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Beach changes from sediment delivered by streams to pocket beaches during a major flood

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ABSTRACT

The significance of sediment delivered via storm-associated stream discharge in altering sediment characteristics, beach form, and volume is evaluated on pocket beaches with different basin characteristics and wave exposures. The focus is on changes on three beaches on Elba Island, Italy caused by a flood event in September 2002 that had an estimated recurrence interval of 200 years. Beach profiles and foreshore sediment samples were gathered in 1999 and 2000 to identify pre-storm characteristics, in September 2002 to reveal the immediate effects of the storm, and in 2003 and 2004 to reveal post-storm recovery.

Foreshore sediments were finer and better sorted and contained no pebbles prior to the flood. Coarsening of the sand and granule fraction was evident after the flood, along with pebble accumulations, especially near major streams. Mean size, sorting values and percent pebbles one and two years after the flood were generally greater than pre-flood conditions but less than immediately after the flood. Beach profiles reveal conspicuous erosion immediately after the flood, when sediment delivered by streams is transported to subaqueous deltas. Thereafter, sediment moves onshore and alongshore to adjacent beaches to restore subaerial volumes. The location of streams within a compartment, relative to the location of capes and headlands, is important in determining the movement of sediment added to the beach by streams. The sites are all sheltered from the highest-energy waves from the west, facilitating longshore transport to the west. Where the largest stream is located at the east end of a compartment, sediment discharged from it is source material for the downdrift beaches to the west. Where the largest stream is at the west end of the compartment, the ability to supply sediment to the beaches to the east is restricted. Hence, broad-scale geologic controls (headlands and capes) enhance or diminish the ability of streams to influence beach change throughout the pocket.

The inability of beaches on two of the sites to migrate landward, due to human development of uplands, will be an issue in the future. Lack of sediment to replenish beaches through erosion of the upland, places increased emphasis on the role of coastal streams in the beach sediment budget. Changing watershed attributes to allow more sediment discharge during high-energy, low-frequency events (e.g. devoting more land to agriculture) would be a way of helping to restore beach sediment.

1. Introduction

The term “pocket beach” describes a beach controlled by a geological structure or a human structure, such as a groin or jetty (Ojeda and Guillén, 2008; Hsu et al., 2010; Short, 2010; Uda et al., 2010). Natural pocket beaches are commonly found on mountainous or rocky coastal regions, often in close proximity to stream mouths (Storlazzi and Field, 2000; Dehouck et al., 2009; Pranzini and Rosas, 2009; Cipriani et al., 2011; Thomas et al., 2012). Pocket beaches are often short, because of close spacing of bedrock boundaries (Short, 2010), but they can be up to 4 km long (Norcross et al., 2002). Pocket beaches may be separated from each other by hundreds of meters (or less) but still exhibit great variability in wave exposure, sediment size, beach slope and bedform characteristics (Dehouck et al., 2009). Pocket beaches, bounded by local rock outcrops, are often nested within larger bays formed by headlands (here termed capes). The rock outcrops may provide local barriers to longshore transport, whereas the adjacent capes provide shelter from the approach of deep-water waves, which are defracted before arriving at the shoreline.

Research on pocket beaches has focused on classifying them based on planform geometry, grain size and wave characteristics (Klein and Menezes, 2001; Bowman et al., 2009), and identifying the temporal and spatial scale of cross-shore and longshore sediment exchange on the beach (Norcross et al., 2002; Ranasinghe et al., 2004). Documentation of sediment transport and changes in beach morphology is sparse despite the common occurrence of pocket beaches along

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rocky coasts worldwide (Dehouck et al., 2009). Evaluations of changes in plan view reveal that shoreline rotation (erosion at one end of the embayment with deposition at the opposite end) is common and can result when storm waves come from a direction opposite the direction of normal wave approach (Sallenger et al., 2002; Basterretxea et al., 2004) or can result from mesoscale (multi-annual to multi-decadal) climate fluctuations affecting waves (e.g., Ranasinghe et al., 2004; Short and Trembanis, 2004; Thomas et al., 2012) or large-scale offshore bathymetric changes (Anthony and Dolique, 2004). In the short term, it is not clear how much of the change at the depositional end of the compartment is from wave approach and how much is from localized sediment input during or just after storm passage.

Pocket beaches are characterized as supply-limited, constrained, or closed systems because of limited sediment exchange between them (Brunel and Sabatier, 2009; Dehouck et al., 2009), but new sediment inputs can occur. Sediment may be introduced to these beaches via longshore bar migration between isolated pocket beaches after storms move sediment offshore in adjacent compartments (Masselink and Short, 1999; Storlazzi and Field, 2000), local nearshore sediment sources (Norcross et al., 2002), erosion of the upland within the pocket (Sallenger et al., 2002) or input from streams (Anthony et al., 2002; Pranzini and Rosas, 2009). Delivery of sediment from streams during stormy periods is the dominant means of sediment delivery in many beach systems on high-relief coasts (Inman and Jenkins, 1999). The quantity delivered is a function of geology of the drainage basin (size, relief, erodibility of rock or sediments), water flow, climate and human modifications to land cover in the basin or damming, diversion or converting the stream channels to concrete culverts (Inman and Jenkins, 1999; Syvitski and Milliman, 2007). Of the total load delivered to the sea, the finer suspended load will be transported offshore whereas the bedload will remain near the mouth of the stream. The capacity of these sediments to be transported alongshore is a function of the wave energy along the adjacent shoreline (Barnard and Warrick, 2010). In pocket beaches, where capes and local headlands contribute to the distribution of wave energy, the quantity and textural properties of the sediment delivered to the mouth of the channel and the ability of this sediment to be distributed alongshore are important to understanding post-event morphologic change.

Sediment flux from streams to the coastal ocean is episodic in some climates, ranging from frequent, through seasonal to longer timescales, up to decadal (Inman and Jenkins, 1999). Rainfall and the resulting fluvial discharge are highly episodic in Mediterranean climates (Hooke, 2006; Barnard and Warrick, 2010). Small streams can contribute significant volumes of sediment to small pocket beaches during short intervals of heavy precipitation, but capturing these events is serendipitous. Documentation of event-driven shoreline responses is rare because of the difficulty of capturing pre- and post-event conditions when the events themselves are difficult to predict (Barnard and Warrick, 2010). Attention on sediment delivery has focused on assessing discharge of dissolved and particulate flux from small streams to the coastal ocean during episodic events (i.e. Wheatcroft et al., 1997; Warrick and Fong, 2004), but few studies have focused on the coarser fraction that remains near the mouth of a stream (Barnard and Warrick, 2010). Evaluating the importance of low frequency, high magnitude events on beach sediment budgets and morphologic change is critical in light of global climate change, which in the Mediterranean could lead to an increase in the frequency of high energy events (Christensen and Christensen, 2004; Sánchez et al., 2004).

The purpose of this study is to evaluate the significance of sediment delivered via storm-associated runoff in altering sediment characteristics, beach form and beach volume on pocket beaches with different basin characteristics and wave exposures. The focus is on changes on three beaches on Elba Island, Italy — Procchio, Capoliveri and Lacona (Fig. 1) caused by a flood that occurred in September 2002. The event, with an estimated recurrence interval of 200 years, lasted for only 8 h but observations at Capoliveri (Fig. 1) revealed that precipitation over a four hour duration (200 mm) was greater than the monthly average (51 mm) (Servetto, 2006). Previous papers reported on the formation of coarse-sediment deltas and transport of fine material offshore in association with this event (Pranzini and Rosas, 2009) and the effects of land use/land cover changes to shoreline position prior to the event (Cipriani et al., 2011). The most extensive morphological changes to stream deltas and adjacent beaches are observed during the first few years after major floods, when the system is furthest from equilibrium (Barnard and Warrick, 2010). Morphologic and sedimentologic data had already been gathered at two sites (Procchio and Capoliveri) in 1999 and sedimentologic data had been gathered at Lacona in 2000 and were available to identify pre-flood conditions. Morphologic and sedimentologic data were gathered a few days after the flood at all three sites. Similar data were then gathered at Lacona and Procchio one to two years after the flood, respectively. The data reveal a sequence of pre-storm, storm and post-storm phases at one site (Procchio), which can be compared with data from two other sites representing at least two of the three phases (pre-storm, storm, and post-storm) at pocket beaches with different orientations and watershed characteristics.

2. Study area

Elba Island (Fig. 1) is the westernmost extension of the Northern Apennines. The structure of the central and eastern portions of the island is complex and consists of nine major tectonic units (Bortolotti et al., 2001). Headlands and beaches are comprised of igneous, metamorphic and sedimentary rocks. Alluvial deposits are primarily of poorly cemented or recently reworked gravel, with local sands and mud. The amounts and physical characteristics of the sediment delivered to beaches by streams have varied, based on changing human uses of the landscape, with iron mining, agriculture and tourism playing key roles. Iron mining began in the 7th century B.C., and iron was smelted on the island when wood was available for processing. Readily available sources of wood became scarce in the 3rd century B.C., and processing moved to the mainland (Canestrelli, 2001). The island was unsafe in the middle ages because of piracy and it is likely that re-vegetation temporarily occurred with the resulting decline in population. A new expansion of mining occurred in the late 19th century and continued in the 20th century until it ceased in 1981 (Tanelli et al., 2001). Much of the vegetated land in the non-mined areas was converted to agriculture in post-Napoleonic times, increasing the potential for delivery of sediment to streams (Nordstrom et al., 2004). By the third quarter of the 19th century, much of the soil had already been eroded from agricultural lands (Pullè, 1879). Tourism increased greatly in the past four decades and now dominates the economy, providing 90% of the total income (ISTAT, 2011) with 2.8 million stays per year. Households expanded to 25,196 by 2001. Larger accommodation structures increased from 15 in 1952 (Cori et al., 2006) to 452 in 2011 (ISTAT, 2011). The census for 1951 registers 29% of the labor in agriculture, falling to 4% in 2001; in the same period, the tertiary sector grew from 34% to 77%.

The coastline of Elba Island now consists of numerous small pocket beaches fed by small channels that cut through relatively steep topography in the higher elevations and have gentler gradients, often in floodplain deposits, in the upland adjacent to the shoreline. The higher elevations are now predominantly forested and have isolated small villages or individual dwellings. The areas at lower elevations have been developed for residences and recreation, especially near beaches, which are now intensively used in the summer. Del Grosso and Pranzini (2003) and Mannori and Pranzini (2004) analyzed land use/land cover data for the 60 year period 1940–2000 at Procchio and Lacona prior to the 2002 flood. Results revealed an increase in forest cover and in impervious surface within the watersheds that drain into bays. This trend is evident throughout the island (Cipriani et al., 2011).