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Seasonal persistence of a small southern California beach fill

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ABSTRACT

Torrey Pines State Beach, a site with large seasonal fluctuations in sand level, received a small shoreface beach fill (about 160,000 m^3) in April 2001. The 600 m-long, flat-topped nourishment pad extended from a highway riprap revetment seaward about 60 m, terminating in a 2 m-tall vertical scarp. A 2.7 km alongshore span, centered on the nourishment region, was monitored prior to the nourishment and biweekly to monthly for the following 2 years. For the first 7 months after the nourishment, through fall 2001, significant wave heights were small, and the elevated beach fill remained in place, with little change near and above Mean Sea Level (MSL). In contrast, the shoreline accreted on nearby control beaches following a seasonal pattern common in southern California, reducing the elevation difference between the nourished and adjacent beaches. During the first winter storm (3 m significant wave height), the shoreline retreated rapidly over the entire 2.7 km survey reach, forming an alongshore-oriented sandbar in 3 to 4 m water depth [Seymour, R.J., Guza, R.T., O'Reilly, W., Elgar, S., 2004. Rapid erosion of a Southern California beach fill. Coastal Engineering 52 (2), 151–158.]. We show that the winter sandbar, most pronounced offshore of the nourishment, moved back onto the beach face during summer 2002 (following the usual seasonal pattern) and formed a wider beach above MSL at the site of the original nourishment than on the control beaches. Thus, the April 2001 shoreline nourishment was detectable until late fall 2002, persisting locally over a full seasonal cycle. In an extended 7-year time series, total sand volumes (summed between the back beach and 8 m water depth, over the entire 2.7 km reach) exhibit multi-year fluctuations of unknown origin that are twice as large as the nourishment volume.

1. Introduction

Beach nourishment can protect shoreline infrastructure and enhance beach recreational use without intrusive hard structures (e.g. seawalls and groins) that may have undesirable local, and even regional, impacts (Marine Board, 1995). Nourishment monitoring, including simultaneous monitoring of nourished and nearby unaltered beaches (Stive et al., 1991), helps improve coastal management practices both by directly observing the nourishment fate and by providing guidance and calibration for numerical models used to plan future nourishments (Marine Board, 1995; Dean, 2002).

In an effort to improve the predictability of nourishments, many monitoring programs track nourishment evolution over a few years, but surveys are usually completed on an annual to biannual basis, with no reports of monthly or seasonal variability. A large beach nourishment (>7 million m^3) of Perdido Key near Pensacola Pass, FL, was surveyed once or twice yearly for 8 years (Browder and Dean, 2000). Significant changes were caused by hurricanes, but the nourishment and adjacent regions remained relatively stable between these events (Work, 1993; Browder and Dean, 2000). Biannual surveys for 2 years recorded losses for a large nourishment at Hilton Head Island, SC (Bodge et al., 1993), showing no seasonal recovery. Monthly monitoring of Atlantic City, NJ (Sorensen et al., 1988) and Pinellas County, FL (Creaser et al., 1993) nourishments reported only end-of-winter or post-storm losses, also with no indication of recovery. Nearly quarterly monitoring of a two-phase nourishment at Ocean City, MD showed two examples of post-storm recovery after a series of closely spaced storms (Stauble and Kraus, 1993). However, in all of these cases, the beach response was dominated by the nourishment profile shape equilibration and the long-term net loss of sediment, often attributed to alongshore transport. None of these observations concern the evolution of a nourishment at a site with a very strong cross-shore seasonal pattern, and very few reports utilized time as the independent variable.

Nourishments in Europe are often monitored frequently initially and then once or twice a year thereafter (Hanson et al., 2002). Dean (2002) recommends 1/2 year to 2 year survey intervals, unless unusual behavior is expected. Our results suggest more frequent monitoring is needed on beaches with large seasonal cycles. At Terschelling, Netherlands, 3 to 4 times yearly surveys were completed as part of an extensive nourishment monitoring program, and a large volume of sand (2 million m^3) was added to the beach so that the nourishment trends would stand out above the seasonal and interannual variability (Hamm et al., 2002). Overall, there are few observations of nourishments on beaches with large seasonal cycles,

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and the predictability of nourishment evolution on these beaches is severely limited (Marine Board, 1995; Capobianco et al., 2002).

In southern California, seasonal fluctuations in wave energy, with moderate energy winter storms and low energy summer waves, drive strong seasonal fluctuations in sand levels. The seasonal cycle is characterized by offshore sand movement causing shoreline erosion and the formation of an offshore bar in winter, and onshore sand migration resulting in shoreline accretion in summer (Shepard, 1950; Winant et al., 1975; Aubrey, 1979). Cross-shore profiles located approximately 2 km south of the present study region showed vertical seasonal sand level fluctuations of about 2 m near the shoreline and the offshore bar (Winant et al., 1975).

In 2002, the San Diego Association of Governments (SANDAG) sponsored the Regional Beach Sand Project, nourishing San Diego County Beaches with 1.6 million m^3 of sand, which was divided between twelve nourishment sites, with each site receiving between 77,000 and 320,000 m^3 of sand along 300 to 1300 m of coastline. The ~160,000 m^3 subaerial nourishment at Torrey Pines Beach eroded rapidly during a November 2001 storm (Seymour et al., 2005). As anticipated by Stive et al. (1991), the shoreline (near MSL) nourishment spread across the entire cross-shore profile. On a beach with a large seasonal cycle, the effects of the nourishment sand may persist after the initial erosion from the subaerial beach because the nourishment sand may be stored in the offshore bar and returned to the beach face during the following summer.

Here, the evolution of nourished and adjacent beach profiles are quantified and compared over several seasonal cycles. In Section 2, the observations are described, and the surveyed alongshore span is divided into nourishment, buffer, and control regions. In Section 3, the evolution of cross-shore profiles in the nourishment is shown, and the horizontal displacement of depth and elevation contours (related to changes in the width of the subaerial beach available for recreation) is compared in these three alongshore spans. The effect of the nourishment on seasonal cross-shore fluxes of sand between the shoreline and the offshore sandbar are examined in Section 4. In Section 5, the evolution of total volumes (sum of shoreline and offshore bar volumes) in the three alongshore spans is contrasted. Results are discussed in Section 6 and summarized in Section 7.

2. Description of observations

Sand levels were surveyed with a GPS-equipped all-terrain vehicle, hand-pushed cart, and personal watercraft with an acoustic depth sounder (Seymour et al., 2005). Locally shore-normal transects, extending from the backing cliffs or revetment seawards to about 8 m water depth, were obtained every 20 m over a 700 m-long reach centered on the fill, and at 100 m alongshore intervals for 1000 m on adjacent up- and down-coast beaches, for a total of 56 transects (Fig. 1b). One pre-nourishment survey was completed at the end of February 2001. Approximately biweekly surveys began following the fill construction in April 2001 (Fig. 1b), continuing through a storm in November 2001, with less frequent surveys thereafter. Beginning with the November 2001 survey, twelve additional transects decreased the survey line spacing immediately south of the nourishment from 100 m to 25 m. Approximately 7 years of observations, through the beginning of 2008, are considered in detail here. Of the 42 full bathymetry surveys collected, 2 were excluded owing to large gaps in the spatial coverage caused by energetic waves and the presence of surfers. Thirty-six additional surveys of the subaerial beach face, between the backbeach (the revetment) and the waterline (about MSL), were obtained with an all-terrain vehicle approximately monthly between February 2004 and January 2007.

Depth contours for a few km on either side of the nourishment are relatively straight and parallel, and waves in the survey area are not influenced by the Scripps Submarine Canyon (Fig. 1a). Wave conditions were monitored with the Coastal Data Information Program wave network (nearby buoys are shown in Fig. 1a). A spectral refraction wave model was combined with offshore buoy observations to estimate wave height on the 10 m depth contour, every 100 m alongshore. Wave height varies seasonally, with larger winter swell arriving from the Northwest

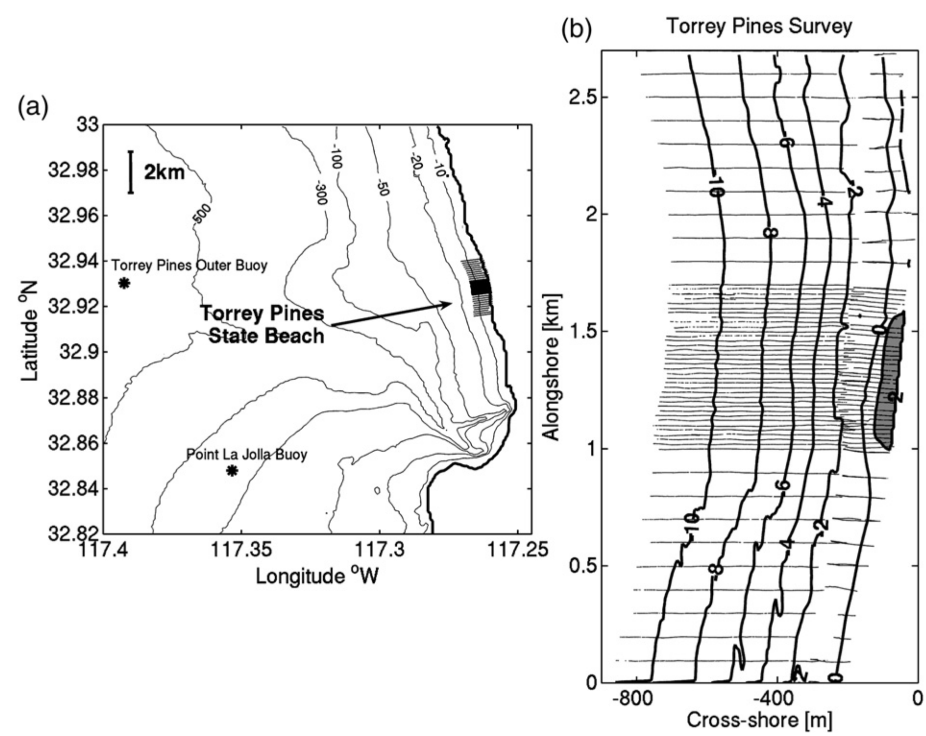

Fig. 1. (a) Location of the Torrey Pines Beach fill surveys (arrow pointing to cross-shore transects) and nearby wave buoys (asterisks). Contours (thin curves) are depth in meters below MSL, and the Scripps Submarine Canyon is in the lower right corner. (b) Plan view of the 2.7 km alongshore span surveyed from the 27–29 April 2001, shortly after the nourishment was completed. Survey data (thin, nearly parallel lines) were collected along cross-shore transects, and estimated elevation contours (bold alongshore curves) are shown in meters above or below MSL. The 2 m high nourishment pad near the shoreline is shaded gray.

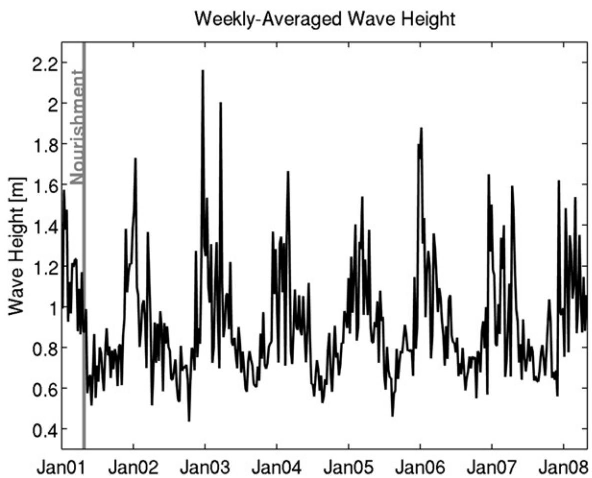

Fig. 2. Weekly-averaged wave height at Torrey Pines along the 2.7 km survey span shows strong seasonal variation. The nourishment was completed on April 27–29, 2001 (vertical gray line).

Pacific, and generally smaller summer swell arriving from the South Pacific (Fig. 2). Tidal vertical ranges were about 1.0 m (neap) and 2.5 m (spring).

3. Displacement of elevation contours

Prior to the nourishment, in February 2001, the beach was in a typical winter state. The subaerial beach was narrow, and shoreline depth contours (e.g. MSL, +1 m) were located close to the backshore revetment or cliff (n_0, pre-nourishment survey, Fig. 3b, +1 m contour shown). Immediately after the nourishment in late April 2001 (n_1, post-nourishment survey, Fig. 3b), the shoreline contours bulged approximately 40 m seaward between alongshore coordinate 1.0 and 1.6 km. This 600 m alongshore span is hereafter referred to as the nourishment region (N). Buffer regions (B) defined adjacent to the nourishment (0.5–1.0 km and 1.6–2.2 km), and control regions (C) defined furthest from the nourishment (0–0.5 km and 2.2–2.7 km), showed little shoreline change during this 2 month period (compare n_1 with n_0, Fig. 3b). Additionally, there was little change in the location of the −4 m contour over the entire 2.7 km alongshore span (compare n_1 with n_0, Fig. 3a).

In the 7 months following the fill completion, the significant height of incident waves was low (typical for summer, Fig. 2). Hourly-estimated significant wave heights were between about 0.4 and 1.5 m, and were usually less than 1 m. Bathymetry changes in B and C, away from the fill region, were consistent with the usual seasonal cycle in southern California with offshore erosion (~1 m of vertical erosion between 2 and 5 m depth) and shoreline accretion (often >1 m) as the winter bar moved shoreward and merged with the shoreline. By October 2001, the +1 m contour in B and C moved an average of 20 m seaward (compare s_1 with n_1, Fig. 3b), with about 1 m of vertical shoreline accretion (Seymour et al., 2005).

Time series of the horizontal location of shoreline elevation and offshore bar depth contours, averaged over N, are shown in Fig. 4, and the evolution of a representative cross-shore profile in N (location indicated with dashed line in Fig. 3) is shown in Fig. 5. During summer 2001, waves reached the fill only once or twice, and shoreline contours moved offshore about 5 m (compare s_1 with n_1, Fig. 4). In detail, the +1 m contour remained rather stationary in the southern fill end (1.0–1.4 km) and moved slightly offshore (accretion) in the northern fill end (1.4–1.6 km, compare s_1 with n_1, Fig. 3b). The offshore bar contours in N were displaced landward (erosion) approximately 30 m (compare s_1 with n_1, Figs. 4 and 5a), but this sand was largely blocked by the nourishment from reaching the shoreline. For example, the nourishment (n_1) and summer (s_1) cross-shore profiles remain nearly unchanged above approximately −1 m water depth, while the offshore sandbar eroded (Fig. 5a). The fate of sand displaced from the bar and blocked from returning to the beach face, is unknown.

The first winter storm in November 2001, with significant wave height exceeding 2 m for about 3 days, eroded the shoreline over the entire surveyed span (Seymour et al., 2005). This storm and subsequent

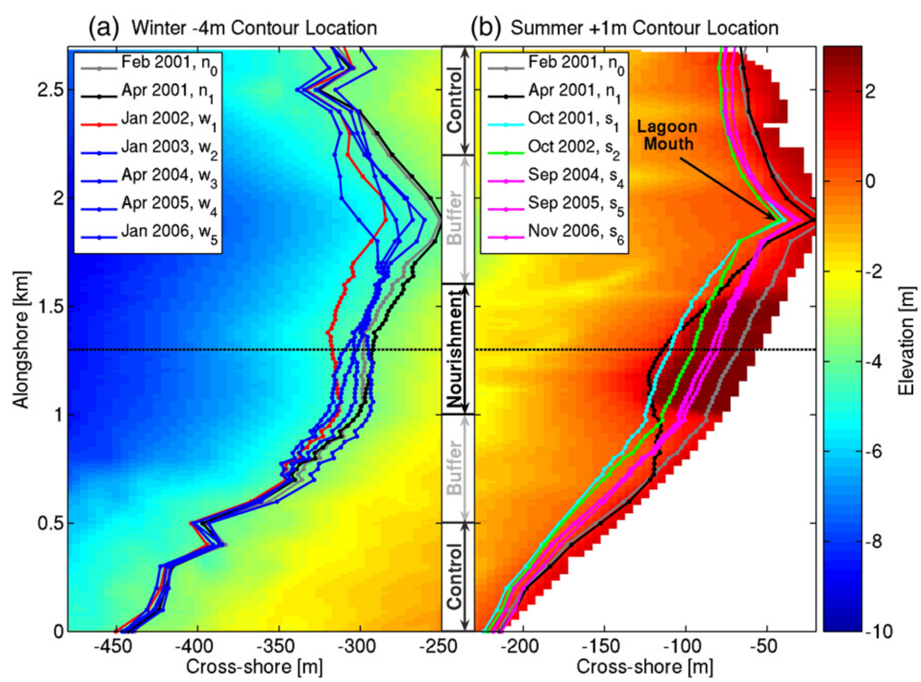

Fig. 3. Plan view of the post-nourishment survey (April 27–29, 2001, color scale is to the right). The beach is backed by steep cliffs or a highway revetment (white area in (b)). The curves indicate the location of the (a) −4 m depth contour in winter (w_{1-5}), when the offshore sandbar is most developed, and (b) +1 m elevation contour during summer (s_{1-6}), when the exposed beach is widest. Legends give survey times and a survey index number for cross-referencing to Figs. 4–8. The pre-nourishment (n_0, gray line) and immediate post-nourishment (n_1, black line) surveys are shown in both panels for reference. The alongshore extents of the nourishment, buffer, and control regions are indicated between the panels.

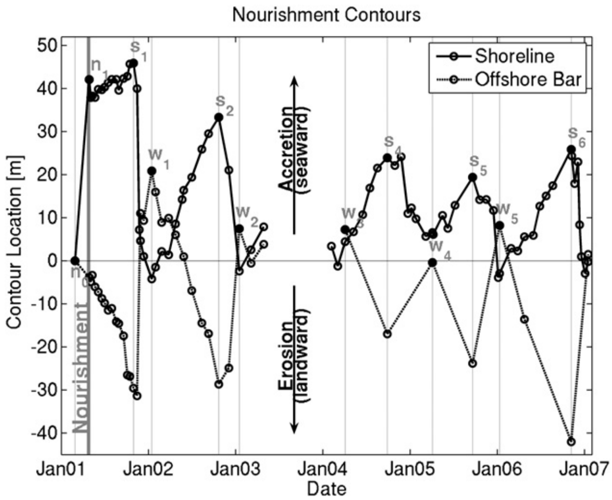

Fig. 4. The elevation contour cross-shore location evolution is shown in the nourishment region (1.0–1.6 km alongshore, see Fig. 3). The shoreline (solid) curve is the average of the 0 m and +1 m elevation contours, and the offshore bar (dashed) curve is the average of the −5 m and −4 m depth contours. Locations are relative to the pre-nourishment survey, with positive change indicating seaward movement (accretion). Observations (circles) were more frequent near the shoreline and show that the offshore surveys between 2004 and 2007 were obtained close to seasonal extrema in shoreline location. Filled circles and vertical lines correspond to surveys shown in Fig. 3.

winter storms removed most of the fill from the shoreline, displacing shoreline contours landward (erosion) about 50 m (compare w_1 with s_1, shoreline, Figs. 4 and 5b). The sand eroded from the shoreline formed an offshore bar, indicated by the 50 m seaward displacement (accretion) of the bar depth contours (compare w_1 with s_1, bar, Fig. 4). The offshore bar volume was enhanced in N, pushing the depth contours further offshore than observed in the subsequent 4 winters (compare w_1 with $w_{2–5}$, Figs. 3a and 5b, and bar curve, Fig. 4). The nourishment sand eroded from the beach face appears to have fed the offshore sand bar during the winter following the nourishment, when it was not yet too widely dispersed to be measured.

During the following summer (2002), the offshore winter bar remerged with the shoreline, again creating a detectable shoreline bulge in the nourishment region (s_2, Figs. 3b and 5a). Offshore erosion moved bar contours landward more than 40 m (s_2, bar, Fig. 4), and shoreline accretion displaced the shoreline seaward more than 30 m (s_2, shoreline, Fig. 4). By the end of the summer, the beach was wider in the nourishment region than observed in the subsequent 3 summers (compare s_2 with $s_{4–6}$, Figs. 3b and 5a, and shoreline curve, Fig. 4). The bulge of sand in the nourishment region was not detectable in the shoreline or offshore bar contour locations after the end of the second summer following the nourishment.

4. Cross-shore fluxes between the shoreline and the offshore bar

To estimate cross-shore fluxes, time series of beach face and offshore bar volumes were estimated for N, B, and C using survey transects common to the 40 selected surveys, extending from the backbeach to approximately 8 m depth. The −2 m depth contour (approximately the pivot point of seasonal sand level changes) was used to separate the beach face and offshore bar regions. Volumes were calculated relative to the pre-nourishment survey (Fig. 6), and normalized volumes (m^3/m, or volume per unit alongshore length) are shown because the alongshore lengths of N, B, and C are different and somewhat arbitrary. Normalized volumes address the effect of the nourishment on local cross-shore transport processes, allowing comparisons between N, B, and C. Non-normalized volumes (m^3) are discussed in Sections 5 and 6. The full bathymetry surveys necessary to estimate volumes were collected biweekly to monthly through mid-2003, then an average of about 3 times yearly from

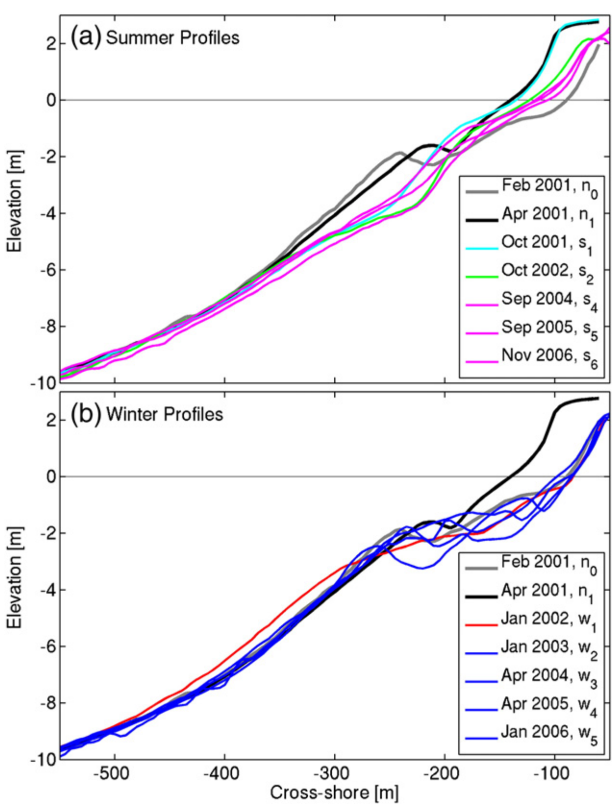

Fig. 5. Cross-shore profiles at a representative transect in the nourishment region (location indicated with dashed line in Fig. 3): (a) summer profiles ($s_{1–6}$) and (b) winter profiles ($w_{1–5}$), with the same legend as Fig. 3. For reference, pre-nourishment (n_0, gray line) and post-nourishment profiles (n_1, black line) are shown in both panels.

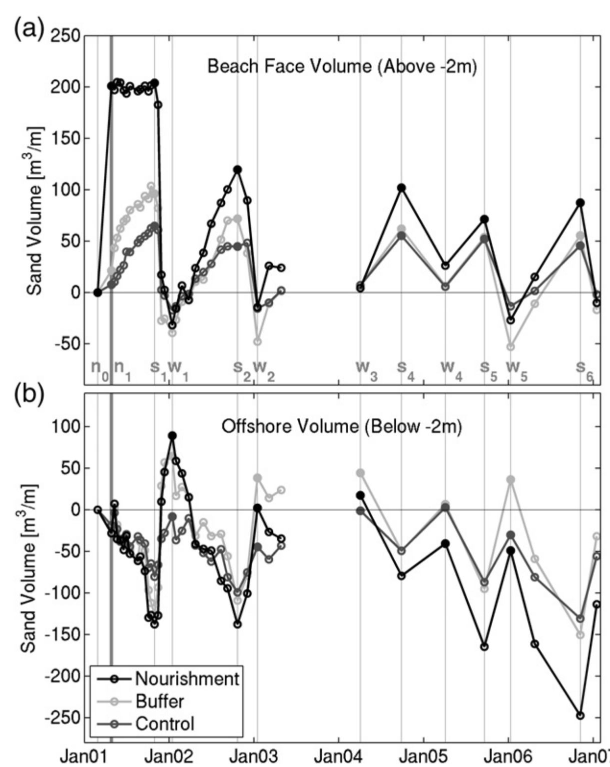

Fig. 6. Normalized sand volume (m^3/m) versus time (a) near the shoreline (above the −2 m contour), and (b) near the offshore sand bar (below the −2 m contour). Volumes normalized by alongshore length of each section are shown for the nourishment, buffer, and control regions, relative to the pre-nourishment survey (n_0). Filled circles and vertical lines identify survey dates shown in Fig. 3.

2004 to 2007 (Fig. 6). Monthly surveys of the subaerial beach show that the biannual to quarterly full bathymetry surveys were obtained close to seasonal extrema in shoreline location (Fig. 4), as desired.

The nourishment was the largest shoreline accretion event (~200 m^3/m volume increase, n_1, Fig. 6a). Between the nourishment and the end of summer 2001, the beach face volume did not change significantly in N (compare n_1 with s_1, Fig. 6a), while accretion occurred steadily throughout this period in B (+100 m^3/m) and C (+75 m^3/m). Alongshore leakage of sand from N to B may have increased the volume in B above C during the first two summers that the nourishment sand was detectable (s_1 and s_2, Fig. 6a).

During the November 2001 storm and the remainder of the 2001 to 2002 winter, the beach face was severely eroded along the entire 2.7 km alongshore reach (losing between 80 and 250 m^3/m), resulting in similar shoreline volumes in each region (w_1, Fig. 6a). That is, the nourishment was completely eroded from the beach face, as shown by Seymour et al. (2005). In the offshore, alongshore leakage of sand from N to B is apparent as B gained 200 m^3/m (difference between w_1 and s_1, Fig. 6b), similar to the N (230 m^3/m), and significantly larger than C (70 m^3/m). The offshore bar volumes in N and B were elevated compared with both C (w_1, Fig. 6b), and with future years in these regions (compare w_1 with $w_{2–5}$, Fig. 6b).

In summer 2002, the offshore bar moved back onshore, and the beach face accreted preferentially in the nourishment region, with a slightly larger sand volume than in any following year (compare s_2 with $s_{4–6}$, Fig. 6a). By the following winter, the nourishment sand eroded from the beach face was not clearly detectable in the offshore bar volumes: N was larger than C, but smaller than B (w_2, Fig. 6b). Cross-shore fluxes of sand from the beach face to the offshore bar in N and B show the presence of an additional bulge of sand (in comparison to C) through a complete seasonal cycle until late fall 2002.

5. Cross-shore integrated volumes

The total volume in each region (sum of offshore bar and beach face, relative to the pre-nourishment survey) does not show large seasonal changes (Fig. 7). Perhaps surprisingly, the total N volume decreased substantially during the first summer after the nourishment (compare s_1 with n_1, Fig. 7). In survey s_1, prior to the November 2001 storm, the offshore bar volume decreased substantially in all regions (25–60 m^3/m, Fig. 6b). However, in B and C there was some compensating shoreline accretion (20–30 m^3/m, Fig. 6a), whereas in N there was not. Thus, low waves during summer 2001, coupled with the blocking of shoreline

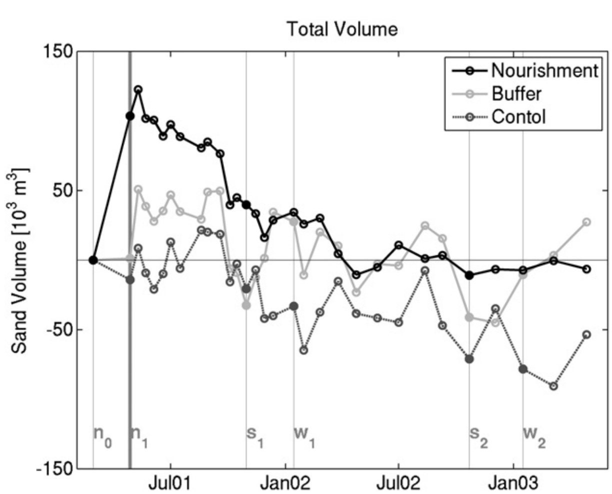

Fig. 7. Total sand volume (m^3) versus time for the nourishment, buffer and control regions. Total volumes relative to the pre-nourishment survey (n_0), are the sum of shoreline and offshore bar volumes (similar to Fig. 6, but here the volumes are not normalized). The first 2.5 years of surveys are shown.

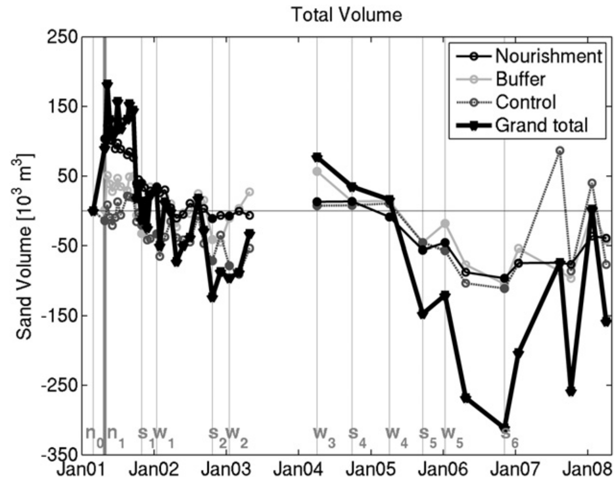

Fig. 8. Total sand volumes (m^3) relative to the pre-nourishment survey (n_0) in the nourishment (N), buffer (B), and control (C) regions versus time (as in Fig. 7, extended for over 7 years). Grand total volume (bold) is the sum of the N, B, and C total volumes.

accretion by the nourishment, caused the loss from the entire cross-shore region of N of roughly two-thirds of the initial nourishment (compare s_1 with n_1, Fig. 7). The first storm of winter moved large amounts of sand from the beach face to the offshore bar, but the total sand volume (sum of beach face and offshore bar) did not vary greatly in any region. By the end of the winter, the total sand volume in B actually increased (compare w_1 with s_1, Fig. 7). By mid-summer 2002 (between w_1 and s_2, Fig. 7), the total N volume decreased and became indistinguishable from C. Thus, the nourishment sand was detectable through fall 2002 from a bulge in shoreline contours (s_2, Figs. 3b, 4, and 5a) and elevated beach face volumes (s_2, Fig. 6a), but not in the total nourishment region volume (Fig. 7).

6. Discussion

Nourishment effects on the local 600 m-long nourishment beach were observed first as a shoreline bulge, then as an enhanced offshore bar, and finally as a reduced shoreline bulge. Total volumes, summed over the entire profile, suggest that sand was leaking from the nourishment region when the nourishment was completed, even though waves were low (Fig. 7). After about 2 years, the nourishment could not be detected in either contour locations or cross-shore integrated volumes.

Volume fluctuations at longer temporal and spatial scales are apparent in sand volume observations extended to April 2008 (Fig. 8). Similar patterns of temporal change in total N, B, and C between 2004 and 2008 indicate spatially coherent sand movement into or out of the survey region. In only 2 years between January 2005 and January 2007, the grand total volume (sum of the cross-shore volume for the entire 2.7 km reach) decreased by 350,000 m^3, about twice the volume of the 160,000 m^3 spring 2001 nourishment. Variations in the grand total volume between surveys in 2007 are also as large as the nourishment volume. Large amounts of sand were presumably transported across the survey boundaries, both alongshore and cross-shore. Unknown, but believed relatively small sand volumes fluxed through a small lagoon mouth (that was sometimes closed) into the buffer region (lagoon mouth identified in Fig. 3b). Over the 7-year survey period, a total of 84,000 m^3 of sand was dredged from the lagoon (on eleven occasions) and placed adjacent to the lagoon mouth near the shoreline. An unknown amount of this sand was pushed into the lagoon mouth by alongshore transport and was thus returned to the beach through the dredging operations. The dredged sand volumes placed on the beach did not appear to cause any significant deviations in the seasonal sand volume changes and are not expected to have affected the observations of the nourishment response. The size of errors arising from the measurements and from the alongshore sampling (100 m spacing outside of the nourishment region), are poorly known.

The lack of shoreline accretion in the nourishment region during summer 2001, seen in both the shoreline contours (Figs. 3b, 4, and 5a) and the beach face volume (Fig. 6a), suggests that the nourishment timing may have impacted its persistence. The shoreline nourishment bulge appeared to effectively block sand that would naturally have returned to the shoreline during the summer, as part of the usual seasonal cycle. If the same nourishment volume had instead been placed on the seasonally accreted beach face in late summer 2001, bringing the maximum beach elevation up to $+4$ m (instead of $+2$ m), the nourishment sand may have remained on the beach face longer, perhaps over several seasons. On the other hand, the benefit of having the widest subaerial beach during the summer months, immediately following the end-of-winter nourishment, is lost. The tradeoffs of different nourishment timing on beaches with strong seasonal cycles are not well understood. Note however that the present nourishment volume (per meter of beach) was smaller than the annual cross-shore exchange of sand between the shoreline and the offshore bar and only spanned 600 m. This nourishment was likely too small, regardless of timing, to have a significant, long-term impact on the beach.

7. Conclusions

The Torrey Pines Beach nourishment (160,000 m^3) was monitored biweekly to monthly for 2.5 years through several seasonal cycles. Although seasonal cross-shore volume fluxes exceeded the total nourishment volume, the nourishment was detectable for nearly 20 months. The nourishment sand formed bulges in both contour locations and volumes at the shoreline (in summer) and at the offshore bar (in winter) until the end of the second summer following the nourishment. An extended 7-year time series of monitoring showed large changes in grand total volume, which were not associated with the seasonal cycle or the nourishment. The origin of these volume fluctuations is unknown. Future monitoring of nourished beaches with large seasonal cycles would benefit from extending the cross-shore profiles further offshore to try to capture all cross-shore fluxes, and from having more observations, through at least one seasonal cycle prior to the nourishment, to establish a better baseline.

Acknowledgements

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