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Nourishment evolution and impacts at four southern California beaches: A sand volume analysis

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ABSTRACT

Four southern California beaches were nourished with offshore sand placed as subaerial pads several meters thick, ~50 m wide, and spanning between 500 and 1500 m alongshore. Three nourishments constructed with coarser than native sand, placed in 2012 at Imperial, Cardiff and Solana Beaches, elevated subaerial sand volumes for several years even when exposed to the energetic winter waves of the 2015-16 El Niño, followed by a stormy 2016-17 winter. As these relatively resilient pads were overwashed, landward tilted subaerial profiles (accretionary crowns) formed at the eroding front face of the originally flat-topped pads and pooling occurred in the backbeach. At Imperial Beach, nourishment sand helped prevent waves from directly impacting riprap fronting houses, while groundwater flooding behind the pad was observed at a location where the pad was elevated ~1.6 m above the street. As the nourishments retreated, alongshore oriented spits grew downdrift from the eroding face. The alongshore displacement of the subaerial center of mass of the 2012 nourishments is positively correlated with the seasonally varying S_{xy} (the alongshore radiation stress component). After four years, the net southward drift of the Imperial Beach nourishment contributed to the winter 2016 closure of the Tijuana River mouth and the associated hyper-polluted and anoxic estuary conditions. Nourishment impacts on sand levels on rocky reefs were not unambiguously detectable in the background of natural variability. Over several years, gains or losses in the total sand volume (integrated from the back beach to 8 m depth, over the few km alongshore survey spans) are sometimes comparable to nourishment volumes, suggesting relatively large interannual sediment fluxes across the control volume boundaries. The clearest trend in total volume is at Torrey Pines; during 16 years since the 2001 nourishment, about 300,000 m^3 of sand has been lost. If the trend continues, the thinning veneer of sand will be removed more often from the subaerial winter beach, exposing rocks and cobbles.

1. Introduction

Beach nourishment, placing imported sand to widen and elevate the subaerial beach (Fig. 1), is used to mitigate flooding and erosion, and to promote tourism and recreation. The observations presented here detail the evolution of four nourished southern California beaches. The Torrey Pines nourishment was one of 12 San Diego County sand placement projects in 2001 ($17.5 million total cost). Cardiff, Solana and Imperial Beaches were nourished in 2012, along with five other sites ($28.5 million total cost) (Griggs and Kinsman, 2016). A 50-year, $160 million plan for repetitive beach nourishments in north San Diego County has been developed (Diehl, 2015). Despite the frequency and expense of beach nourishments worldwide (Clayton, 1991; Haddad and Pilkey, 1998; Trembanis and Pilkey, 1998; Valverde et al., 1999; Hanson et al., 2002; Cooke et al., 2012; Luo et al., 2015), the wave-driven redistribution of nourishment sand is rarely monitored in detail and previous studies are limited. Wave conditions are often not observed (Cooper, 1998; Davis et al., 2000; Gares et al., 2006; Benedet et al., 2007; Park et al., 2009; Roberts and Wang, 2012) or are crudely approximated (Kuang et al., 2011). Monitoring schemes may be constrained in temporal resolution (Cooper, 1998; Browder and Dean, 2000; Gares et al., 2006; Benedet et al., 2007; Park et al., 2009; Bocamazo et al., 2011), duration (Elko and Wang, 2007), alongshore span (Anfuso et al., 2001), cross-shore extent (Gares et al., 2006), or by the accuracy of the survey technique (e.g. aerial photography) (Bocamazo et al., 2011). Cost-benefit analysis of beach nourishment impacts, crucial as seas rise (Stocker et al., 2013) and global coastal populations increase (McGranahan et al., 2007), are hindered by a lack of comprehensive observations of waves conditions and sand level evolution. More thorough studies include the well monitored "Sand Engine mega-nourishment" on the Dutch coast (de

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Fig. 1. Mechanical sand placement underway, from south to north, at Imperial Beach. Black dots roughly outline the original placement region.

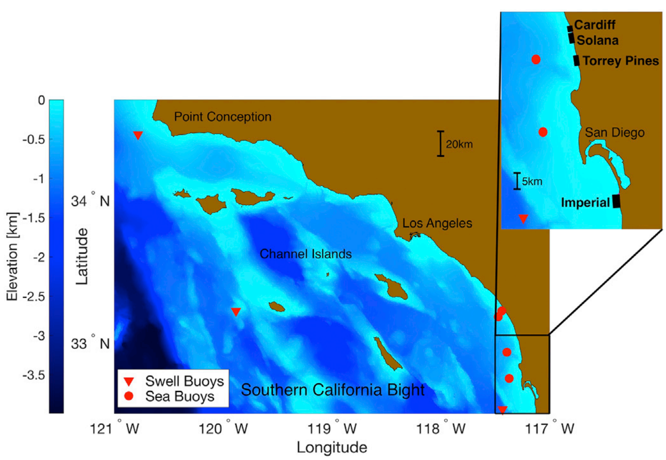

Fig. 2. Map of the southern California Bight, with wave buoy locations (circles are used for local seas, triangles for swell). The inset shows the locations of the study beaches.

Schipper et al., 2016), and the combined impacts of beach nourishment, shore nourishment and a bypassing system on the Gold Coast, Australia (Castelle et al., 2009).

Here, we discuss uniquely detailed sand level observations at four nourished southern California beaches, extending the work of Seymour et al. (2005), Yates et al. (2009) and Ludka et al. (2016). The most recent study (Ludka et al., 2016) considered subaerial sand level observations at these beaches through mid-winter of the erosive 2015-16 El Niño. The present analysis is extended seaward to 8 m depth, and includes recovery of the subaerial beach during summer 2016, followed by the response to the energetic 2016-17 winter (the third most erosive winter during the 16 year monitoring period, ranking behind the 2009-10 and 2015-16 El Niño). Observations of waves and sand levels are described in section 2. Section 3 describes nourishment evolution at Imperial Beach, including pad retreat and accretionary crowns (section 3.1), spit formation and alongshore transport (section 3.2), and nearshore sand volume analysis (section 3.3). Section 4 compares and contrasts nourishment evolution at all sites and includes an investigation of nourishment impacts on sand levels over rocky reefs (section 4.4). Conclusions are summarized in section 5.

2. Observations

2.1. Waves

Swell waves (10–25s) were observed at offshore buoys (triangles, Fig. 2) and propagated shoreward over the complex bathymetry of the Southern California Bight using a spectral refraction model (O'Reilly and Guza, 1998). Island shadowing and local shoals can create sharp spatial gradients, and swell wave heights can vary substantially over less than a few km. A regional wave model, initialized offshore of complex bathymetry, is used to model this spatial structure. In contrast, local sea wave (2–12.5s) heights are usually highly correlated over distances of O (10 km) and are estimated using nearby buoys (circles, Fig. 2). The swell and sea models are combined to estimate hourly directional wave estimates every 100 m alongshore at Monitoring and Prediction (MOP) locations in 10 m depth (O'Reilly et al., 2016). In winter relatively energetic waves arrive from the north, and in summer milder waves come from the south. With roughly N-S study beach orientations (Fig. 2 inset), the radiation stress component S_{xy} has strong seasonal variation.

2.2. Sand levels

Monitoring at each of the 4 individual nourishment sites spans between 1.7 and 4.1 km alongshore and 8–16 years. Quarterly bathymetric surveys from the backbeach to 8 m depth were performed on cross-shore transects spaced 100 m apart. A few surveys had finer alongshore resolution; 20 m at Torrey Pines centered on the nourishment placement, and 50 m at Cardiff. Monthly subaerial elevation surveys were on shore-parallel tracks spaced ~10 m in the cross-shore. Surveys are mapped to a coastline following grid (Appendix A). During monitoring, each beach was nourished with between 68,000–344,000 m^3 of sand, over subaerial alongshore spans between 500 and 1 500 m (Table 1). Imperial Beach was the largest nourishment, had controversial impacts (Hargrove, 2015; Baker, 2016), and is described in the most detail. Additional results for other sites are in Supplementary Material.

3. Nourishment evolution at Imperial Beach

In September of 2012, 344,000 m^2 of relatively coarse grained sand (compared to native, Table 1) was mechanically placed at Imperial Beach (Fig. 1). Much of the nourishment sand remained subaerial for several

Table 1
Nourishment statistics.

Beach	Native Grain Size [*mm*][a]	Nourishment Grain Size [*mm*][b]	Nourishment Volume [m^3][c]	Subaerial Survey Area [m^2]	Jumbo Survey Area [m^2]
Torrey	0.23	0.2	187,000	171,715	1,094,546
Imperial	0.25	0.53	344,000	252,358	1,610,518
Cardiff	0.16	0.57	68,000	95,499	629,437
Solana	0.15	0.55	107,000	104,968	1,213,960

[a] D_{50} at MSL. Torrey, Imperial and Cardiff from Ludka et al. (2015). Solana from Group Delta Consultants (1998).
[b] D_{50}. Torrey from Seymour et al. (2005). Imperial, Cardiff, and Solana from Coastal Frontiers (2015).
[c] Coastal Frontiers (2005, 2015).