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Dramatic beach and nearshore morphological changes due to extreme flooding at a wave-dominated river mouth

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ABSTRACT

Record flooding on the Santa Clara River of California (USA) during January 2005 injected ~5 million m^3 of littoral-grade sediment into the Santa Barbara Littoral Cell, approximately an order of magnitude more than both the average annual river loads and the average annual alongshore littoral transport in this portion of the cell. This event appears to be the largest sediment transport event on record for a Southern California river. Over 170 m of local shoreline (mean high water (MHW)) progradation was observed as a result of the flood, followed by 3 years of rapid local shoreline recession. During this post-flood stage, linear regression-determined shoreline change rates are up to $^-45$ m a^{-1} on the subaerial beach (MHW) and −114 m a^{-1} on the submarine delta (6 m isobath). Starting approximately 1 km downdrift of the river mouth, shoreline progradation persisted throughout the 3-year post-flood monitoring period, with rates up to +19 m a^{-1}. Post-flood bathymetric surveys show nearshore (0 to 12 m depth) erosion on the delta exceeding 400 m^3/m a^{-1}, more than an order of magnitude higher than mean seasonal cross-shore sediment transport rates in the region. Changes were not constant with depth, however; sediment accumulation and subsequent erosion on the delta were greatest at −5 to −8 m, and accretion in downdrift areas was greatest above –2 m. Thus, this research shows that the topographic bulge (or "wave") of sediment exhibited both advective and diffusive changes with time, although there were significant variations in the rates of change with depth. The advection and diffusion of the shoreline position was adequately reproduced with a simple "one line" model, although these modeling techniques miss the important cross-shore variations observed in this area. This study illustrates the importance of understanding low-frequency, high volume coastal discharge events for understanding short- and long-term sediment supply, littoral transport, and beach and nearshore evolution in coastal systems adjacent to river mouths.

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1. Introduction

River mouth beaches are highly dynamic in terms of both physical energy and morphologic variability, particularly in Mediterranean climates where rainfall and the resulting fluvial discharge are seasonal and episodic (Hicks and Inman, 1987; Inman and Jenkins, 1999). Extremely high rates of shoreline change can be associated with these features but rates have rarely been quantified in high-energy, wave-dominated coastal settings (Hicks and Inman, 1987). Wave/storm event-driven shoreline response on non-river influenced, wave-dominated coasts is understood to be important (e.g., Morton et al., 1995; Dail et al., 2000; Morris et al., 2004; Aagaard et al., 2005; Adams et al., 2008; Hansen and Barnard, 2009), but event-driven shoreline response studies are rare owing to the difficulty of capturing both pre- and post-event conditions when the events themselves are rare and difficult to predict, as well as obtaining sufficient data to adequately characterize the morphologic response over time. Most research to date on the evolution of river mouths has been on tide-dominated coasts (e.g., Katikati Inlet, New Zealand, Hicks et al., 1999; Bay of Bengal, Gopinath and Seralathan, 2005; Normandy, France, Robin et al., 2007). A study conducted by Backstrom et al. (2008) on the fetch-limited Mediterranean southern coast of Spain documented the short-term response of a small, low-energy river delta to a storm, and showed that coastal orientation, shoreface morphology and physical forcing resulted in spatial differences in the morphological response.

Some of the highest short- and long-term shoreline change rates in the world are associated with river mouths that experience highly variable river discharge (e.g., San Lorenzo River mouth delta, ~200 m a^{-1} (1 year rate) at 5 m isobath; Hicks and Inman, 1987), channel switching/abandonment (e.g., Albanian Coast, 7 to 30 m a^{-1} between 1968 and 1990; Fouache et al., 2001) and/or anthropogenic activities such as sediment impoundment by damming and shore-parallel structures (e.g., Rosetta Promontory, Nile Delta, Egypt, −106 m a^{-1} (20 year rate); Frihy and Komar, 1993; Frihy et al., 2008), and subsidence due to subsurface fluid withdrawals (e.g., Mississippi River Delta, Louisiana, −9.4 m a^{-1} (short-term, <30 yrs) and −6 m a^{-1} (long-term); McBride and Byrnes,

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1997; Penland et al., 2005). Other high rates are associated with global climate change, such as on the Arctic coast where a 60 km segment of coastline on the Alaskan Beaufort Sea has experienced mean annual erosion rates of 13.6 m a^{-1} since 2002 (Jones et al., 2009).

Rain events that cause flooding in the Southern California coastal watersheds are the dominant source of littoral sand to Southern California littoral cells, and are thus vital for sustaining the region's valuable beaches (Inman and Jenkins, 1999; Willis and Griggs, 2003). However, direct observations of large sediment input events and associated effects generally are lacking, largely owing to the rarity of large events and the difficulty of obtaining appropriate data (Warrick and Milliman, 2003). To understand the importance of these infrequent, high-discharge events on the long-term morphodynamics of the system, we combine 16 years of pre-flood survey data analysis with a detailed analysis of 3 years of post-flood morphologic changes. This study provides an in-depth morphological analysis of coastal response to an extremely rare flooding event: the most extreme high-discharge conditions on record for the Santa Clara River that occurred during a record flooding event in January 2005.

2. Regional setting

The Santa Clara River (SCR) drains a 4220 km^2 watershed of the Western Transverse Ranges of Southern California. The Western Transverse Ranges contain among the highest rates of sediment yield in North America owing to active tectonics, steep drainage basins, weak sedimentary lithology, and intense winter rainfall events (Inman and Jenkins, 1999). The mean sediment discharge from the Santa Clara River from 1969–1999 was approximately 7 million t a^{-1} (Mt a^{-1}), but Warrick and Mertes (2009) note that annual loads can vary by orders of magnitude and that over half of the sediment load is contributed by the rare events with recurrence intervals of greater than 10 years.

The Santa Clara River empties into the Santa Barbara Littoral Cell (SBLC), which extends 150 km from Pt. Conception to Mugu Canyon (Fig. 1). Predominant westerly swell drives almost unidirectional alongshore sediment transport from west to east, although reversals do occur during summer south swell events (Adams et al., 2008; Patsch and Griggs, 2008; Elias et al., 2009). The Channel Islands, located 30 km offshore, and Pt. Conception (Fig. 1) shelter much of the SBLC from larger open ocean swells (O'Reilly, 1993; Adams et al., 2008), which typically have annual maximum significant wave heights in excess of 6 m, with heights approaching 10 m during extreme events, as measured at the Harvest deep-water (549 m) wave buoy (Figs. 1 and 2a; Scripps Institution of Oceanography, 2009). Inside the Santa Barbara Channel, wave heights are commonly only a quarter to half of those on the unprotected coast, although wave heights are highly dependent on wave direction (Adams et al., 2008; Xu and Noble, 2009). North of the Santa Clara River, the mostly south-facing, structurally-controlled coastline around Santa Barbara becomes west-facing as bluff-backed beaches transition into the wide, flat alluvial Santa Clara River plain (Revell, 2007). This shift of the coastline into the predominant wave direction, coupled with less sheltering from the Channel Islands, results in a sharp increase in wave energy and rates of littoral transport (Elias et al., 2009). Numerical model-predicted wave heights from 2003 through 2008 reached 6.9 m in February 2008 at the 10-m isobath adjacent to the river mouth (Station VE402; Fig. 1), but typically peak at ~4 m each winter (Fig. 2; Scripps Institution of Oceanography, 2009). The time-averaged significant wave height (H_s), peak period (T_p) and peak direction (D_p) during the 5-year analysis period were 1.0 m, 12.6 s, and 250°, respectively. Mean grain size in the swash is 0.26 mm in the SBLC, but coarser mean values (>0.40 mm) are found at the Santa Clara River mouth. Beach slope averages 10% at the Santa Clara River mouth, moderately steeper than the 8% average for the rest of the SBLC (Barnard et al., 2009b).

The Santa Clara River is the major source of littoral sand to the SBLC, and is the largest source of sediment to the Southern California coast overall owing to the active tectonics and weak sedimentary rocks in the watershed (Brownlie and Taylor, 1981; Inman and Jenkins, 1999; Warrick and Mertes, 2009). The influence of Santa Clara River sediment on the SBLC can be seen in alongshore changes in harbor-dredging rates, which increase from ~500,000 m^3 a^{-1} at Ventura Harbor (2 km updrift) to ~750,000 m^3 a^{-1} at Channel Islands Harbor (8 km downdrift; Patsch and Griggs, 2008; United States Army Corps of Engineers (USACE), Los Angeles District, pers. comm., 2009; Fig. 1). Although the average sediment discharge from the Santa Clara River is ~7 million t a^{-1} (Mt a^{-1}), this discharge is highly episodic (Warrick and Mertes, 2009). Rare large events deliver many times the annual mean sediment volume, and Warrick and Milliman (2003) estimate that over a 50-year record, 75% of the total sediment discharge occurred in only 30 days (0.16% of the record), with many of these days occurring during the same year. Sediment discharge is negligible 75% of the time due to very low sediment concentration and/or zero discharge (Inman and Jenkins, 1999).

Because high-discharge events are rare, low-flow conditions are common, and littoral-drift rates are high in this area, the mouth of the Santa Clara River typically is closed (Fig. 3a), as has been observed for many other Southern California rivers (Schwarz and Orme, 2005). However, during significant discharge events the beach berm fronting the river mouth is eroded by the river (O'Hirok, 1985), and river sediment is discharged directly into the sea, resulting in the formation of a deltaic sediment "wave" in the littoral system (Fig. 3b). The impacts of river floods on continental-shelf sediment transport and sedimentation have been examined by Drake (1972), Hunsinger et al. (2008), and Warrick et al. (2008), but the effects of river flooding on the adjacent beach and nearshore morphology (e.g., Fig. 3) have not been well documented.

3. Methods

Table 1 summarizes the data used in this study. Only brief descriptions of the methods used to collect and analyze topographic and bathymetric data for "focus" surveys are given below; detailed descriptions of those methods are available in Barnard et al. (2009b).

3.1. Precipitation

Precipitation data was obtained from the Remote Automated Weather Station (RAWS) in Ojai, California, operated by the USDA Forest Service's State and Private Forestry (S&PF) organization (Fig. 1). The Ojai weather station is in the foothills adjacent to the Santa Clara River watershed at an elevation of 233 m. Station data were obtained from the California Climate Data Archive at: http://www.calclim.dri.edu/ccda/data.html.

3.2. River sediment discharge

Sediment discharge from the Santa Clara River was estimated using a combination of U.S. Geological Survey (USGS) historical sediment transport data and inferred transport based on river gauging data. For consistency with previous work, river sediment transport calculations followed the general techniques of Brownlie and Taylor (1981). Both Inman and Jenkins (1999) and Willis and Griggs (2003) reported that the techniques and formula developed for the Santa Clara River by Brownlie and Taylor (1981) continue to be appropriate for estimating sediment fluxes from the river, based on recent USGS data that show no time-dependent changes in sediment transport relationships for this system.

Suspended sand and bedload formulas from Brownlie and Taylor (1981) and USGS sediment sampling results were used to estimate daily littoral-grade (greater than 0.125 mm as shown below) sand