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Temporal and spatial variations in sand budgets with application to southern Monterey Bay, California

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ABSTRACT

Often in calculating a sediment budget there is an unknown contribution, which is ascribed to the residual of the balance, and the budget cannot be fulfilled. The temporal and spatial variations and sediment size within a littoral cell provide additional information to define sediment budgets. The approach here is to consider only medium to coarse sand (grain size > 0.25 mm) over a long time period during significant changes of natural and anthropogenic inputs and losses that allow calculating several budgets to isolate the unknown inputs and outputs to close the system. Considering only medium to coarse sand eliminates including the cross-shore transport of fine sand by waves, which is poorly quantified. To demonstrate these concepts, shoreline recession rates measured over a 101-year time period are used to calculate sediment budgets for southern Monterey Bay, California, littoral cells. The coarse sandy shoreline is backed by extensive bluffs and dunes that reach 44 m in elevation. Intensive sand mining of coarse sand derived directly from the beach and surfzone started in 1927 and continues today. A contribution of about 100 k m^3/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 k m^3/year attributed to different mining operations that captured the littoral transport. The primary contributions of medium to coarse sand to the littoral system is approximately 180 k m^3/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.

1. Introduction

Sediment budgets have been shown to be useful tools in understanding regional sediment processes (e.g. Rosati, 2005; Patsch and Griggs, 2007; Limber et al., 2008). The approach is to quantify the inputs, losses and storage for a littoral region, or littoral cell, with well-defined lateral boundaries. The most useful boundaries are located where there is a well-defined input or sink, such as a river mouth or submarine canyon. Sediment inputs to a cell include rivers, bluff and dune erosion, beach nourishment, littoral alongshore transport entering the cell and shoreward transport by waves. Losses include littoral alongshore transport leaving the cell, sand mining, submarine canyons, cross-shore transport by waves and wind. The off-shore transport by waves is not well quantified. For example, assessing the amount of seaward moving sand by waves requires estimating an ill-defined closure depth where the bottom profile does not change with time (Hallermeier, 1981). This cross-shore transport value is often treated as an unknown and appear as a residual, leaving less confidence in the budget.

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Three approaches are proposed for solving this problem. The first approach is to simplify the budget by defining a littoral cutoff diameter that determines the minimum grain-size diameter of the sediments to be considered (Limber et al., 2008). Only medium to coarse sand (grain size > 0.25 mm, herein referred to as beach sand) will be considered. Second, by considering separate, but connected littoral cells, the boundary condition of the adjoining cells may be solved independently (e.g. Patsch and Griggs, 2008). Third, if a long enough time series of the inputs and losses are available during which significant natural and anthropogenic changes occur, it may be possible to isolate an unknown input or output to close the system.

To demonstrate these concepts, beach sand budgets in southern Monterey Bay, California, (hereafter referred to as SMB) are calculated for a littoral cell from Sand City to the Salinas River (Fig. 1). Several sediment budgets have been calculated for SMB, but considerable variations exist in the estimates (Dorman, 1968; Patsch and Griggs, 2007; PWA et al., 2008; amongst others). The sediment budgets are complicated by both spatial and temporal changes to the inputs and losses to the littoral cell over the last century. A large natural change to the littoral cell occurred when the discharge location for the Salinas River changed from discharging through Elkorn Slough to north of the head of the

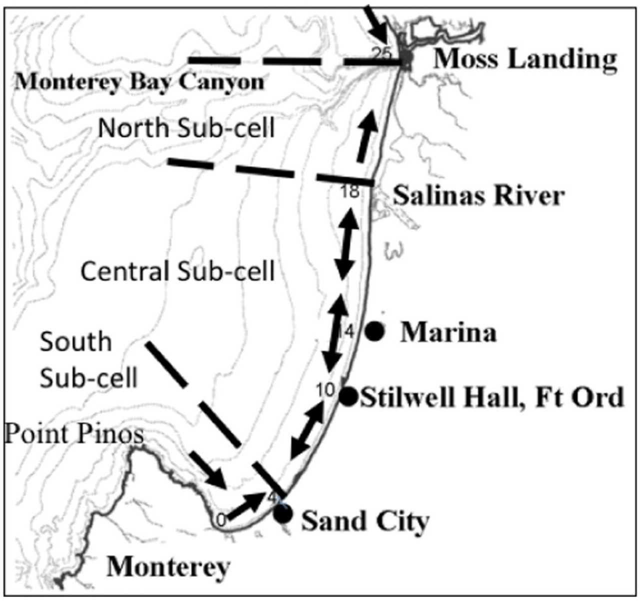

Fig. 1. Map of southern Monterey Bay. Dominant features are the Monterey Bay Submarine Canyon, bulge of sand at the Salinas River, and Point Pinos headland at the southern end. Littoral cells are delineated. The distances in km relative to Wharf II (0) in Monterey are shown. The arrows indicate the direction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

Monterey Submarine Canyon, which blocks sand from reaching SMB, to its present location 6 km south in 1910 (Chin et al., 1988). The current Salinas River location added a sediment source to the SMB littoral cell. The Salinas River was subsequently dammed by the small Salinas dam in 1941 and the larger San Antonio and Naciomento dams in 1956 and 1965, decreasing and modifying its input (Willis and Griggs, 2003). A second, more important, anthropogenic change has been the large volumes of coarse sand selectively mined directly from the surf zone and beach in SMB starting in 1927, with the volumes and locations mined changing with time.

An impetus for the sediment budget studies started in the 1970s with an attempt to determine whether or not sand mining was responsible for the observed high recession rates in SMB, with recession rates as much as 2 m/year at Fort Ord (Fig. 1). SMB was identified as the most erosive shoreline on average along the entire California coast over the period 1945 to 1998 with an average erosion rate of 0.8 m/year (Hapke et al., 2006). The mined sand is economically valuable owing to high silica content, hardness, grain roundness, amber color and wide range of usable sizes. Uses include filtration, sandblasting, foundry purposes, packing for water wells, and surface finishing (Combellick and Osborne, 1977).

The study objectives are 1) to demonstrate techniques for calculating sediment budgets by only considering the coarser fraction of the sediments, considering spatially connected littoral cells to solve the boundary condition of littoral transport between them, and examining a long enough time period during significant changes to calculate several budgets, and 2) to provide new data on dune recession and to refine the sediment budget estimates in southern Monterey Bay based on an accumulation of knowledge from recent studies. The timelines of significant events are summarized in Table 1. Taking advantage of temporal changes, the contribution by the Salinas River is isolated and measured between when it first started flowing into SMB in 1910, before significant sand mining in 1945. Beach sand budgets are calculated for two time periods to examine the impact of sand mining. The first budget is calculated from 1940 to 1989 during the time of intensive drag-line sand mining of the surf zone focused on the south end of the littoral cell. The second budget is calculated from 1989 to 2011 after all the drag-line mines were closed leaving only a dredge pond mining operation at the north end of the littoral cell.

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	Naciomento 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

2. Geology setting

Monterey Bay is the largest open embayment along the central California coast. SMB shoreline is characterized by sandy beaches backed by dunes and pervasive sea cliffs composed of Quaternary dune deposits, which will be referred to in the text as dunes. The arcuate shape of the bay suggests that the bay has an equilibrium form. The entire shoreline morphology is characterized as a transverse- bar and rip-beach, or alternatively, low-tide terrace-bar incised by rip channels (Short, 1999).

Prominent morphologic features in SMB are the Monterey Submarine Canyon, the sediment lobe offshore of the Salinas River, and the Point Pinos headland at the south end of the bay (Fig. 1), all features that significantly modify the incident wave field. SMB forms a closed littoral cell bounded at the north by the Monterey Submarine Canyon, which extends almost to the shoreline at Moss Landing and intercepts the predominant drift from the north (Wolf, 1970; Smith et al., 2007). The effectiveness of the Monterey Submarine Canyon as a barrier to littoral transport is substantiated by the change in heavy mineral provinces across the canyon (Sayles, 1966) and textural and petrographic differences of sand samples north and south of Moss Landing (Clark and Osborne, 1982).

The southern end of Monterey Bay is bounded by the rocky Point Pinos headland around which no sand appears to enters the bay (Storlazzi and Field, 2000). Within the southern bight is the impermeable concrete wall at Wharf II built in 1950 defining the eastern side of Monterey harbor located on an east-west oriented shoreline (Fig. 1). The wall forms an effective barrier to littoral transport from the east, and therefore forms the southern end of the littoral cell. Locations on the map and in the text are referenced by distance from Wharf II.

2.1. Shelf sediments

Considerable information regarding the sediment budget is provided by examining the distribution of sediment size and sand characteristics. The surface sediments on the shelf based on mean grain size reveal: 1) a mid-shelf mud belt (not important to this study), 2) a lobe of sediments offshore the Salinas River composed of sediments < 0.25 mm, 3) coarse sand deposits referred to as rippled scour depressions in 10–60 m water depths, and 4) a near-shore sand corridor (Eittreim et al., 2002).

The bulge of sediments off the Salinas River extends to water depths of 10 to 90 m. The lobe has a maximum thickness of 35 m located 2.5 km seaward of the river mouth and thins in all directions. The adjacent shelf areas are characterized by a thin (2 to 5 m thick) and uniform veneer of fine sediments. Acoustic stratigraphy of the bulge is characterized by at least three uniformity-bounded depositional sequences of marine deposits formed during interglacial highstands and/or during early stages