2. SEDIMENT BUDGET

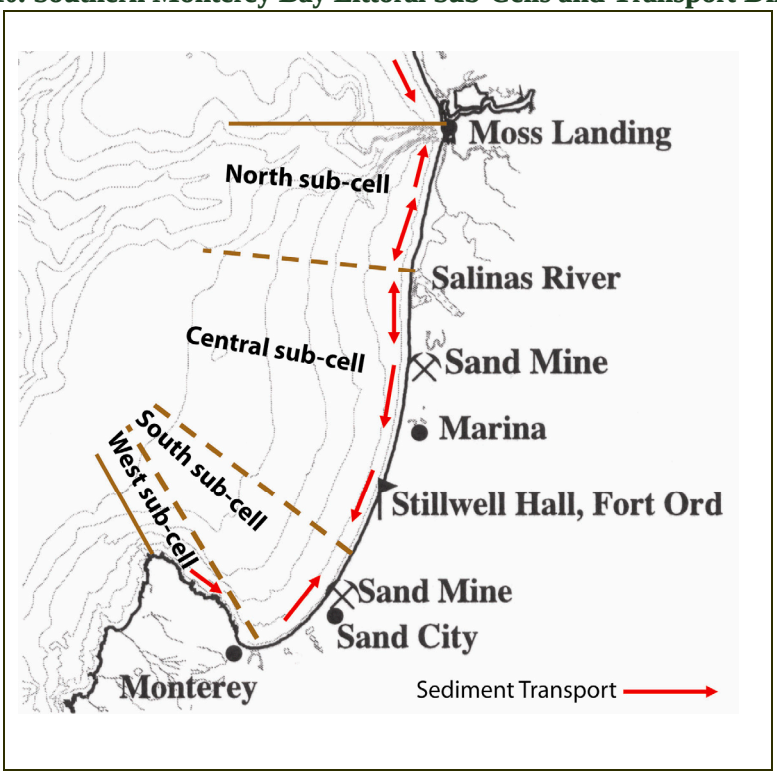
Sediment (sand) budgets are important tools in understanding regional sediment processes (Best and Griggs, 1991; Rosati, 2005) and to quantify the sediment sources (inputs) and sinks (outputs) from a littoral cell; a defined length of shoreline along which the cycle of sediment erosion, transportation, 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, sediment transported by wind, and any sediment within the surf/swash zone and out to the depth on the shoreface at which wave energy stops transporting sediment. Some of the sediment inputs and outputs are not well defined, such as those from or to offshore, and these components are often treated as an unknown and estimated by the residual in the budget.

2.1 DEFINITION OF 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 10). The boundary between the north and central sub-cells is located at the Salinas River mouth. Refraction of waves over Monterey Submarine Canyon (Section 1.4.2) 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 10) (Habel and Armstrong, 1978). Thornton et al. (2006) suggested seasonal variability in sand transport directions in the central sub-cell. During winter, sand is transported to the north, with transport to the south during the rest of the year, with an overall net southerly movement. The northerly transport during the winter coincides with the time of year when the Salinas River is flowing into the bay and providing sediment input (Section 2.3.1), suggesting that most of the river sediments are transported to the north.

Figure 10. Southern Monterey Bay Littoral Sub-Cells and Transport Directions



A third (south) sub-cell exists within the southern bight between Wharf II and to north of Sand City (Figure 10). Orzech et al. (2008) showed that the net sand transport at Sand City is to the north, resulting in a convergence of alongshore transport with the net southerly transport at Fort Ord (Section 2.2). At the location of convergence, approximately three 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 southerly transport into the south sub-cell.

A fourth (west) sub-cell is defined between Point Piños and Monterey Harbor (Coast Guard Pier) where the alongshore sand transport is to the east (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 pier increased in width to 80 feet by 1990 (Storlazzi and Field, 2000) and has since stabilized at about that width.

Monterey Harbor requires periodic dredging. Approximately 4,000 yd^3 was dredged in 2003 and it is estimated that approximately 75,000 yd^3 could be targeted for dredging in 2010-2011. The

sand in the harbor appears to be primarily 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.

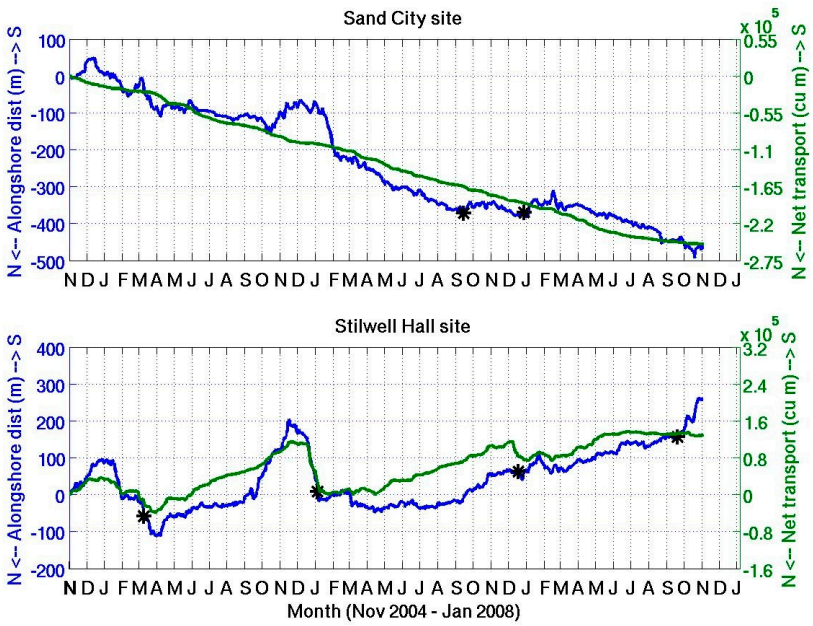
Based on the potential for sand to be transported from the central sub-cell into the north sub-cell, it is recommended using Monterey Submarine Canyon as the northern boundary of the littoral cell (the littoral cell defined by Patsch and Griggs, 2007) (Figure 10). The 16 miles of shoreline between Monterey Submarine Canyon and Wharf II encapsulates all of the sediment that should be considered in RSM for southern Monterey Bay.

2.2 SEDIMENT 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 the Monterey Submarine Canyon, and the evolution of the shoreline in response to the wave climate. Southern Monterey Bay is essentially a crenulate-shaped bay between the Monterey Peninsula and Monterey Submarine Canyon. The shoreline is a near-equilibrium shape. These processes along with the shorelines exposure to the North Pacific, results in large total sand transport but a small net transport rate over a given year or longer period. The near-normal incidence of waves approaching the southern Monterey Bay shoreline is conducive to rip current generation and maintenance, creating a cross-shore component to the sediment transport (Thornton et al., 2007).

Sediment transport rate calculations are inherently inaccurate and it is most important to get the transport direction correct. Orzech et al. (2008) measured the daily migration of rip current channels over a three year period (2005-2008) using time-lapse video images taken at Sand City, Fort Ord and Marina, and hypothesized 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 an offshore NOAA wave directional buoy (Buoy ID: 46042) (Figure 8). 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 11). Sediment transport at Stilwell Hall (Fort Ord) and Marina (not shown 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 net calculated rate to the south of approximately 0-40,000 yd^3/year.

Figure 11. Calculated Sediment Transport (green) and Net Transport of Rip Channel Morphology (blue)

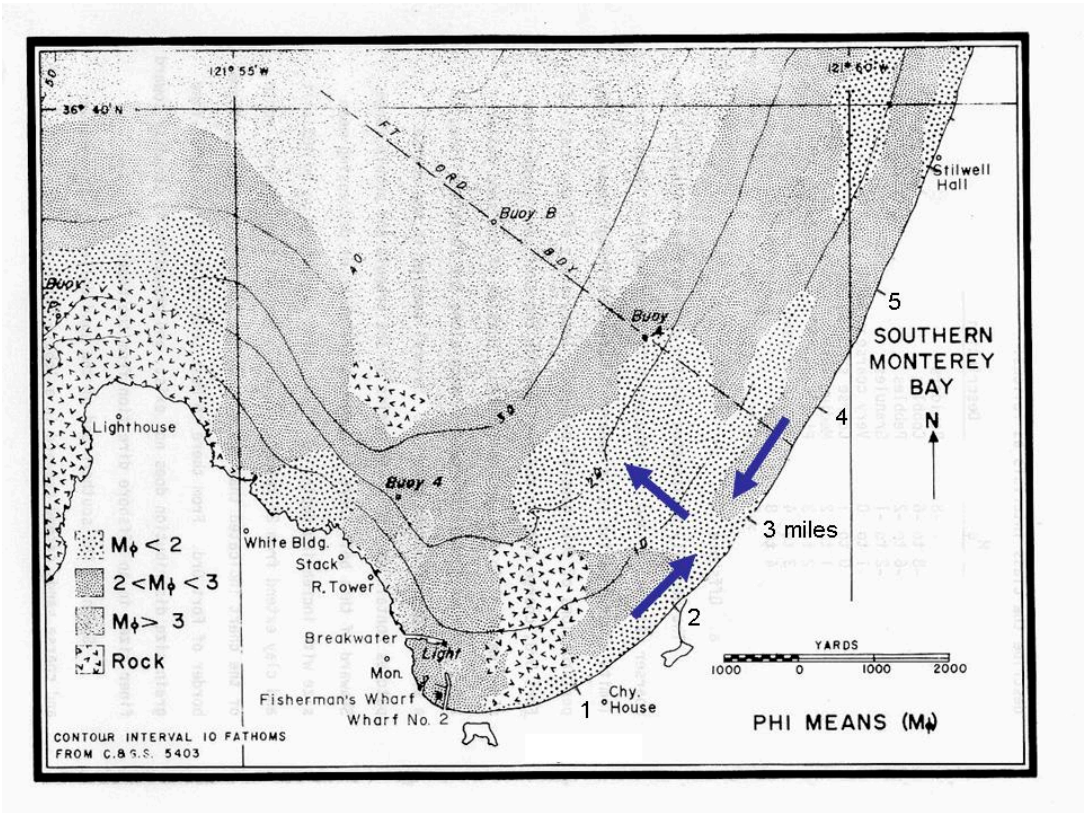


Source: Adapted from Orzech et al. (2008)

An important boundary in the alongshore sediment transport regime is north of Sand City where sand transported south from Fort Ord meets sand transported north from Monterey to form a zone of 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 gradient of wave energy (Section 1.4.2) creates a pressure gradient driving currents to the south that are seasonally variable and strongest in the winter when waves are largest. The resulting net transport is to the north is calculated to be approximately 0-80,000 yd^3/year.

Evidence corroborating a convergence zone is found in Combellick and Osborne (1977) and Reid et al. (2006). Combellick and Osborne (1977) combined the surface sediment studies at the southern end of Monterey Bay by Dorman (1968) and Greene (1970). They found a relatively narrow band 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 12). The location of the shore connection of this band of sand is consistent with the location of the sediment transport convergence zone.

Figure 12. Distribution of Surface Medium and Coarse Sand South of the Salinas River



Source: Adapted from Dorman (1968). Medium sand (less than 2 phi = greater than 0.25 mm). Fine sand (2-3 phi = 0.125-0.25 mm). The blue arrows indicate the direction of net sediment transport. Distance in miles from Wharf II is indicated.

Sand mining in southern Monterey Bay has increased erosion rates, and modified shoreline orientation and sand transport rates (Battalio and Everts, 1989). A detailed review of historic shoreline positions and a sand budget indicated that sand mining in Sand City and Marina had caused the bay shoreline to recede landward in the vicinity of the mines, thereby increasing alongshore sand transport toward the mines. The Fort Ord shoreline experienced the highest erosion rates due to its location between the Sand City and Marina mining operations, and also due to the greater wave exposure (Battalio and Everts, 1989). The conceptual model and numerical model used to evaluate these processes is based on an equilibrium shoreline with small net transport, but large gross (back and forth total) transport, where perturbations like sand mining and river discharge result in net transport toward and away, respectively, from the perturbation (Section 5.2). Therefore, the net alongshore sand transport rate has varied over time in response to sand mining, which continues today.

The important sediment transport findings are:

- net sand transport is to the north in the southern bight and converges with the net southerly transport from the north near Sand City
- sand transport between Fort Ord and the Salinas River is to the north in the winter when the Salinas River is flowing and contributing sediments to the littoral budget (Section 2.3.1)
- transport of sand is to the north during the winter when the dredge pond at Marina is being filled extracting sediments from the littoral system (Section 2.5.4)
- calculated net transport rates are potential rates which may be affected by sediment availability
- gross transport rates are higher owing to the seasonal variation in the direction of transport
- higher gross and low net transport rates are pertinent to sand placement design considerations.

Apart from the littoral cell boundaries at Moss Landing (jetties) and Wharf II (breakwater), 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, the mining of sand from the back beach at Marina is a major barrier to sediment transport (Section 2.5.4).

2.3 SEDIMENT SUPPLY

Sources of sand to the southern Monterey Bay littoral cell are discharge by 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-size sediment that is contributed to the littoral cell by the Salinas River 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 the sediment processes are characterized by an over supply of fine sediments (McGrath, 1987). The sediments are generated partially from the natural dryness of the eastern portion of the watershed, partially from the expansion of agriculture, and partially 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 13).

Figure 13. Salinas River during a Flood and Bar Breach

Source: Unknown

The majority of sediment delivered to the coast during flood events is very fine sand and mud that bypass the inner shelf as a plume. The fate of fine sediments supplied by the Salinas River and other rivers to the California coast was summarized by Farnsworth and Warrick (2007). The Salinas River discharges on average nearly two million tons of fine sediment annually, which dominates the discharge of fine sediments along the central coast. After sediment is introduced into coastal waters, it undergoes intervals of deposition, resuspension, and transport until it is ultimately deposited where it will no longer be disturbed (Wright and Nittrouer, 1995). A distinct fine-sediment region is present in the northern Monterey Bay mid-shelf. This Salinas River mud lobe is a convex bulge on the mid-shelf in water depths of 30 to 300 feet covering an area of 28 square miles (Figure 4) (Chin et al., 1988). Due to the fine particle size of this sediment, it is not a source of material for beach nourishment.

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, decreasing the flow rate. In addition, the dissipation of the flood waves 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) 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 sediment before it can be carried to the coast.

Further evidence that the 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 indicating that the coarse-sand fraction is deposited before reaching the bay. They found that the sand in the river near the 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 texture, petrographic and Fourier grain-shape analysis 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 river even after the major flood of 1978. Based on statistical analysis tests, they found little similarity in shape between the river sand and that of the southern beaches or offshore areas. 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 appears to be minimal except to those within 1.6 miles south of the Salinas River mouth. Another possible reason the river contribution does not extend to the south may be that the medium to coarse sand contribution is intercepted by the Marina sand mine located approximately two miles south of the river, that was started in 1965.

Willis and Griggs (2003) studied river sediment discharge along the entire California coast, but focused on the Salinas River as a specific example, which provides 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 upsteam 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. The fraction for sand particle size >0.063 mm of suspended load was included. However, the bedload was not measured and was assumed to be 20% of the total annual suspended flux and sand size or coarser. The calculated average annual sand and gravel flux at Speckels was calculated at 490,000 yd^3/yr. However, this is judged an overestimate for several reasons:

- sand on the beaches of southern Monterey Bay contain little fine sand smaller than 0.25 mm, which is the majority of suspended sediments
- the river is depositional between the measurement locations at Spreckels and the bay

- the assumption that the bedload is equivalent to 20% of the suspended sediments appears to be an overestimate.

McGrath (1987) focused only on beach sand-size sediments. He first quantified the hydraulic behavior of the 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, ultimately applying a modified Einstein approach. McGrath (1987) estimated that approximately 50,000 yd^3/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 yd^3/year if these particle sizes are included. Since the study was completed in 1987, the estimates do not include the water years to date during a time of positive PDO and increased rainfall, which could increase the yearly average 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 yd^3/year is used. Given the distance over which the Salinas River sands have been found south of the 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, the budgetary contribution to the south is judged to be relatively small. For this sediment budget a value of 10,000 yd^3/year is estimated. This leaves approximately 55,000 yd^3/year of sediment transported north, supporting the contention of Patsch and Griggs (2007) that most of the supply from the Salinas River is driven north and potentially lost into Monterey Submarine Canyon.

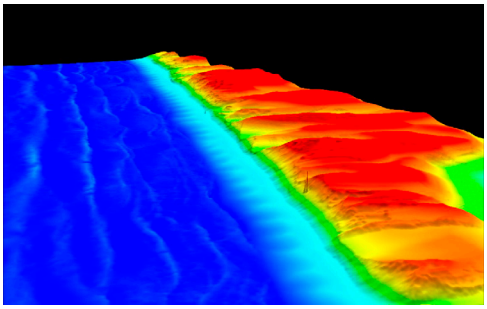
2.3.2 Potential Barriers to River Sediment Transport

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 has reduced sediment discharge by impounding sediment behind the dam and by changing (usually reducing) the sediment carrying capacity by reducing flow in the river, particularly during times of floods. Slagel and Griggs (2006, 2008) calculated that at Spreckles (11 miles upstream of the mouth) the impact of the dams has been to reduce the total annual sediment flux by 31%.

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 in northern San Luis Obispo County is a 210-feet 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 115 miles from the southern Monterey Bay shoreline.

2.3.3 Dune and Beach Erosion South of the Salinas River



The largest input to the sediment budget of the southern Monterey Bay littoral cell is from erosion of the coastal bluffs south of the Salinas River, 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. This process causes aprons or cones of loose sand to accumulate at the top of the beach (Figure 3), 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 re-build active dunes, such as those to the north of the Salinas River, 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 sandy bluffs behind the beaches.

Long-term dune erosion

Long-term erosion of the dunes has been previously measured using a variety of techniques and references. Two recent studies were undertaken by Thornton et al. (2006) and Hapke et al. (2006), and their results are presented below.

Dune erosion was measured by Thornton et al. (2006) using a combination of stereo-photogrammetry (1940, 1946, 1956, 1966, 1970, 1976, 1978, 1980, 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 operation at Marina (Section 2.5.4). The comparative results are presented in Table 3. The dune erosion rates between 1940 and 1984 equate to an average sand volume of approximately 350,000 yd^3/year to the littoral cell. Between 1985 and 2005 this volume decreased to 200,000 yd^3/year. Since some of the dune sand is finer than the beach sand, it is estimated that about 75% of the sand volume (or about 150,000 yd^3/year) stays on the beach (Section 2.6). The differential changes in erosion rate in the vicinities of Sand City and Monterey (decreases) and Marina (an increase) (Table 3) may be related to cessation of sand mining at Sand City and an increase in sand extraction at Marina due to the ongoing operations.

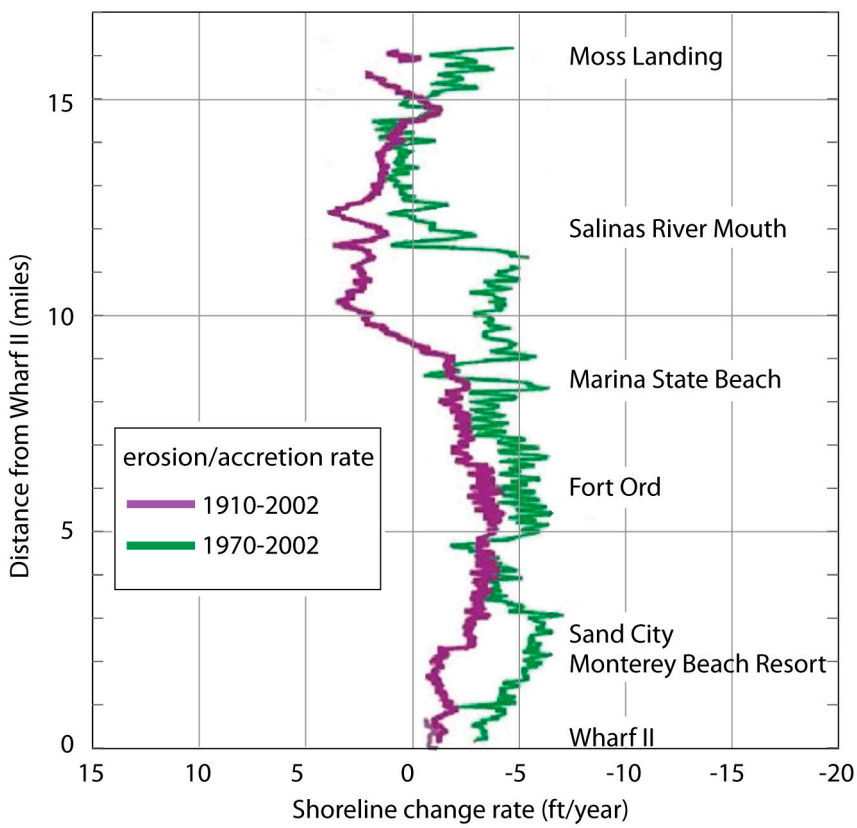
Table 3. Estimated Historic Long-term Average Erosion Rates (ft/year)

Location	Thornton et al. (2006)	Thornton et al. (2006)	Hapke et al. (2006)	Hapke et al. (2006)
Year	**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 line of mean high water (MHW) along the entire California coastline. Corrections were made to adjust the measured high water line on the survey charts (T-sheets) to MHW to minimize biases between shoreline reference features. Erosion rates were calculated as end points between 1910 and 2002 and between 1970 and 2002. The mean erosion rate from 1970 to 2002 of 4.0 ft/year for southern Monterey Bay between the Salinas River mouth and Monterey was the highest for all of California. However, between 1910 and 2002, the shoreline for several miles south of the Salinas River was accretional (Figure 14) whereas from 1970 to 2002 it eroded. This anomaly may be related to the ongoing sand mining operation 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 edge erosion rates calculated by Thornton et al. (2006) during the same time period shows that the results are 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 8).

Figure 14. Dune Erosion Rates in Southern Monterey Bay



Source: Adapted from Hapke, et al. (2006)

Long-term beach stability

Reid (2004) used the 1930 T-sheet and combined it 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, indicating that the beaches are maintained by the constant supply of sand from erosion of the dunes.

Over the long-term the southern Monterey Bay shoreline is migrating landward through space as the dunes erode but the beaches maintain their width, except in locations of coastal armoring such as Monterey Beach Resort and Ocean Harbor House.

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 14). During the winter months, high-energy waves move sand offshore where it forms nearshore bars, and in the process steepens and narrows 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. 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 other 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 yd^3 of sediment offshore. The 1997-98 El Niño also caused the most severe erosion along southern Monterey Bay when the volume of sand eroded from the dunes was 2.4 million yd^3, a seven-fold increase from the average annual volume (Thornton et al., 2006).

As the high-energy conditions subside in late spring and early summer, the beach recovers as sand is moved onshore to rebuild the beach berm, which flattens and widens the beach profile. At the end of the summer or 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 the winter storms have moved it offshore.

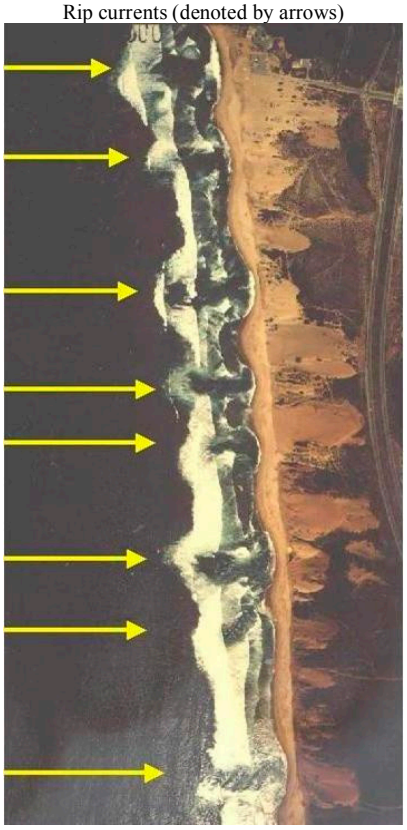
Enhanced erosion due to rip currents

The mean erosion rate in southern Monterey Bay is the highest in California (Hapke et al., 2006). Thornton et al. (2007) hypothesized that the 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 15, 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 face. '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 15 (right panel) shows volumetric change between October 1997 and April 1998. The rip currents and associated rip channels and mega-cusps migrate (Orzech et al., 2008) moving the hot spots along the shore, eroding the dune at an enhanced rate. The rip current's strength, 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 in the protected southern bight between Monterey and Sand City and more effective in the Fort Ord and Marina areas.

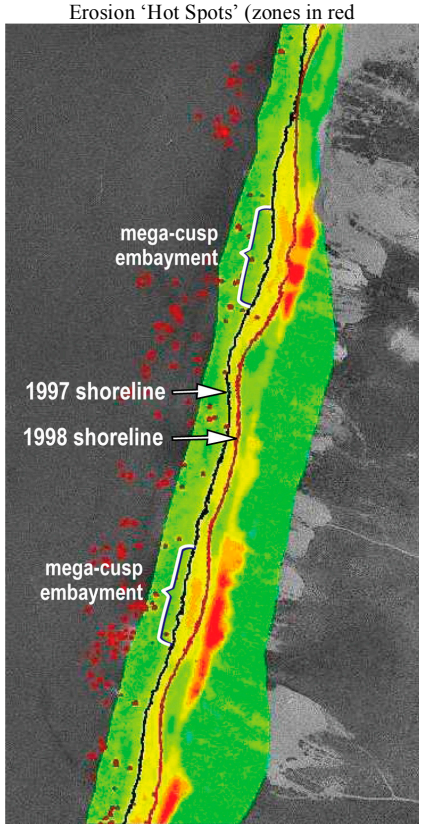
Figure 15. Rip Currents and Erosion 'Hot Spots'

Rip currents (denoted by arrows)



Source: Thornton et al. (2007)

Erosion 'Hot Spots' (zones in red



Source: Thornton et al. (2007)

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 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 erosion rate of the dunes will accelerate (and the littoral shoreline will continue to translate inland) in response to

higher sea level. Higher baseline water levels will result in a greater occurrence of waves impacting the toes of the dune bluffs, increasing their susceptibility to erosion. However, without proliferation of coastal armoring in southern Monterey Bay, beach widths should be maintained, continuing to provide recreation, ecologic, and economic opportunities.

The U.S. Geological Survey (Gutierrez et al., 2007) convened a scientific committee to address potential shoreline changes due to sea-level rise along the U.S. Mid-Atlantic region. Although the west coast shoreline is different, the conclusions are relevant and adopted here. The committee decided from the outset that existing shoreline change prediction techniques such as the Bruun Rule (Bruun, 1962), extrapolation of historic shoreline change rates (NRC, 1987) and simple inundation of a static topography are based on assumptions that are either difficult to validate or too simplistic to account for the complex processes of shoreline change. The committee agreed that the sediment budget is a critical determinant on how the shoreline will respond to rising sea-level, but is also dependent on physical processes (e.g. increased or decreased storminess) and anthropogenic influences (e.g. erosion mitigation efforts such as beach nourishment or the cessation of sand mining).

A different 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). 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.

Over the next century, the Intergovernmental Panel on Climate Change (IPCC, 2007) predicted a global average rate of sea-level rise of approximately 0.6 to 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. In this Coastal RSM Plan a rate of 3.0 ft/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 Coastal Commission measures which require consideration of a three feet sea-level rise over the next century (Susan Craig, Coastal Commission, personal communication).

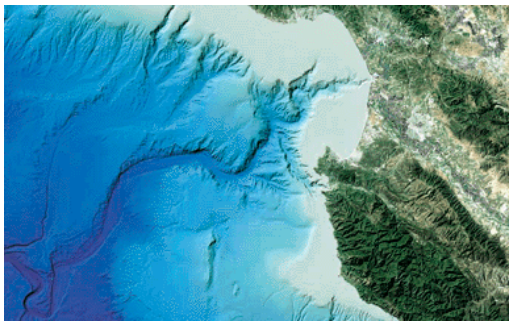
2.5 SEDIMENT SINKS

Potential sand sinks in the southern Monterey Bay littoral cell include removal by wind on to adjacent active dunes, Monterey Submarine Canyon, sand mining (currently only Marina), and offshore transport onto the continental shelf during winter storms.

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 has slowly accreted (Figure 14). Recent 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 recent dunes to the north of the river extend to Elkhorn Slough and vary in width from 300 to 600 feet with crests rising 20-30 feet above sea level. Overall, the shoreline between Moss Landing and the Salinas River appears stable, with a relatively small net output of approximately 10,000 yd^3/year from the littoral budget by wind-blown sand building dunes.

2.5.2 Monterey Submarine Canyon



Monterey Submarine Canyon 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 4), 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 yd^3 of sand per year. This Coastal RSM Plan estimates that approximately 45,000 yd^3/year of this 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 this sand before it is lost down the canyon and beneficially re-use it for beach nourishment (Section 6.5.1).

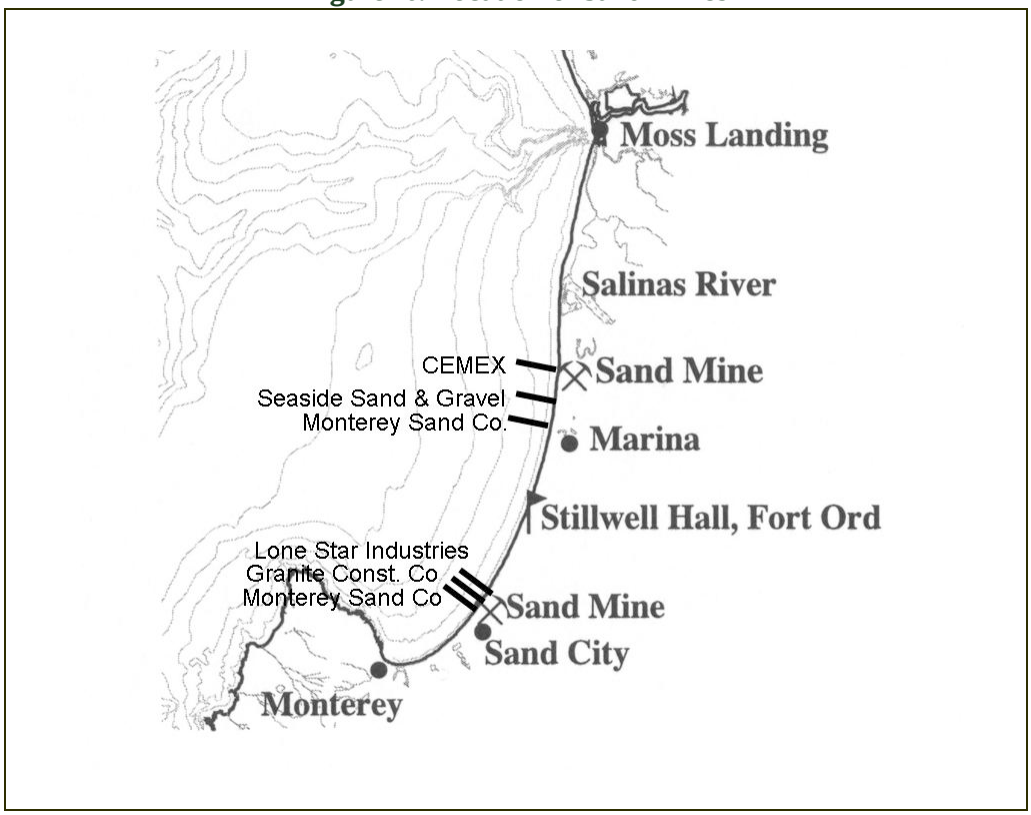
2.5.3 Historic Sand Mining at Marina and Sand City Using Drag Lines

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 16). Five of these operations used drag lines to mine coarse sand from the surf/swash zone. In the summer months, when swell waves transported finer particle sizes 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 RMC Cemex is ongoing (Section 2.5.4). The sand of southern Monterey Bay is economically valuable owing to high silica content, hardness, roundness, amber color and a wide range of usable sizes, and is used for a variety of purposes including filtration, packing for water well casings, sandblasting, foundry and surface finishing (Combellick and Osborne, 1977). The time line of sand mining in southern Monterey Bay is as follows:

- ***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

Figure 16. Location of Sand Mines



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 yd^3/year to 52,000 yd^3/year. In the 1960s, the sand mining companies obtained a court order, which made the volumes of sand mined from 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 yd^3/year to 150,000 yd^3/year to protect the environment. After the first ten-year lease expired, the Corps concluded that the sand mining caused coastal erosion, and the permits were not renewed. Estimates of sand mining rates and the effects of sand mining can be found in Battalio and Everts (1989).

The actual quantities of sand mined as reported to the CSLC have now been obtained through a Freedom of Information request. A decadal break down of the volumes extracted at each mining operation is provided in Table 4. The mines were located either in Sand City or Marina (Figure 16) and their distances from Wharf II are shown. 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.

Table 4. Decadal Sand Mined at Sand City and Marina (yd^3/year x 1000)

	Sand City				Marina				
	MSC[4]	GC[5]	PCA[2]	Sub-total	MSC[4]	SS[3]	PCA[1]	Sub-total	Total
Miles from Wharf II	3.0	3.1	3.5		9.1	9.5	9.8		
Years of Operation	1931-1990	1950-1969	1927-1986		1944-1986	1957-1970	1965-		
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

[1]PCA = Pacific Concrete and Aggregates was bought by Lone Star Industries and then by RMC Cemex in 2005
[2]PCA = Pacific Concrete and Aggregates was bought by Lone Star Industries
[3]SS = Seaside Sand and Gravel Company was bought by Floyd Bradley in 1970 and then sold to Standard Resources in 1974.
[4]The Monterey Sand Company decreased the reported values by 3% to account for wash loss, and this has been added back into the volumes.
[5]GC = Granite Construction.

2.5.4 Ongoing Hydraulic Sand Mining at Marina

The biggest change in the volume of sand mined in southern Monterey Bay was the introduction in 1965 of the dredging operation on the back beach at Marina (Table 4). The sand is mined by a floating dredge creating a large pond just landward of the beach berm (Figure 17, 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 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 refilled with sediment every year as documented by aerial photographs. An example of when the pond has been filled is shown in Figure 17 (right panel) with the wrack line landward of the outline of the pond indicating the maximum extent of the swash carrying sediments onto the beach. This is direct evidence that the sand being mined in the dredge pond is derived directly from the ocean and constitutes a loss of sand from the littoral system.

Figure 17. Aerial Photographs of Marina Sand Mine

Normal dredging operation showing extent of dredge pond (Photo taken: October 28, 2005; California Coastal Records project by Kenneth and Gabrielle Adelman)

Pond filled by high waves at high tide carrying sand over the berm. Note dredge for scale (Photo taken: January 15, 2008 by Robert Wyland, NPS)

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 yd^3/year to 98,000 yd^3/year. After 1970, PCA's Marina permit was to be combined with their Sand City operation, but was never implemented, and the subsequent volumes of sand mined at Marina were not reported. The last reported

value of 98,000 yd^3/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 increased with the new improved dredging operation, and that the mine increased their operation after the other mines closed in 1990, to meet consumer demand.

The total amount of sand sold annually today from the ongoing operation at Marina is 3.0 million tons, or approximately 235,000 yd^3/year, as reported by RMC Cemex (the owners since March 2005). It is assumed that at least 85% of the sand mined is from the dredge pond (the other 15% from dune sand), or approximately 200,000 yd^3/year (Table 4). This value is conservative (some dune sand is mixed with the beach sand to create the correct constitution for construction sand) and similar to the estimate obtained by assuming the pond is effectively filled every year and subsequently dredged to the area measured from aerial photographs, which is approximately 20,000 yd^2. The maximum depth of the dredged pond is based on the depth to which the dredge can reach, which is estimated to be 23-33 feet based on the reach of the dredge head. Assuming the pond could be dredged to the maximum depth, and no sand migrates into the pond from the ocean during the dredge period, the potential amount of sand mined ranges from 153,000 to 220,000 yd^3/year, which is consistent with the reported amount.

2.5.5 Offshore

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 sediment 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 operation during the summer). Based on the mean, skewness, and sorting characteristics of sand distributions collected in southern Monterey Bay, Dorman (1968) concluded that sand moved offshore at the convergence of littoral currents just north of Sand City. The Fourier grain-shape analysis of Clark and Osborne (1982) showed that in southern Monterey Bay the offshore sands at 30 feet water depth are similar to the beach sands. However, the maximum distance that beach sands are transported offshore has not been resolved. The distance that rip currents can transport sand offshore is less than two surf zone widths (MacMahan et al., 2005). Using an extreme wave height estimate of 33 feet, two surf zone widths is a depth of approximately 40 feet.

2.6 SAND BUDGET

2.6.1 Sand Inputs and Outputs

In order to understand the sedimentary processes operating in the region, the sediment budget is broken down into spatial and temporal components. Table 5 presents a sand budget for the portion of the littoral cell between Moss Landing and the Salinas River mouth (north sub-cell).

This length of shoreline is fairly stable based on the 1970-2002 erosion/accretion rate data of Hapke et al. (2006) (Figure 14); the prevailing onshore winds are blowing sand onto the low accreting dunes backing the beach (Section 2.5.1). The balance of the beach-size sediment is lost down Monterey Submarine Canyon or to the offshore.

Table 5. Sand Budget Salinas River to Moss Landing (x1000 yd^3/year)

	Volume
Inputs	
Salinas River	55
Dune erosion	0
Outputs	
Dune accretion	10
Canyon and offshore	45

Table 6 presents a sand budget for the portion of the littoral cell between Wharf II and the Salinas River mouth. The budget is estimated for the 1940-1984 period when drag line sand mining was operational and 1985-2005, during which time drag line mining ceased, but hydraulic mining at Marina continued. In the 1985-2005 budget the residual offshore loss is much less than 1940-1984. This might suggest that either the shoreline is out of balance or the impact of mining sand directly out of the surf zone caused dune erosion to progress at a higher rate, possibly due to a higher overfill ratio compared to filling the dredge pond with marine sand. Overfill ratio refers to the fact that the primary replacement for the mined sand is dune sand, which has a smaller mean particle size than the mined sand; hence more dune sand is required to replace the mined 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%.

Table 6. Sand Budget Wharf II to Salinas River mouth (x1000 yd^3/year)

	Volume	
Inputs	1940-1984	1985-2005
Salinas River	10	10
Dune erosion	350	200
Outputs		
Sand mining (Sand City and Marina)	190	200
Littoral transport and offshore	170	10

The sand budget for the portion of the littoral cell between Wharf II and north of Sand City encompassing three miles of shoreline (the south sub-cell) is presented in Table 7. The northern boundary of this sub-cell is assumed to coincide with the location of the medium sand stretching

into the offshore (Figure 12). The historical drag line sand mining operations at Sand City were located between 3.0 and 3.5 miles from Wharf II (Figure 16). In the historical sediment budget (1940-1984) only the Monterey Sand Company extraction located at 3.0 miles is included, which is a gross estimate as the littoral transport is to the south. The residual of balance is assumed to be sand transported offshore. Assuming the offshore sediment transport is constant over time, the sediment budget since the sand mining ceased suggests that the dune erosion input is out of balance, and that it is possible further decreases in dune erosion rates may occur in the future or the offshore rate is incorrect.

Table 7. Sand Budget Wharf II to Sand City (x1000 yd^3/year)

	Volume	
Inputs	1940-1984	1985-2005
Dune erosion	48	21
Outputs		
Sand mining (Sand City)	37	0
Littoral transport	11	11

2.6.2 Sand Deficits Analysis

The above sediment budget analysis does not include the volume of sand lost with the recession of the beach. Beach recession means that the sand has eroded and not returned. The volume of sand associated with beach recession can be calculated based on the recession rate, the length of shore, and the height of the shore profile. Taking the height of the profile to be approximately 46 feet (Battalio and Everts, 1989), the conversion becomes 1.7 yd^3 per square foot of beach change. In this way it is possible to convert shore recession to the sand deficit for the entire littoral cell. The net sand deficit to southern Monterey Bay can be estimated by calculating the volume of beach sand eroded minus known sinks and plus known sources (Section 2.6.1).

Using an average erosion rate of 4.0 ft/year for the nine miles of shoreline between Sand City and the Salinas River, and assuming 1.7 yd^3 of sand equates to one square foot of beach, means that approximately 320,000 yd^3/year of sand is lost from these beaches. The same calculation for the three-mile stretch of beach between Sand City and Wharf II (southern bight) using an average erosion rate of 1.5 ft/year, indicates that 40,000 yd^3/year of sand is lost. Summing these two estimates equates to approximately 360,000 yd^3/year of sand eroded from the beaches of southern Monterey Bay between the Salinas River and Wharf II. Between the Salinas River and Moss Landing the four miles of beaches are accreting at a rate of approximately 1.0 ft/year, which equates to a beach-sand gain (sink) of 35,000 yd^3/year. In addition, the dunes here are also accreting with approximately 10,000 yd^3/year of sand (Figure 14).

Table 6 shows that bluff erosion provides approximately 200,000 yd^3/year to the southern Monterey Bay littoral cell. Multiplying this value by a 75% overfill factor (about 25% of the dune

sand is too fine) indicates that 150,000 yd^3/year is retained within the littoral system. Approximately 200,000 yd^3/year is removed by the beach sand mining operation at Marina (Section 2.6.1).

Summing all these estimates indicates that between Moss Landing and Wharf II there is a sand deficit of 265,000 yd^3/year. This deficit equates to an erosion rate of 2.5 ft/year over the 12 miles of shoreline of the littoral cell (assuming 1.7 yd^3 of sand equates to one square foot of beach). Using an overfill factor of 25% reduces dune supply to 50,000 yd^3/year, and a lower net deficit of approximately 165,000 yd^3/year, which is equivalent to an erosion rate of 1.5 ft/year. This calculation indicates that coastal erosion will continue, but at a lower rate, due to a sediment deficit even if beach sand mining is stopped.

If the sand mining has a greater effect because coarser material is selectively mined, then the 200,000 yd^3/year mining rate has an amplified effect. Selecting a range from 1.5 to 4.0 (mined volume to shoreface volume), the 200,000 yd^3/year is similar to 300,000 to 800,000 yd^3/year of beach volume, which would increase net loss to 100,000 to 600,000 yd^3/year. The net deficit calculated previously (265,000 yd^3/year) is within this increased beach volume, indicating the net sediment deficit could be completely attributed to sand mining. This indicates that sand mining is a significant contribution to erosion; the post-sand mining recession rate may be small and governed by sea-level rise rather than sediment deficit. Based on this analysis it appears that sand mining contributes to between 50% and 100% of the erosion.

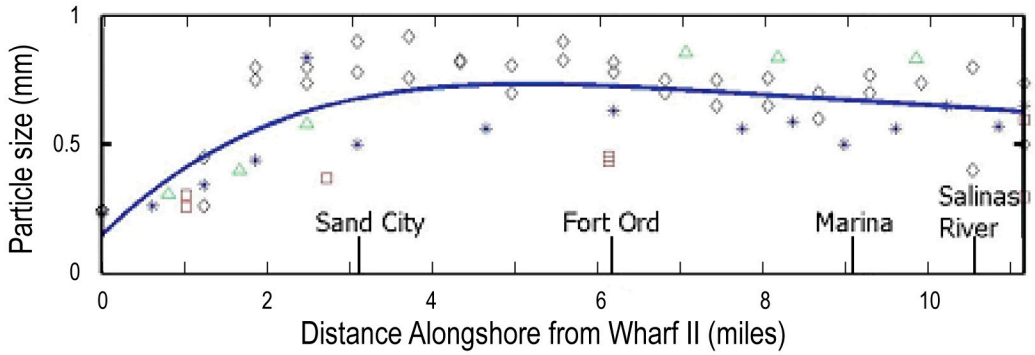
2.7 BEACH AND SHOREFACE SEDIMENT PARTICLE SIZE

The beaches and shoreface of southern Monterey Bay are potential receiver sites for beach nourishment and it therefore important to characterize their particle size distribution.

2.7.1 Beach Sand

Beach sand particle size distributions have been measured in several previous studies and the mean particle sizes are summarized in Figure 18 and Tables 8 and 9. 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 acquired approximately three feet above the line of 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 18. Mean Particle Size of Beach Sand



Samples acquired by Sayles, 1965 (triangles), Combellick and Osborne, 1977 (diamonds), Clark and Osborne, 1982 (stars), and Dingler and Reiss, 2002 (squares). The solid line is a second order polynomial fit in a least-square sense

Table 8. Mean Particle Size of Beach Sand in Southern Three Miles

Distance 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)

[1]Sample taken February 1975.
[2]Sample taken June 1975.
[3]Sample taken September 1988.
[4]Sample taken April 1989.

Table 9. Mean Particle Size of Beach Sand North of Sand City

Distance 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)

[1]Sample taken February 1975.
[2]Sample taken June 1975.
[3]Sample taken September 1988.
[4]Sample taken April 1989.

The smallest mean particle size of approximately 0.2 mm (fine sand) occurs near Monterey Harbor (Figure 18 and Table 8). 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 9). The composite particle size envelope south of Sand City is between 0.2 (fine) and 0.8 mm (coarse), but this range

increases significantly approximately two miles from Wharf II. South of this two-mile marker the envelope is approximately 0.2-0.4 mm (fine-medium), whereas from mile two to mile three the envelope is larger at 0.4-0.8 mm (medium-coarse). North of Sand City the composite particle size envelope is between 0.5 and 0.9 mm (coarse).

Seasonal variations 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 alongshore variability in particle size also appears to 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. The increasing particle size of the beaches from Wharf II to Marina is positively correlated with wave height (Thornton et al., 2007).

2.7.2 Shoreface Sand

The shoreface is the part of the littoral cell between the beach (above 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 from the north to Sand City the sediment particle sizes are much smaller than on the beach. However, a considerable region of medium-size sand occurs on the outer shoreface and further offshore at Sand City, which is comparable in particle size to the beach sands to the south. The sand offshore of the shoreface could be a potential source for nourishment for the south sub-cell.