting sediment-rating curves through time.

Discussion

Given that rivers provide, on average, 75%–90% of beach material in California (Bowen and Inman 1966; Best and Griggs 1991), significant reductions in fluvial sediment discharge over decadal time scales will cause beaches to diminish in size, assuming constant longshore, onshore, and offshore transport over the same time scale. Figure 11 depicts an idealized stretch of sandy beach backed by a coastal bluff in a net downdrift direction from a coastal stream mouth. In this simplified sediment budget, we have ignored on- and offshore sediment transport and sediment contributions from the eroding cliff backing the beach. If the longshore transport potential remains constant and fluvial sediment flux decreases, the only way to balance

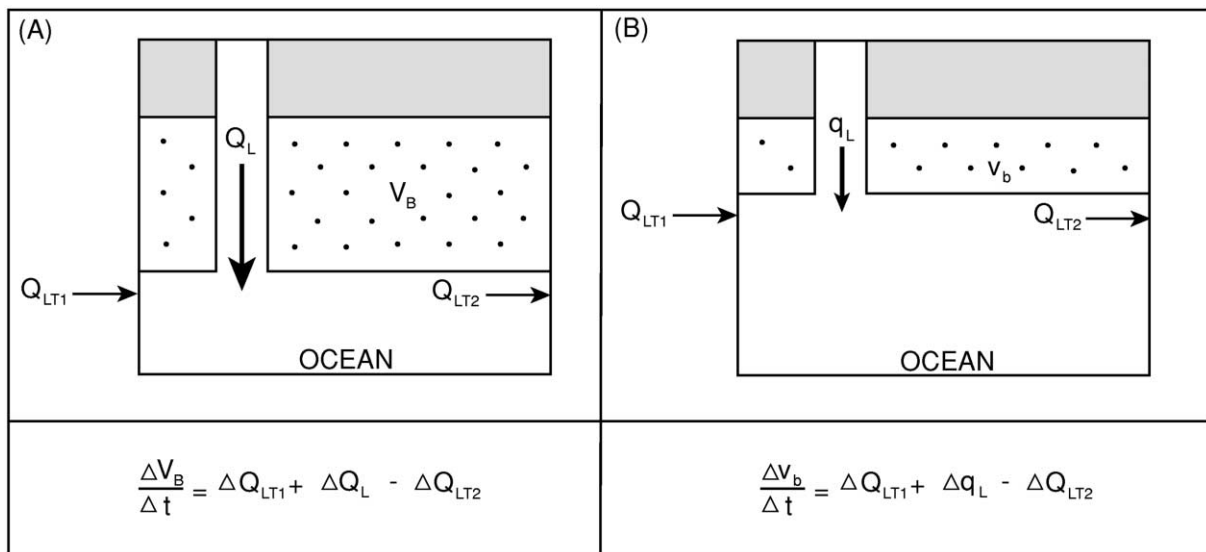


Figure 11. Schematic of an idealized littoral sediment budget for a California beach, ignoring onshore and offshore transport and sediment contributions from cliff erosion. If fluvial sediment flux, Q_L in A, diminishes significantly to q_L in B and littoral transport, Q_{LT} , remains constant, the initial beach volume, V_B , must decrease to v_b to balance the budget.

this sediment budget is to decrease the volume of the downdrift beach. Clearly, sediment budgets in California are not this simple. Longshore transport has been significantly disrupted by coastal structures up and down the California coast, sediment contributions from eroding cliffs have been diminished by coastal armoring, and beach nourishment projects have periodically added sand to the littoral system. In addition, fluvial discharge events are highly episodic. California beaches have evolved in littoral systems in which large pulses of sediment are delivered to the coast at 5–10-yr intervals, with very little sediment being delivered in the intervening years. The large submerged deltas at stream mouths that often form after large flood events have been shown to serve as a sand source for downdrift beaches for several years (Hicks and Inman 1987). We selected four rivers to compare how dams affected sand and gravel discharges in low-discharge versus high-discharge years. While the absolute volume of sediment denied delivery to the coast by dams is much larger during high-discharge years, dams on the Salinas, Santa Clara, and San Luis Rey Rivers have a larger relative impact during the low-discharge years (table 2). Thus, the dams have enhanced the episodicity of fluvial sediment delivery, and the beaches downdrift of these rivers are likely even more dependent on the high-discharge years for replenishing sediment supplies.

In southern California, artificial nourishment

has kept pace with sediment losses from dam construction during the twentieth century. As large harbors were excavated along the southern California coast between 1940 and 1960, more than 100 million cubic meters of sand were placed on the region's beaches (Flick 1993). In some areas, the nourishment likely built beaches that were larger than what was previously maintained by the natural system. In other areas, the nourishment simply offset sand losses caused by dams. However, since the early 1970s, harbor construction and the associated nourishment activities have been curtailed; therefore, in the nine littoral cells where current fluvial sediment input is at only two-thirds or less of predam levels, beaches can be expected to narrow over the long term (fig. 7). Approximately 67% (or 1200 km) of California's coast has been characterized as sandy beaches (Habel and Armstrong 1978). About 23% (or 275 km) of California's beaches are located in a net downdrift direction from rivers that have had sediment supplies reduced by 33% or more and have a high potential for future long-term, permanent beach erosion (fig. 7). Significantly, the majority of these beaches with high potential for long-term erosion (192 km, or 70%) are located in southern California, where most of the state's beach recreation and tourism is concentrated. To date, there have been few comprehensive studies to determine whether long-term beach loss is occurring in California. However, per-

Table 2. Sediment Discharge Reductions in High- and Low-Discharge Water Years

River	Low-discharge years ^a		High-discharge years ^b	
	Frequency (%)	Average reduction in Q_L (%)	Frequency (%)	Average reduction in Q_L (%)
Russian	50	17	21	17
Salinas	67	69	20	27
Santa Clara	71	48	21	20
San Luis Rey	87	76	10	36

Note. Definitions of low- and high-discharge years; Q_L = gravel discharge.

^a Low-discharge years are defined as less than one-half of average annual Q_L .

^b High-discharge years are defined as >2 times average annual Q_L .

sistent exposure of cobble beaches that have been historically covered with sand in Ventura County (Capelli 1999) and in northern San Diego County are indicative of sand-deficient environments; in response, the San Diego Association of Governments has recently initiated a \$16 million beach nourishment project for San Diego County (Kulchin et al. 2001).

Conclusions

Dams have dramatically reduced fluvial sediment supplies to the California coast, but a number of factors may permit watershed management actions to increase present rates of sediment delivery. First, 70 dams (or just 13%, shown in fig. 7) are responsible for 90% of the sediment reductions to the coast and make any sediment management efforts far more localized and tractable problems than if all 539 coastal dams were equally responsible for reducing sediment supplies. Second, half of these 70 dams are more than 50 yr old and are losing significant quantities of storage capacity as a result of sediment infilling; therefore, they are providing minimal flood control or water storage benefits. Dams that have lost much of their storage capacity, such as Matilija Dam on the Ventura River in southern California, may be good candidates for removal (Capelli 1999). Other dams, such as San Clemente Dam on the Carmel River, are structurally compromised and are in need of expensive repairs (Evans 1999). Such extensive repairs may not be justified when balanced against the water storage benefits and environmental costs that will be incurred, and dam removal may be the preferred

alternative. Dam removal is an increasingly popular management choice in the United States, where more than 450 dams have been removed (Maclin and Sicchio 1999). In some cases, structural repairs may provide opportunities for design improvements or retrofitting with engineering devices designed to mobilize impounded sediments and move them below the dam (Wasyl et al. 1978). Regardless of the strategy, some form of large-scale, continuous sediment management will be necessary in the San Pedro, Oceanside, Mission Bay, and Silver Strand littoral cells—the cells that bound the California coast from Los Angeles to San Diego—to prevent permanent beach losses.

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