Temporal and Spatial Variations in Sand Budgets with Application to Southern Monterey Bay, California

Edward B. Thornton

Dept. of Oceanography, Naval Postgraduate School, Monterey, CA 93943

thornton@nps.edu

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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 180K m³/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.

Keywords: sediment budget, shoreline sand mining, Monterey Bay

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, 1978). 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

52 medium to coarse sand (grain size > 0.25 mm, herein referred to as beach sand) will be
53 considered. Second, by considering separate, but connected littoral cells, the boundary
54 condition of the adjoining cells may be solved independently (e.g. Patsch and Griggs,
55 2008). Third, if a long enough time series of the inputs and losses are available during
56 which significant natural and anthropogenic changes occur, it may be possible to isolate
57 an unknown input or output to close the system.

58 To demonstrate these concepts, beach sand budgets in southern Monterey Bay,
59 California, (hereafter referred to as SMB) are calculated for a littoral cell from Sand City
60 to the Salinas River (Figure 1). Several sediment budgets have been calculated for SMB,
61 but considerable variations exist in the estimates (Dorman, 1968; Patsch and Griggs,
62 2007; PWA et al., 2008; amongst others). The sediment budgets are complicated by both
63 spatial and temporal changes to the inputs and losses to the littoral cell over the last
64 century. A large natural change to the littoral cell occurred when the discharge location
65 for the Salinas River changed from discharging through Elkhorn Slough to north of the
66 head of the Monterey Submarine Canyon, which blocks sand from reaching SMB, to its
67 present location 6 km south in 1910 (Chin et al, 1988). The current Salinas River location
68 added a sediment source to the SMB littoral cell. The Salinas River was subsequently
69 dammed by the small Salinas dam in 1941 and the larger San Antonio and Nacimiento
70 dams in 1956 and 1965, decreasing and modifying its input (Willis and Griggs, 2003). A
71 second, more important, anthropogenic change has been the large volumes of coarse sand
72 selectively mined directly from the surf zone and beach in SMB starting in 1927, with the
73 volumes and locations mined changing with time.

An impetus for the sediment budget studies started in the 1970's 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 (Figure 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 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 (Figure 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 Figure 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 (Figure 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.

A change in mean grain-size and composition of beach sands occurs at Sand City at about 4.3 km from Wharf II (Figure 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 (Figure 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 (Figures 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 (Figure 4) were calculated by refracting directional wave spectra measured every six hours by the NOAA direction wave buoy 46042 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) 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 (Figure 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 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 (Figure 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 (Figure 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) (Figure 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 (Figure 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 $\sim +1\text{m}$ 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 500m 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 (Figure 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 (Figure 6). All linear regression fits had R^2 values exceeding 0.85 except for the recession at 13.5 km alongshore 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 Figure 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 (Figure 2).

Beach width variations throughout Monterey Bay were examined over a 71-year period between 1930 and 2001 by Reid (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 Reid (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 (Figure 7). Beach height is equal to the difference between the elevation of the dune toe and the maximum depth of medium sand (grain-size $>0.25\text{mm}$), 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 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 Figure 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 (Figure 5b) times the dune height (Figure 5a). The beach erosion rate per unit alongshore is similarly calculated as dune recession rate times the beach height (schematically shown in Figure 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 0.35mm with only 22% being greater than 0.5mm, whereas the mean grain-size of the beach sand is 0.65 mm with 60% being greater than 0.5mm. 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 Figure 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 $K f_{dune}(\phi)$ (shaded area in Figure 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 ¼ volume is compatible with the beach sand with ¾ of the volume of fine sand transported offshore, which is included in the sand budgets (Table 2).

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 $10^6 \text{ m}^3/\text{year}$, which includes all sediment size fractions.

Willis and Griggs (2003) calculated annual discharge of the sand size fraction (grain size $> 0.063\text{mm}$) 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 percent 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 $> 0.063\text{mm}$) 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 $> 0.25 \text{ mm}$ 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 rates for the time periods 1854 to 1998, 1910 to 1998 and 1945 to 1998 (Figure 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 (Figure 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 to 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 (Figure 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 Figure 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 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 (Figure 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 (Figure 7) and integrated alongshore as before. The height of the beach, h_{ms} , varies as the wave height in Figure 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 (Figure 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 (Figure 3).

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 m³/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 Figure 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 (Figure 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 less than 200 m of reveted shoreline in the central sub-cell fronting Stillwell Hall at Fort Ord between 1978 to 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 (Figure 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 m³/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 m³/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 Figure 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 (Figures 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 (Figure 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 Figure 11 over the sand budget time periods (Table 2). The biggest uncertainty in the sand budget analysis is the amount of dredge pond mining (Figure 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 to 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 ± 8 percent differences in beach erosion when integrated
alongshore and ± 7 percent 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 7,000 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's

A basic assumption of the analysis is that the average annual river discharge measured between 1929 to 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 1910-1940, 8 from 1940-1989, 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 (Figure 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 (Figures 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 (Figure 5b). The recession curves shown in Figure 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

596 been changes in erosion rates between the 1940's-1989 and 1989-2011. Hypothesis tests
597 were applied to determine whether the regression slopes changed between these two time
598 periods using a two-sided student-t distribution test with a 95% level of confidence (e.g.,
599 Bowker and Lieberman, 1961). It was previously shown that erosion had statistically
600 decreased south of 4 km alongshore (Thornton et.al., 2006). At the north end of the
601 littoral cell at 13.5 km alongshore there has been a statistically significant increase in
602 erosion between these two time periods with the caveat that the earlier regression line,
603 although representative, has a low R^2 value. It could not be statistically concluded that the
604 recession rates have changed in the middle sections from 6-10 km alongshore during
605 these same time periods.

606 The interpretation of the spatial and temporal changes in erosion volume rates is
607 complicated by the differences in dune elevation alongshore. For example, even though
608 the average shoreline recession increased in the north end of the central sub-cell between
609 1989 to 2011, the total volume contribution by dune erosion decreased because of the
610 lower dune heights in the north end.

611 The largest temporal change was from accretion to erosion about the Salinas
612 River that is seen when comparing the 1945-1998 with 1910-1998 shoreline recession
613 rates (Figure 9). The erosion coincides with the start-up and continued sand mining near
614 the river mouth. It also closely followed the damming of the Salinas River in 1956 and
615 1965. Evidence that the erosion is more associated with the mining is that the change
616 from accretion to erosion only occurs south of the river, whereas the shoreline accretion
617 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 1940's. 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 percent 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 1940's, 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 1940-1989, 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.

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 (Figure 9). Short-term recession rates were calculated based on the end points of the 1945 and 1998 surveys (Figure 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/yr and a short-term error of ± 0.4 m/yr (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 $1/2 \text{ km}^{-1}$ (Figure 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 (Figure 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 (Figure 10, black line) and for the section 12.3 to 25 km alongshore between 1854 and 1945 (Figure 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 to 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 (Figure 10, green line).

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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

**Table 2. Sand Budget for SMB Central Sub-cell. Values in m³/year x 10³.
Uncertainties are presented with the values.**

	1940-1989	1989-2011
Mean Recession (m)	-1.0	-1.3
Dune Erosion	190	155
Dune Erosion x 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 x 0.29	6 ± 2	3 ± 1
Sand Mining	-174 ± 43	-205 ± 50
Residuals	41 ± 69	-2 ± 71

Table 3. Average annual discharge of beach sand (>0.25mm) by the Salinas River and the 0.27 contribution to SMB.

Period	Total discharge ($\times 10^3 \text{ m}^3/\text{year}$)	SMB contribution ($\times 10^3 \text{ m}^3/\text{year}$)
1910-1945	373 ¹	101 ²
1940-1989	209	56
1989-2011	126	34

1. River discharge of beach sand based on measurements between 1929 and 1945.

2. Beach sand accretion measured using shoreline surveys.

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 x 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

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956 Figure 1. Map of Southern Monterey Bay. Dominant features are the Monterey Bay
957 Submarine Canyon, bulge of sand at the Salinas River, and Point Pinos headland at the
958 southern end. Littoral cells are delineated. The distances in km relative to Wharf II (0) in
959 Monterey are shown. The arrows indicate the direction of sediment transport. The dark
960 circles are the locations of video stations.

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Figure 2. Alongshore distribution of mean sediment size (mm) of beach and dune sands. Beach sand (open symbols) collected at mean tide level by Sayles (1965) triangles; Dorman (1968) squares; Combellick (1976) diamonds; Dingler and Reis (2001) inverted triangles; and collected at +1 m MSL by Clark and Osborne (1977) and Clark and Osborne (1982) circles. Dune samples (closed symbols) collected by Dorman (1968), Clark 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.

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983 Figure 3. Mean-grain-size (phi units) in the southern bight of Monterey Bay showing
 984 confluence of sediments at Sand City (modified from Dorman, 1968). Arrows indicate
 985 direction of sediment transport. The littoral sub-cells are indicated.

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Figure 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).

Figure 5. a) Alongshore variation of dune height and due 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.

Figure 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.

Figure 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} .

Figure 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.

Figure 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.

Figure 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.

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1102 Figure 11. Annual amounts of sand mining reported to State Lands Commission (solid
 1103 lines) and estimated dredge pond annual amounts (dashed lines) at Sand City (blue line)
 1104 at Marina (black line) and total (red line). Vertical dashed line indicates when the drag-
 1105 line mines were all closed in 1989. Sand mined after 1985 is estimated based on reported
 1106 amount in 2000.

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1110 Figure 12. Aerial photographs of dredge pond during operation in April 2005. Copyright
 1111 2005 Kenneth and Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org (upper panel) and when dredge pond is filled with sediments in
 1112 the winter (photo taken by Rob Wyland 15 January 2008) (lower panel).
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