Journal of Coastal Research	29	3	579–596	Coconut Creek, Florida	May 2013

Dispersal of Fine Sediment in Nearshore Coastal Waters

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ABSTRACT

Warrick, J.A., 2013. Dispersal of fine sediment in nearshore coastal waters. *Journal of Coastal Research,* 29(3), 579–596. Coconut Creek (Florida), ISSN 0749-0208.

Fine sediment (silt and clay) plays an important role in the physical, ecological, and environmental conditions of coastal systems, yet little is known about the dispersal and fate of fine sediment across coastal margin settings outside of river mouths. Here I provide simple physical scaling and detailed monitoring of a beach nourishment project near Imperial Beach, California, with a high portion of fines (~40% silt and clay by weight). These results provide insights into the pathways and residence times of fine sediment transport across a wave-dominated coastal margin. Monitoring of the project used physical, optical, acoustic, and remote sensing techniques to track the fine portion of the nourishment sediment. The initial transport of fine sediment from the beach was influenced strongly by longshore currents of the surf zone that were established in response to the approach angles of the waves. The mean residence time of fine sediment in the surf zone—once it was suspended—was approximately 1 hour, and rapid decreases in surf zone fine sediment concentrations along the beach resulted from mixing and offshore transport in turbid rip heads. For example, during a day with oblique wave directions and surf zone longshore currents of approximately 25 cm/s, the offshore losses of fine sediment in rips resulted in a 95% reduction in alongshore surf zone fine sediment flux within 1 km of the nourishment site. However, because of the direct placement of nourishment sediment on the beach, fine suspended-sediment concentrations in the swash zone remained elevated for several days after nourishment, while fine sediment was winnowed from the beach. Once offshore of the surf zone, fine sediment settled downward in the water column and was observed to transport along and across the inner shelf. Vertically sheared currents influenced the directions and rates of fine sediment transport on the shelf. Sedimentation of fine sediment was greatest on the seafloor directly offshore of the nourishment site. However, a mass balance of sediment suggests that the majority of the fine sediment moved far away (over 2 km) from the nourishment site or to water depths greater than 10 m, where fine sediment represents a substantial portion of the bed material. Thus, the fate of fine sediment in nearshore waters was influenced strongly by wave conditions, surf zone and rip current transport, and the vertical density and flow conditions of coastal waters.

ADDITIONAL INDEX WORDS: *Fine-grained sediment, nearshore processes, beach processes, continental shelf, grain size, surf zone processes.*

INTRODUCTION

The transport and fate of fine sediment (silt and clay) particles in marine settings influences patterns of pollution, water quality, turbidity, and sedimentation on the seafloor, which can in turn influence marine habitats, ecosystem health, and geologic records. The majority of studies of surf zone and nearshore physical process have not focused upon fine sediment, but rather on water fluxes, for the purpose of providing better insights into nutrient, bacteria, and pollutant pathways (Grant *et al*., 2005; Reniers *et al*., 2009) or bed material sediment transport for the purpose of coastal morphodynamics (Masselink and Hughes, 1998; Wright and Short, 1984). These studies have provided a wealth of insights into the processes, rates, and patterns of along- and across-shore exchange in a wide distribution of coastal settings (*e.g.,* Brown *et al*., 2009; Clark, Feddersen, and Guza, 2010; McMahan, Thornton, and Reniers, 2006; Spydell and Feddersen, 2009; Spydell, Feddersen, and Guza, 2009). However, the application of these studies to fine sediment dispersal processes and patterns is still lacking.

The most common settings for coastal fine sediment research are river mouths and deltas, because of the large fluxes of suspended sediment into these systems from rivers (Meade, 1996; Mertes and Warrick, 2001; Milliman and Syvitski, 1992; Syvitski *et al*., 2005; Wright and Nittrouer, 1995). Along active tectonic margins fine sediment is commonly discharged directly into coastal waters in positively buoyant (hypopycnal) plumes of river water that spread offshore and across shore in response to buoyancy, tidal forcing, and wind forcing (Geyer *et al*., 2000; Hill *et al*., 2007; Liu *et al*., 2007). Passive tectonic margins, in contrast, have large estuaries that may trap significant portions of fine sediment in estuarine convergence zones far upstream of the estuary mouth (Geyer, Woodruff, and Traykovski, 2001; Meade, 1969; Scully and Friedrichs, 2007). Other common coastal settings for fine sediment research include midcontinental shelf "mud belts" that retain fine

DOI: 10.2112/JCOASTRES-D-12-00087.1 received 11 May 2012; accepted in revision 16 September 2012; corrected proofs received 26 November 2012.
Published Pre-print online 18 December 2012.
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sediment discharged from coastal rivers (*e.g.,* Harris *et al.*, 2008; Nittrouer, 1999; Wright and Friedrichs, 2006).

In comparison with these well-studied settings, fine sediment unassociated with river discharge within surf zone and nearshore settings has received much less attention. The source of fine sediment to these nearshore waters may be resuspension of native sediment, aeolian flux, cliff or bluff failure, or engineering projects such as beach nourishment. Regardless of source, a general hypothesis is that this fine sediment should be incorporated into surf zone currents in a tracer-like manner (Inman, Tait, and Nordstrom, 1971).

The objective of this paper is to provide observations and insights to fine sediment transport and dispersal patterns within surf zone and nearshore coastal waters. The source of sediment for this study was a beach nourishment project that used mixed sediment with approximately 40% silt and clay fraction by weight. Monitoring was undertaken manually along the beach and at sea, remotely with airborne sensors, and continuously at benthic tripods and moored buoys. This research was designed to address the following research questions: How quickly and over what spatial scales does fine sediment disperse from the beach to the inner continental shelf? What are the pathways of sediment dispersal and how are these pathways influenced by environmental conditions (waves, tides, winds)? Where is the location of sediment deposition, and how is this related to transport directions and patterns? Finally, how does grain size influence dispersal pathways and patterns of sedimentation?

Theoretical Considerations

Inman, Tait, and Nordstrom (1971) used turbidity patterns from fine particulate matter to track longshore currents in the surf zone, and a tracer assumption was used for the sediment in their work. Tracer-like behavior should be expected for neutrally buoyant fine particles, but lithogenic sediment particles have densities that are two to three times greater than water, causing vertical settling of particles downward toward the seafloor that will preferentially segregate particles toward the lower portion of the water column. Under scenarios that particles are preferentially near the bed because of vertical settling, the rates and directions of particle transport will not mimic—and may even oppose—those predicted by neutrally buoyant tracers because of shear in nearshore currents. Thus, the tracer assumption for fine sediment will be invalid when vertical settling velocities are large with respect to rates of vertical mixing. Because particle size exerts a first-order control on vertical settling velocity (Ferguson and Church, 2004), the tracer assumption will be least valid for the larger sediment particles (*e.g.,* sand).

One way to evaluate whether sediment particles mimic tracers is with a dimensionless settling parameter (S):

$$S = a\frac{w_s T}{h} \tag{1}$$

where w_s is the vertical setting velocity (m/s), T is the period of the resuspending process, such as wave bores (seconds), h is the water depth (m), and a is a dimensionless parameter related to how well mixed the water column is in response to the resuspending process (1 = fully mixed, 0 = not mixed). For example, if this framework is applied to the surf zone, a first-order approximation can be made that surf zone bores fully mix the vertical water column during their passage (*cf.* Feddersen, 2007). The derived values of S will be approximately equivalent to the proportion of the water column that is sediment free after the increment of T.

Table 1. *Example calculations of the dimensionless settling parameter (S) for different coastal settings and sediment particle sizes. All values are rounded to one significant figure.*

	Swash Zone	Rip Cell
Water depth, h (m)	1	3
Period, T (s)	10	300
Vertical mixing parameter, a	1	1
Settling velocity, w_s (m/s)[a]		
1-μm clay	0.000001 [b]	0.000001 [b]
20-μm silt	0.0004 [b]	0.0004 [b]
Fine sediment floc	0.001	0.001
400-μm sand	0.06	0.06
Settling parameter (S)		
1-μm clay	0.000001 [b]	0.0001 [b]
20-μm silt	0.004 [b]	0.4 [b]
Fine sediment floc	0.01	1
400-μm sand	0.6	>1

[a] Settling velocities for clay, silt, and sand after Ferguson and Church (2004) and for fine sediment flocs after Hill, Milligan, and Geyer (2000).
[b] Assumes individual particle settling and no flocculation.

Example calculations of S for simplified coastal settings using four different sediment particle sizes are shown in Table 1. Two different settings are considered: a swash zone where resuspension occurs with each wave bore, and a rip current circulation cell where resuspension occurs in the wave breaking region nearshore but is minimal while waters circulate offshore of the breakers in the rip and return flow. It is assumed that it takes several minutes for waters to leave and return to the surf zone in this rip circulation (MacMahon, Thornton, and Reniers, 2006). Calculated S values for fine sediment in the swash zone are generally equal to or less than 0.01; this suggests that particle settling has a negligible effect on the concentration profiles of fine sediment. Under these conditions fine sediment particles should behave as tracers. Over the time scales that waters are expelled from and return to the surf zone in a rip circulation cell ($T \sim 300$ s), fine sediment will have a much longer time to settle, and if fine sediment is flocculated, the entire sediment mass of fines may settle toward the seafloor (*i.e.,* $S = 1$) during the excursion from the surf zone (Table 1). Thus, silt particles in the swash zone are likely to be tracer-like, owing to the minimal vertical settling that would occur between each wave bore. However, vertical settling will become important with larger particles and in more quiescent regions—such as in rip circulation cells—and under these scenarios, the sediment-tracer assumption is not likely valid. These assumptions are tested with monitoring of the nourishment project described below.

Study Area

Beach nourishment projects were conducted during 2008 and 2009 at the Border Field State Park of California, which is the most southerly beach of the U.S. west coast (Figure 1). The

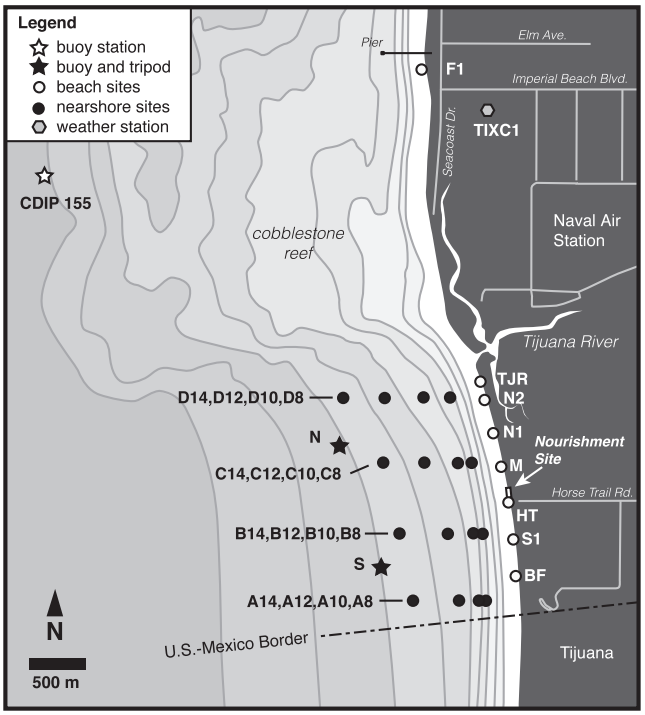

Figure 1. Study area and sampling sites for the nourishment project. Coastal bathymetry shown at 2-m increments from –3 to –19 m after Finlayson and Warrick (in press).

beach of the project site is part of the greater Silver Strand littoral cell, which extends north to the Coronado Peninsula and south past the United States–Mexico international border (Flick, 1993; Inman, 1976; Kuhn and Shepard, 1984). The beaches of this littoral cell are primarily sandy, and although the primary source of this beach sand is the Tijuana River, there have been numerous sand nourishment projects in this littoral cell to attempt to limit, stop, or reverse coastal erosion (Flick, 1993; Moffatt & Nichol, 2009). There is also a broad cobblestone reef in the study area (Figure 1) between the Tijuana River mouth and the Imperial Beach pier that supports perennial kelp beds.

The Tijuana River mouth serves as conduit for tidal exchange between the ocean and the Tijuana River estuary and as the outlet for Tijuana River discharge (Zedler, Nordby, and Kus, 1992; Figure 1). The mouth of the Tijuana River is rarely closed, resulting in relatively constant tidal pumping and exchange of water and sediment through the river mouth (Svejkovsky *et al*., 2010). River discharge is ephemeral, with little to no discharge during the dry summer and fall and high flows following winter rainfall. Based on 46 years of historical data, Farnsworth and Warrick (2007) calculated that the Tijuana River annually discharges approximately 90,000 m^3 of suspended sediment to the Pacific Ocean, roughly 70,000 m^3, or 77%, of this river sediment is fine grained (<0.063 mm). However, the annual discharge of sediment from the Tijuana River is highly variable, ranging from 0 to ~2,000,000 m^3/y over the historical record (1937–1990).

The wave climate in the study area is dominated by three modes: (1) westerly to northwesterly swell of the winter generated by midlatitude storms over the North Pacific, (2) wind waves during the spring to summer from the prevailing northwesterly winds along the regional coast, and (3) southerly to southwesterly swell of the summer from storms in the Southern Hemisphere or the tropics of the North Pacific (Adams, Inman, and Graham, 2008; Inman and Masters, 1994). The largest waves generally occur during the winter, although all of these modes are influenced by regional climatic patterns, including the El Niño–Southern Oscillation and the Pacific Decadal Oscillation (Adams, Inman, and Graham, 2008). Offshore deepwater significant wave heights are generally 1–2 m with peak periods of 11–15 seconds, although waves have exceeded 6 m during winter storms (Adams, Inman, and Graham, 2008). These deepwater waves are modified by refraction and shoaling from the numerous islands, seamounts, and other bathymetric complexities of the Southern California Bight (Adams, Inman, and Graham, 2008). One such complexity near the study site is the large cobblestone reef in the northern portion of the Tijuana study area (Figure 1) that causes substantial wave refraction and focusing toward the southern end of this reef (Lescinski, Van Ormondt, and Warrick, 2011). Three years of wave observations (December 2006 to January 2010) at Coastal Data Information Program (CDIP) Station 155 offshore of this reef (Figure 1) resulted in mean significant wave heights and peak periods of 1 m and 13 seconds, respectively, with significant seasonal patterns. This seasonality is exhibited in mean monthly significant wave heights that ranged from 1.2 m in February to 0.7 m in August and in extreme significant wave heights that exceeded 3 m in November to April (reaching a measured maximum of 3.7 m) but that never exceeded 1.5 m during July–September. The tides of the region are mixed, semidiurnal and diurnal, with a spring tidal range (mean higher-high water to mean lower-low water levels) of 1.6 m and a mean range (mean high water to mean low water levels) of 1.1 m, as shown by NOAA National Ocean Service Tidal Station 9410230 in La Jolla, California, which is 30 km north of the study site.

Nourishment Project

Sediment for the nourishment project was obtained from two debris basins within the Border Field State Park. These debris basins capture sediment from the Goat Canyon drainage basin within Mexico for the purpose of reducing sedimentation rates in the Tijuana estuary. Dry sediment was acquired from the sediment basins and sorted for trash and debris (including gravel sized sediment). Sediment nourishment was carried out with dump trucks directly in the intertidal zone (Figures 1 and 2). Detailed descriptions of the sediment nourishment project can be found in Warrick *et al*. (2012).

The primary nourishment project for this study was conducted during late September and early October 2009 (Figure 3). During this project approximately 27,000 m^3 of sediment was placed over a 12-day interval of time (Figure 3). Nourishment was conducted only during the daylight hours of 0700 to 1700 Pacific Daylight Time (PDT), and during nine

Figure 2. Photographs of the study site and sediment nourishment project. (a) Overview perspective from the United States–Mexico border showing the sediment placement site (arrow) and southern-directed turbid plume on October 1, 2009, at 1447 Pacific Daylight Time (PDT). (b, c) Sediment placement within the swash zone. (d) A recently placed pile of sediment in the swash. (e) Turbid surf zone immediately adjacent to the sediment placement site.

total days. The bulk grain-size distribution of the nourishment sediment was 60% sand and 40% silt and clay, and over 80% of the fine sediment mass was silt (0.002–0.063 mm; Warrick *et al*., 2012).

Concurrent with the sediment nourishment project, the Imperial Beach 2009 (IB09) study was conducted near the Imperial Beach Pier (Figure 1) by the Scripps Institution of Oceanography. The IB09 study used current meters, drifters, and dye releases to evaluate nearshore circulation, and some of the sampling for our study was conducted through a partnership with the IB09 research group.

METHODS

An abbreviated description of the study methods are contained herein, full descriptions and raw data are available online through Warrick *et al*. (2012). A number of sampling techniques were used for this study: (1) surf zone sampling of swash and beach sediment, (2) airborne remote sensing of coastal water color and temperature, (3) nearshore water and sediment sampling from a small boat, and (4) oceanographic instrumentation on moored buoys and benthic tripods.

Swash Water Sampling and Analysis

Suspended-sediment sampling of swash water was conducted at stations both north and south of the nourishment site (Figure 1). Seven primary swash sampling stations (TJR to BF) were located in the immediate vicinity of the nourishment site, and one secondary station (F1) was 3.8 km north of the nourishment site and was sampled only following the end of nourishment. Water samples were collected at water depths of 10–20 cm and placed directly into 500-mL bottles. Sampling was conducted both during the early morning hours before nourishment began (a.m. samples) and during the midday and afternoon during active nourishment (p.m. samples). Duplicate water samples were obtained for suspended-sediment concentration and the particle-size distribution analyses.

Suspended-sediment concentration samples were wet sieved through a 63-μm sieve and analyzed for both sand (>63 μm) and fine (<63 μm) sediment concentrations. Sand concentrations were measured from oven-dried sand masses; fine sediment concentrations were measured by filtering on pretared glass fiber filters. For samples that had adequate mass of suspended sediment, the duplicate samples were used to measure grain-size distributions of both the sand and the fine fractions with a Beckman Coulter LS230 laser diffraction particle-size analyzer (see Warrick *et al.,* 2012).

Beach Sediment Sampling and Analysis

Beach sediment grain-size distributions were measured before, during, and after the nourishment project. Two sampling methods were used. First, the upper 2 cm of sediment was sampled at the seven primary beach stations (TJR to BF; Figure 1). Each station was sampled at three elevations: the lower swash zone, the middle swash zone, and the upper extent of the swash zone. Second, after the nourishment project was completed, the beach was sampled at depth with pits and one across-shore trench to characterize the amount of fine sediment remaining within the beach.

All beach samples were analyzed for grain-size distributions. First, organics were digested with hydrogen peroxide and heating and solubles were removed with deionized water rinses. Particle-size distributions for dispersed samples were determined using a Beckman Coulter LS230 laser diffraction particle-size analyzer. Sand and fine sediment fractions were

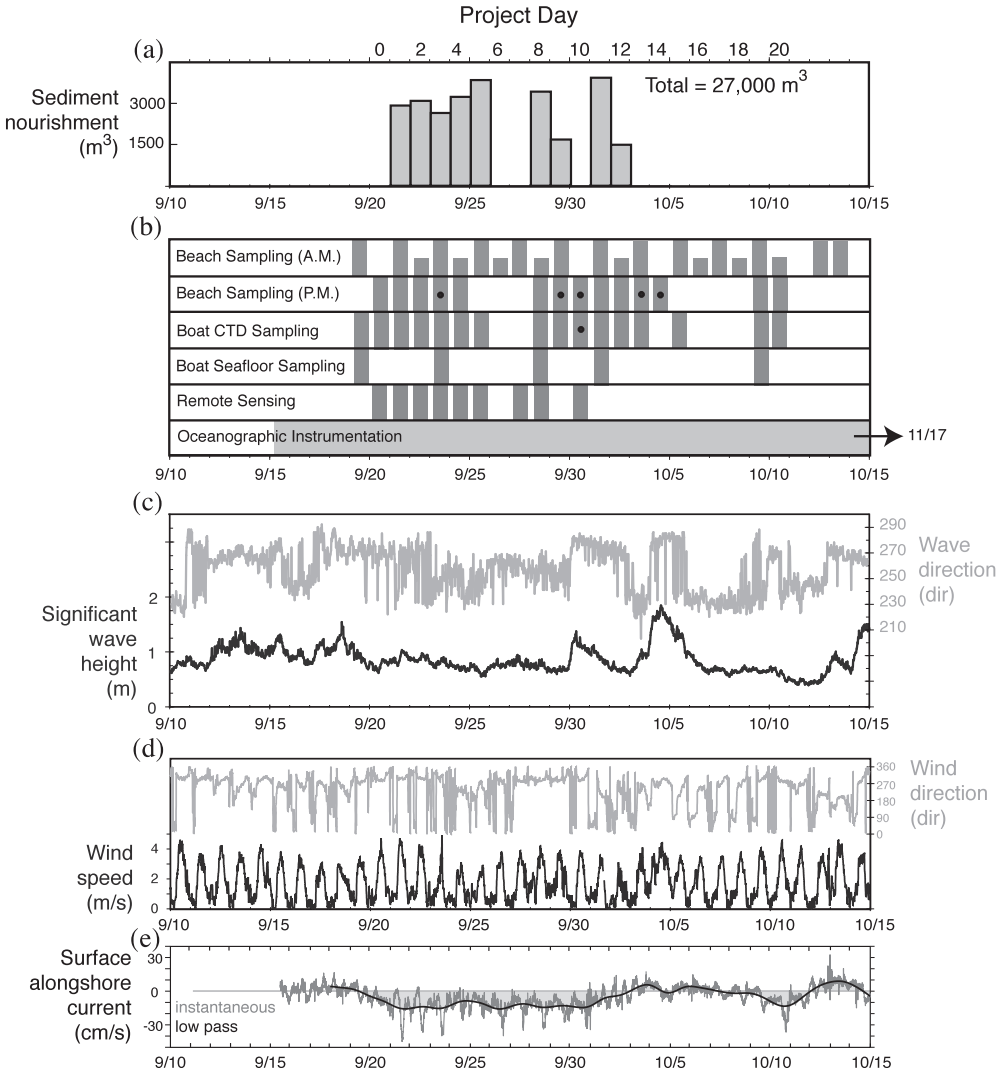

Figure 3. Nourishment and sampling schedule during 2009. (a) Sediment nourishment schedule in total placement *per* day. (b) Sampling schedule from the various monitoring methods (see text for details). (c) Significant wave height and dominant wave direction from CDIP Buoy 155. (d) Wind speed and direction from Tijuana estuary weather station. (e) Alongshore current speed of the upper 2.5 m of the water column at the north tripod location.

processed separately, and results were merged using the mass concentrations of sand and fine sediment.

Airborne Remote Sensing

Airborne remote sensing of coastal water color and sea surface temperature was conducted on 9 days, which included 1 day before the nourishment project and 8 days during the project (Figure 3). Remote sensing was undertaken by Ocean Imaging Corporation using a SpecTerra DMSC-Mk2 aerial imaging system flown at an altitude of 1372 m. The sensor collected radiance measurements centered at the following wavelengths: 450, 551, 577, and 640 nm, all with a 10-nm bandwidth, and a fifth channel for a thermal infrared sensor was also included. For the purposes of this paper, the optical radiance measurements were combined to produce pseudo-true color images at a spatial scale of 70 cm. Full resolution imagery is available from Warrick *et al*. (2012).

Coastal Water and Sediment Sampling

Sampling of the water column properties and seafloor sediment was also conducted from a small vessel. Eighteen stations were sampled on a regular basis, and these stations consisted of four transects (A–D) sampled at the 8-, 10-, 12-, and 14-m bathymetric contours, and samples were also taken adjacent to each of the combined tripod-buoy stations at 15-m water depth (Figure 1). When conditions were adequately safe, additional stations were sampled to characterize the water properties within and across rip cell heads between the regular stations and the surf zone.

For each of these stations, water properties were measured using a Seacat 19 Plus Profiler conductivity, temperature, and depth (CTD) sensor that also included a 25-cm path-length Wetlabs 650 nm (red) C-Star transmissometer, and a D&A Instruments 850 nm (infrared) OBS-3 turbidity sensor (optical backscatter sensor [OBS]). The CTD was sampled at 4 Hz, and downcast samples were averaged into 0.25-m increment bins. For each station a surface water sample was also obtained in a 1-L bottle and analyzed for total suspended-sediment concentration by the filtration methods described for swash water sampling.

Seafloor sediment sampling was also conducted at the 18 regular sampling stations to evaluate whether surficial grain-size distributions changed during or after the nourishment project. Sediment samples were obtained on five occasions (Figure 3) using a small (6-inch) Ponar Type grab sampler. The upper 2–3 cm of sediment was sampled, and sediment samples were analyzed for grain-size distributions using the techniques described for beach sediment sampling.

Tripods and Moored Buoys

Tripods and moored buoys were deployed with oceanographic instrumentation at a north site (N) and south site (S), both in 15-m water depth (Figure 1). These stations were deployed on September 15, 2009, and recovered on November 17, 2009. The tripods were 2-m high and included upward-looking 1200-kHz acoustic Doppler current profilers (ADCPs), downward-looking Sontek single-point current meters (acoustic Doppler velocimeters [ADVs]), CTDs, transmissometers, and OBS to measure water turbidity properties. The buoys had CTDs and OBS located at approximately 1 m below the water surface. All the OBS sensors were mounted with ZebraTech wipers to clean optical windows every 2 hours. The ADCPs were sampled every 20 minutes for current magnitude and direction in 1-m vertical bins. The ADVs were sampled for currents every 30 minutes for a duration of 20 minutes with a sample volume centered approximately 53 cm above bed. Wave orbital velocities (u_w) were calculated from the root mean square error of each 20-minute velocity record from the ADV multiplied by a factor of 1.414. Further details of instrument placement, sampling, and data processing are provided in Warrick *et al*. (2012).

Additional Data Sources

Additional data for this study were provided from a CDIP wave buoy at Imperial Beach (CDIP Station 155) and the weather station maintained by the National Estuarine Research Reserve System (Figure 1). The CDIP buoy provided wave properties (significant wave height, dominant period, dominant direction, and wave spectra) at 30-minute increments. Weather station data from the Tijuana River Reserve station (National Data Buoy Center station identifier TIXC1) were used to characterize wind conditions at the site from the meteorological data generated every 15 minutes.

RESULTS

Initial Erosion and Alongshore Transport of Fine Sediment

Initial erosion and suspension of the nourishment sediment in the surf zone was rapid. Piles of sediment placed directly in the swash (Figure 2c and 2d) were eroded by wave action within several minutes of placement. The erosion of this sediment resulted in turbidity in the surf zone immediately adjacent to the placement area (Figure 2e), and surf zone turbidity was most commonly observed to extend northward from the project site (Figure 4).

During and after nourishment the fine sediment concentrations in the swash were greater than the ambient concentrations measured before the project (Figure 5). Before the project began, swash concentrations of fine sediment were generally less than 10 mg/L, with higher values measured on the northern and southern limits of the study area beach (Figure 5a). During the nourishment project, fine sediment concentrations within the swash were highest and most variable near the nourishment site (Station HT; Figure 5b). Fine sediment concentrations at Station HT varied by over three orders of magnitude during active nourishment (7 to 9600 mg/L). Fine sediment concentrations during nourishment decreased with distance away from the nourishment site and were generally higher on the northern side of the project than on the southern side (Figure 5b).

Following nourishment activities, the fine sediment concentrations of the swash zone decreased with time. Within a day of nourishment activities, fine sediment concentrations were still several times to an order of magnitude greater than the prenourishment levels across most of the sampled beach (Figure 5c). After several days, the fine sediment concentrations had decreased to levels at or slightly above the prenourishment levels (Figure 5d).

A more detailed presentation of the time dependence of swash fine sediment concentrations is shown in Figure 6 for two representative stations: N2 on the north side of the nourishment site and S1 on the south side. North of the nourishment project there was a clear increase in concentrations during active nourishment, shown by concentrations of 50–200 mg/L (Figure 6a). Concentrations of fine sediment at both sites were most commonly lower during the early morning (*i.e.,* the a.m. samples; Figure 6) than during active nourishment (p.m. samples; Figure 6). The southern station, in contrast, exhibited lower fine sediment concentrations during the first week of nourishment (5–15 mg/L) and higher concentrations during the second week of nourishment (5–50 mg/L; Figure 6b).

Fine sediment concentrations during active nourishment were compared with the wave direction and height measurements at the nearby CDIP buoy. These wave properties were not projected to the shore using refraction and shoaling assumptions to obtain breaking-wave properties, owing to the complex bathymetry (Figure 1) and observed complex refraction patterns (*e.g.,* see raw remote sensing data in Warrick *et al*., 2012) of the study area. Dominant wave direction was shown to explain roughly half of the variance in the fine sediment concentrations during active nourishment (Figure 7). These relationships were strongest for the stations north of the nourishment site, although no significant relationship was found for Stations HT and M, the two closest stations (Figure 7). For the stations north of the nourishment site (N1 to TJR), waves from more southerly directions resulted in higher fine sediment concentrations (Figures 7a–c). South of the nourishment site, concentrations

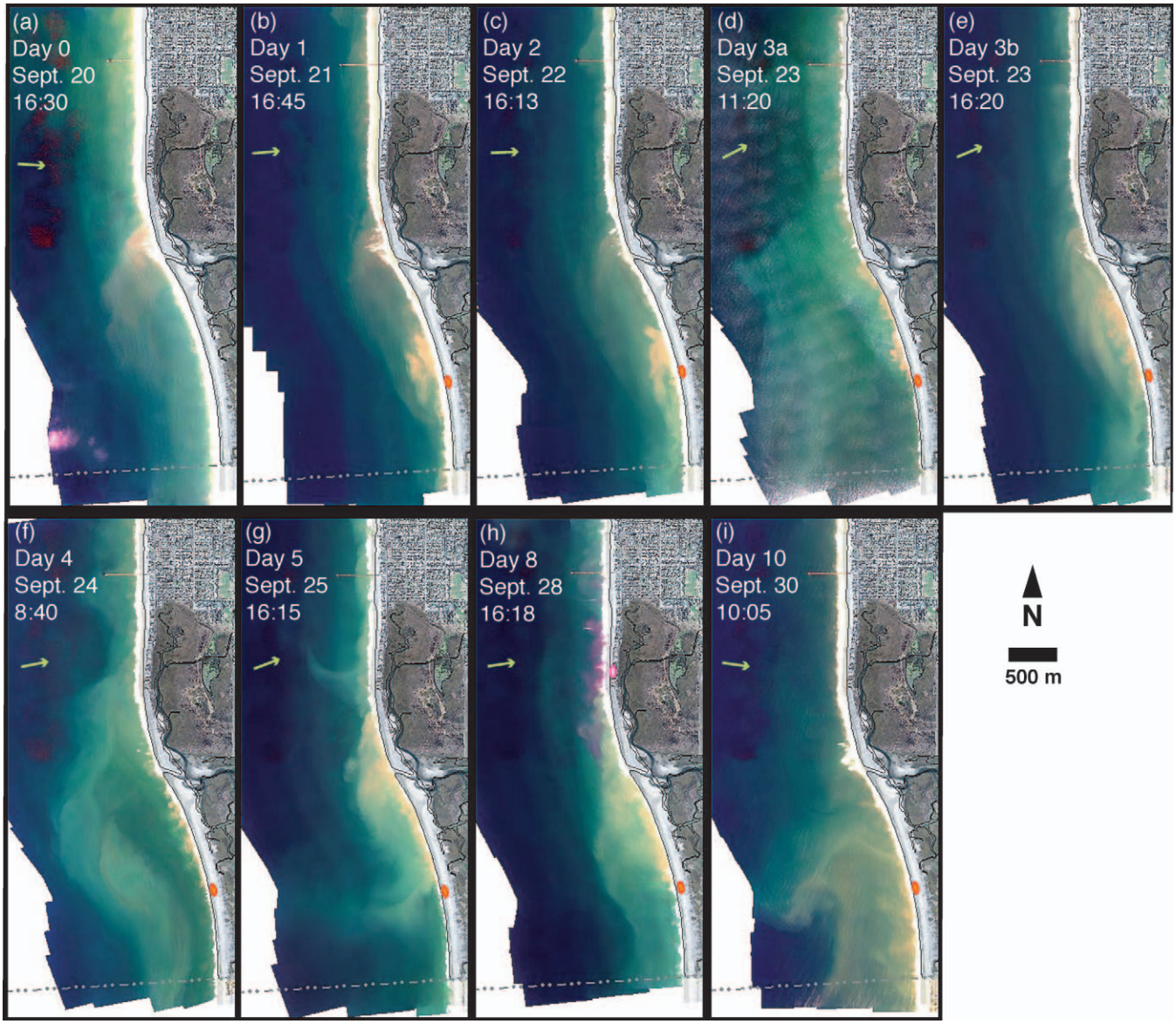

Figure 4. Aerial remote sensing of the coastal waters near the sediment nourishment site before and during the project. Dates and times for each image shown in local time (PDT). The nourishment site is shown with a red symbol in each image, and the international border is shown with a dashed line. The mean dominant wave direction at CDIP 155 during the proceeding 3 h is shown with arrows. Notable features include (a) outflow of estuary turbidity before the project initiation, (b–c) weak northerly surf zone flow of turbidity from nourishment, (d–h) strong northerly surf zone flow of turbidity from nourishment, (h) dye release from IB09 experiment (source shown with purple symbol), and (d, f, i) farther across-shore extent of turbidity observed during the morning following nourishment than (b, c, e, g, h) during the afternoon of nourishment.

were highest during westerly waves, although the correlation coefficients (r^2) for these linear regressions were only 0.37 to 0.43 ($p < 0.001$; Figures 7f and g). Use of multiple variable regressions with both dominant wave direction and significant wave height raised to a power between 0.5 and 3 did not improve these correlations, suggesting that wave height did not have a significant effect on swash fine sediment concentrations for the conditions observed.

Following the nourishment project, the swash fine sediment concentrations decreased over time and were at prenourishment concentration ranges within 1 to 5 days after the end of nourishment (Figure 8). There was substantial variability in these postnourishment concentrations, however, as shown by broad ranges in measured concentrations on the first day after nourishment: 14–18 mg/L at F1; 15–80 mg/L at N2, 20–68 mg/L at N1, 20–157 mg/L at M, and 13–240 mg/L at HT (Figure 8). After October 7 (5 days following nourishment), swash concentrations were all within the range of values measured before the nourishment project (Figure 8).

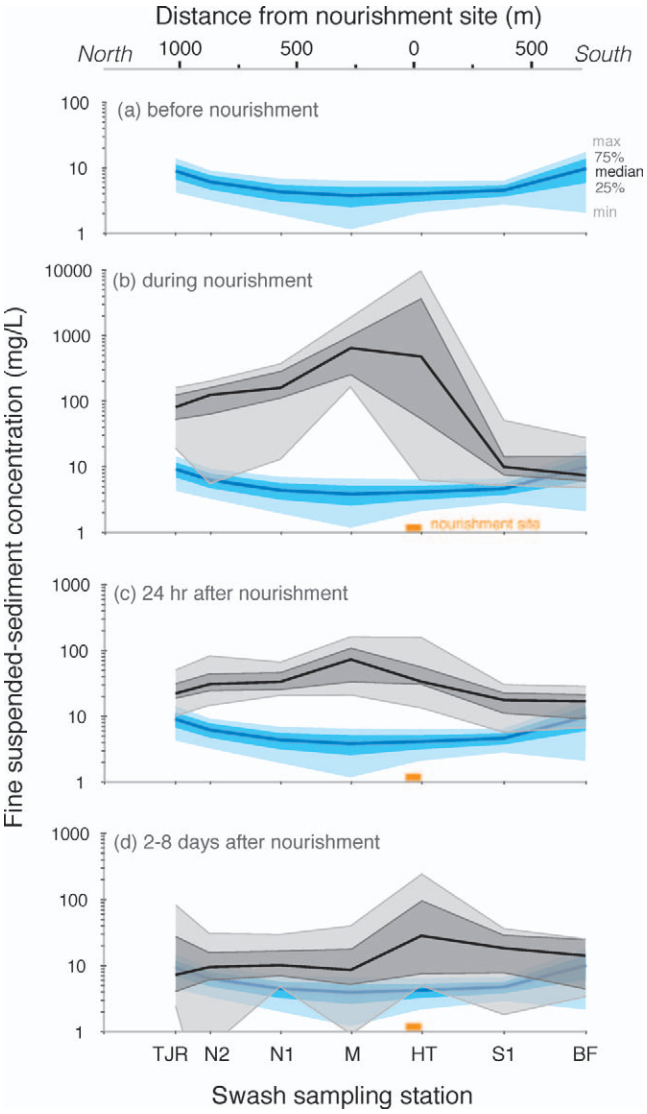

Figure 5. Swash concentrations of fine (<0.063 mm) suspended sediment before, during, and after beach nourishment. Sample values have been summarized into ranges of the extremes (min, max) and quartiles (25%, median, 75%) for each station under four conditions: (a) before nourishment, (b) during active nourishment, (c) on the day following nourishment, and (d) 2 to 8 days following nourishment. The "before" nourishment data (blue shading) is replicated in (b–d) for comparative purposes.

The grain size of the fine suspended sediment in the swash was dominated by silt-sized fractions during the nourishment project, and these were coarser than those measured before nourishment (Figure 9). During the nourishment project approximately 60% of the fine sediment in suspension in the swash zone was medium and coarse silt (*i.e.,* 16 μm to 62 μm; Figure 9b). The coarsest sediment distributions were measured adjacent to the nourishment site (Station HT) and distributions generally fined with distance away from the nourishment site (Figure 9b).

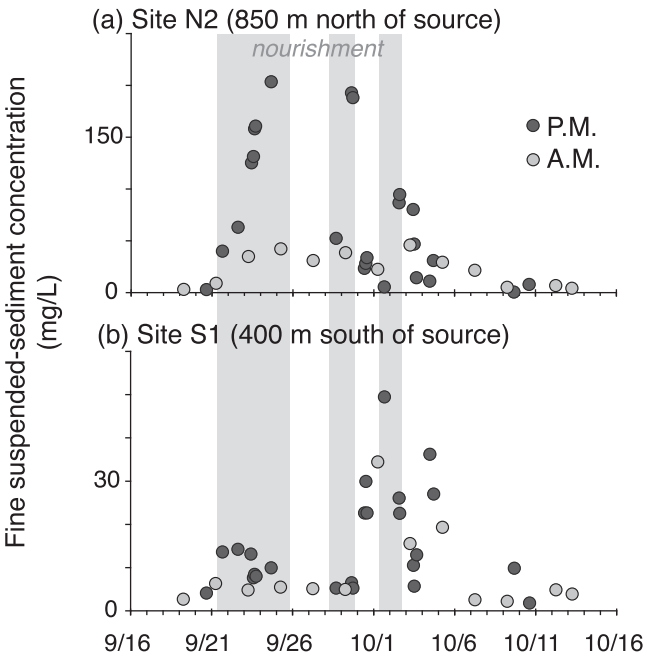

Figure 6. Time series of fine (<0.063 mm) suspended-sediment concentrations for two swash zone sampling stations (N2 and S1) on either side of the nourishment site. Intervals of active nourishment are shown with tan shading. Two types of sampling are shown: early morning samples before nourishment began (a.m., light symbols) and midday and afternoon sampling (p.m., dark symbols). Note the difference in scales between (a) and (b).

Across-Shore Transport from the Surf Zone to Nearshore Waters

Observations from the beach, small boat sensors, and airplane sensors all revealed that turbid waters exited the surf zone in rip cell heads (*e.g.,* Figure 4). Turbid rip cell heads had sharp fronts when they initially left the surf zone, and the fronts became more diffuse after 1–2 minutes of offshore movement. Sampling within turbid rip cell heads revealed that the light attenuation of surface waters within 100 m of the surf zone was consistently greater than 8 m^{-1} (Figure 10). Seven surface water samples were obtained from the small boat within these turbid rip cell heads, and their concentrations of fine suspended sediment averaged 79 mg/L, with a range of 25 to 175 mg/L.

Although the turbidity of the surface waters made the rip cell heads easily recognizable, water profiling data suggest that the near-bed waters had even greater turbidity than the surface waters. Example profiles of light attenuation within and immediately outside of a rip cell head are shown in Figure 10a. These data show that light attenuation doubled between the surface water and the near-bed water for the two profiles closest to shore ("c" and "e" in Figure 10a). If a conservative assumption is made that grain-size distributions remained constant with depth, then the turbidity profiles suggest a doubling of suspended-sediment concentration with depth. If grain size increased with depth, the near-bed concentrations

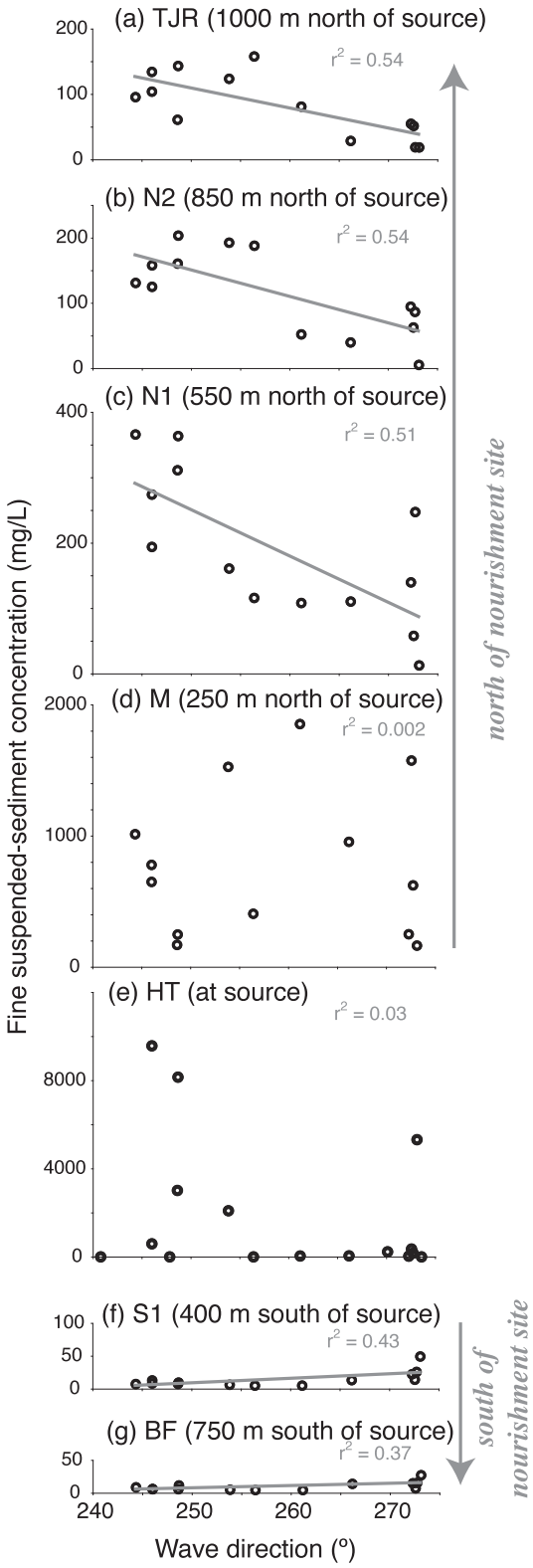

Figure 7. The relationship between dominant wave direction and fine (<0.063 mm) sediment concentrations at the swash sampling sites during days of nourishment. Gray lines are significant ($p < 0.05$) least-squares fit linear regressions, and correlation coefficients are shown for these regressions. Note that the vertical scales are equivalent for all figures except (d) and (e).

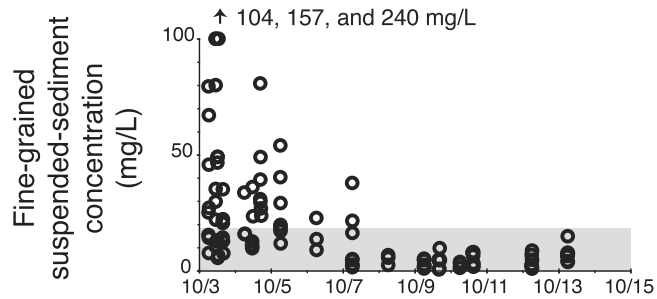

Figure 8. Swash zone concentrations of fine (<0.063 mm) suspended sediment during the days following the completion of nourishment for all stations. The range of concentrations measured before the nourishment project shown with shading. Concentrations in excess of the vertical scales are shown with symbols and arrows.

would be more that twice the surface water concentrations as a result of the grain-size dependencies of beam attenuation (*cf.* Baker and Lavelle, 1984). Thus, significant vertical gradients in suspended-sediment concentrations were observed in rip cell heads offshore of the surf zone.

Fine Suspended Sediment in Nearshore Waters

The nearshore waters far offshore of the surf zone revealed vertical gradients in water temperature, alongshore and across-shore currents, and fine sediment concentrations. For example, typical water column profiles from Station B12 before and during the nourishment project are shown in Figure 11. The water column was observed consistently to have a 5°C temperature gradient throughout the experiment (Figure 11a), but there was a negligible gradient in salinity (data not shown).

Turbidity of the water column increased measurably during the nourishment project, although the greatest increases in turbidity occurred in the lower part of the water column (*e.g.,* Figure 11b). Before the nourishment project, the water column was observed to have low turbidity, and the depth-averaged light attenuation of most profiles was less than 2 m^{-1} (Figure 12). As shown for Station B12, the highest turbidities during

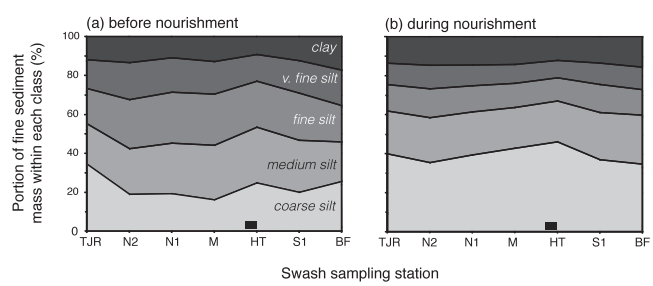

Figure 9. Mean grain-size distributions of the fine fraction (<0.063 mm) within all of the beach swash samples obtained (a) before and (b) during nourishment. Grain-size classes based on single phi-sized increments of the Wentworth scale. The nourishment site is shown with a symbol near the base of each figure.

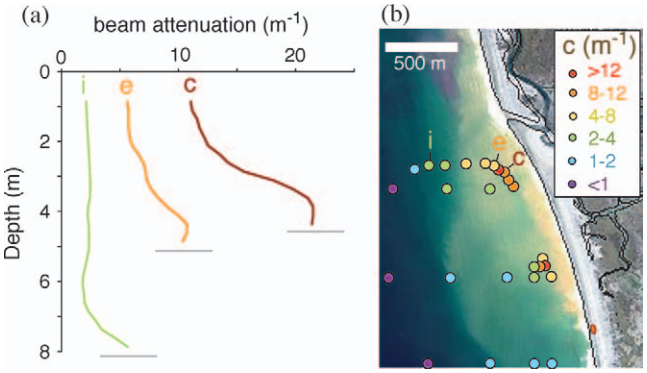

Figure 10. Light attenuation of the seawater in and around rip current heads near the nourishment site on project Day 8 (September 28, 2009). (a) Example profiles north of the site, profile locations shown in (b). Depth of the seafloor for each profile shown with a horizontal line. (b) Light attenuation of the surface water (mean of the upper 2 m). Water sampling conducted between 1100 and 1300 PDT, aerial imagery obtained at 1618 PDT.

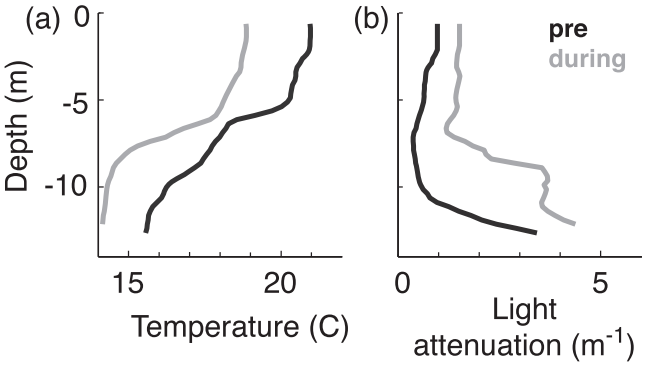

Figure 11. Example water column properties from Station B12 on the day before nourishment, September 20, 2009 (dark lines, "pre") and after 5 days of nourishment, September 25, 2009 (light lines, "during"). Notable characteristics include a strong temperature gradient in the mid–water column and increased turbidity with time, especially in the lower half of the water column.

the prenourishment sampling were consistently measured in the nephloid layer 1–2 m above the seafloor (Figure 11b).

During nourishment the depth-averaged light attenuation measurements increased to generally 1.5 to over 5 m^{-1} for the coastal stations (Figure 12). The highest light attenuation values were observed nearest to the shore and north of the nourishment site during the beginning of the project. Later in the project, the highest light attenuation values were observed nearest to the shore and south of the nourishment site (Figure 12). For example, on October 1, 2009, the highest turbidity values were observed to the south of the nourishment site (Figure 12), and this corresponded with observations of southward transport along the beach (Figure 2a) and westerly swell at the CDIP buoy (275°; Figure 3c).

On the day following completion of the nourishment project, the turbidity of the water column decreased markedly to levels consistent with the prenourishment conditions (Figure 12). The largest swell of the project occurred 2 days later (October 5, 2009), when the highest values of light attenuation for all sampled stations were observed (Figures 3c and 12), and this is consistent with the high fine sediment concentrations observed in the swash zone during the days following nourishment (Figure 8).

Estimates of the mass of sediment suspended within these coastal sampling sites were made by transforming beam attenuation values to suspended-sediment concentrations, then integrating linearly across the sampling domain. These estimates used the linear regression between measured fine suspended-sediment concentrations (in mg/L) and beam attenuation (in m^{-1}) that resulted in a slope of 5.8 and a zero offset ($r^2 = 0.60$; see Warrick *et al*. 2012 for raw data). This linear slope suggests that mean particle sizes were approximately 20 μm (Baker and Lavelle, 1984; Hill *et al*., 2011), which is consistent with our grain-size distribution results (*cf*. Figure 9). For comparison purposes, estimates of sediment mass were converted to volume of nourishment sediment using a bulk density of 1300 kg/m^3, which was the estimated bulk density of the nourishment sediment.

The results of this sediment mass balance suggest that the amount of suspended sediment within the study area approximately doubled after the start of the nourishment and remained relatively constant until the end of the nourishment (Figure 13). After an initial decrease in suspended sediment after completion of the nourishment project (October 3, 2009), the highest suspended-sediment volume of 252 m^3 was estimated for October 5, 2009 during resuspension associated with the largest waves of the sampling record (Figure 13; *cf*. Figure 3c).

Tripod Time Series of Suspended Sediment

Time series of oceanographic measurements from the two tripods on the inner continental shelf provide further insights to the dynamics of these turbidity patterns at distances of 1.2 to 1.3 km offshore of the beach (Figure 1). Although this places them within the turbidity plume observed from the airborne ocean color sensor on September 23 and 24 (Figure 4), there was no obvious increase in near-bed turbidity at these stations during the first 2 to 3 days of the nourishment project (Figures 14a and b). However, during and following the latter portion of this first week, the turbidity increased at both tripods (Figures 14a and b).

Starting on September 25, the turbidity at the northern tripod site was observed to increase and pulsate at regular intervals of approximately 12 hours (Figure 14a). These patterns in turbidity occurred at similar time intervals as the dominant oscillations in across-shore currents both near the seafloor and at the water surface, and peaks in turbidity at this time corresponded with the strongest offshore currents near the bed (Figure 14d). It is important to note that there was consistent shearing in these across-shore currents for the duration of the study with oscillations of approximately 12 hours, and peak speeds in these across-shore currents were commonly 10–20 cm/s (Figure 14d). In contrast, the alongshore currents were strongly southward in the surface waters throughout much of the study, while near the seabed the alongshore currents were more negligible (Figure 14e).

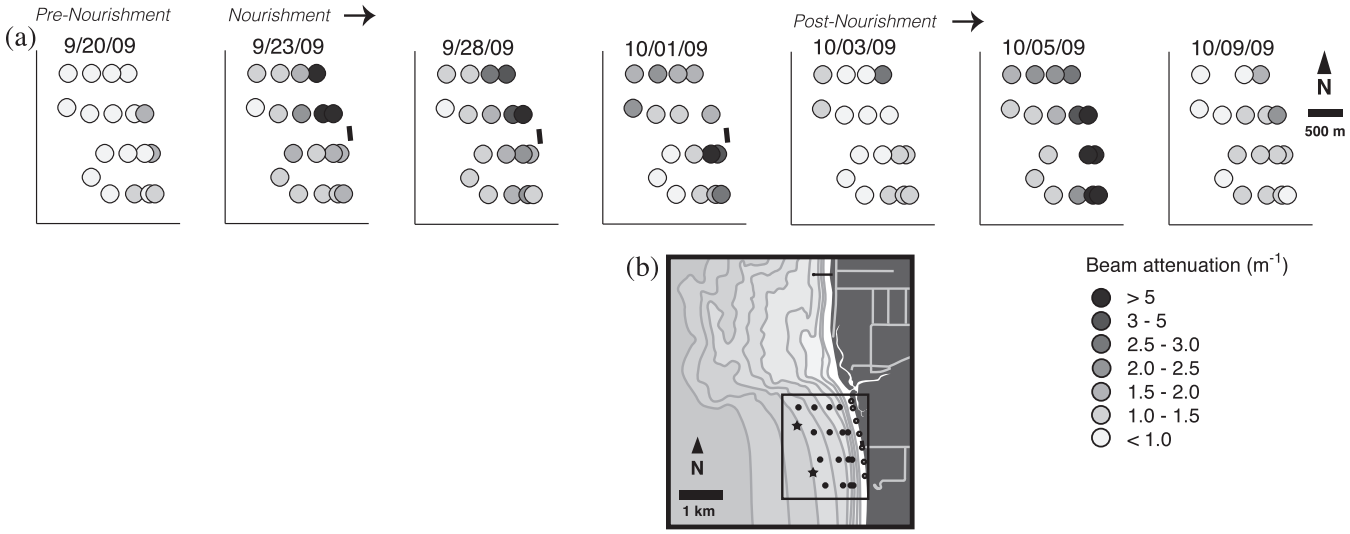

Figure 12. (a) Mean water column turbidity before, during, and after the nourishment project. Only 7 of the 16 study area sampling dates are shown to highlight the general conditions observed, including prenourishment (September 20, 2009), nourishment with turbidity to the north (September 23, 2009 and September 28, 2009), nourishment with turbidity to the south (October 1, 2009), and postnourishment (October 3, 2009; October 5, 2009; and October 9, 2009). The location of the nourishment site is shown with a rectangle on the dates of active nourishment. The box for each date represents the area between –117.147° and –117.123°E and 32.532° and 32.556°N as shown in (b) the inset map.

The increase in turbidity at the northern tripod site occurred during an interval of time without elevated wave orbital velocities. For example, light attenuation data from the preproject and first week of nourishment are compared with the second week of nourishment in Figure 15. Although orbital velocities were approximately similar during these two intervals of time (upper box plots; Figure 15), the light attenuation values were over three times greater during the latter interval of time (right-hand-side box plots; Figure 15). The light attenuation values during the first interval of time were significantly, albeit weakly, correlated with wave orbital

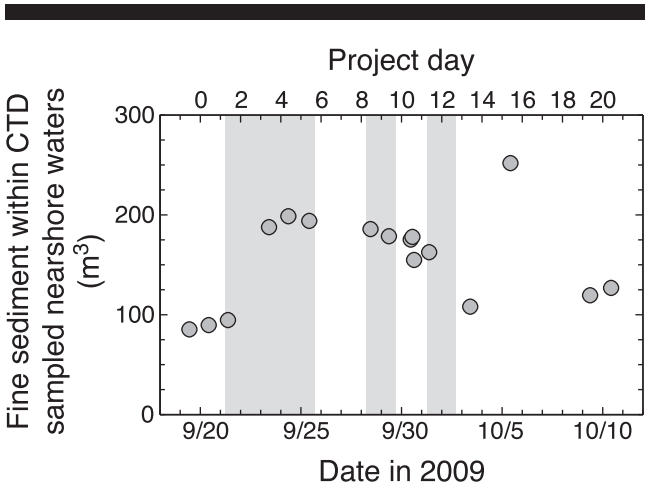

Figure 13. The integrated volume of fine suspended sediment in the nearshore waters as sampled by small boat. The timing of sediment nourishment is shown with shading.

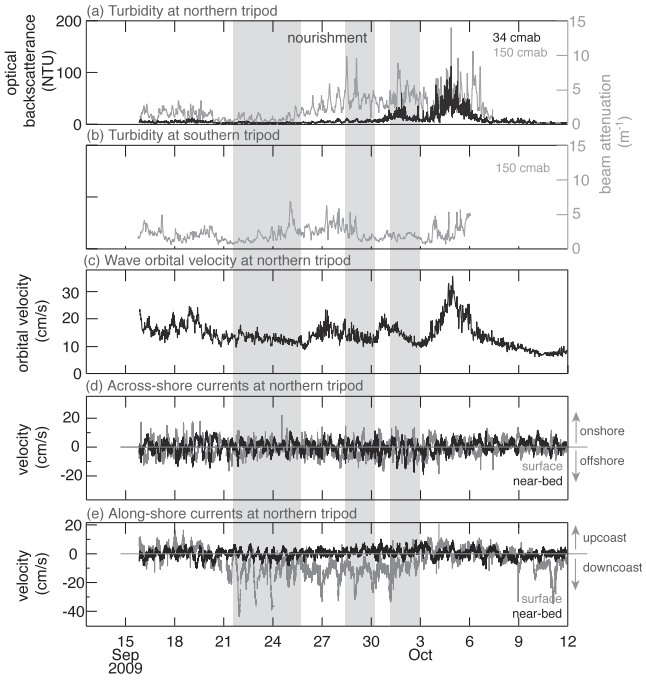

Figure 14. Observations of turbidity and currents at the two benthic tripods placed offshore of the nourishment project. Intervals of active nourishment are shown with tan vertical bars. Heights of sensors shown in centimeters above the bed (cmab). Currents from ADCP profiles are shown for both the surface and near-bed waters, which are averages of the upper and lower 2.5 m of the sampled water column.

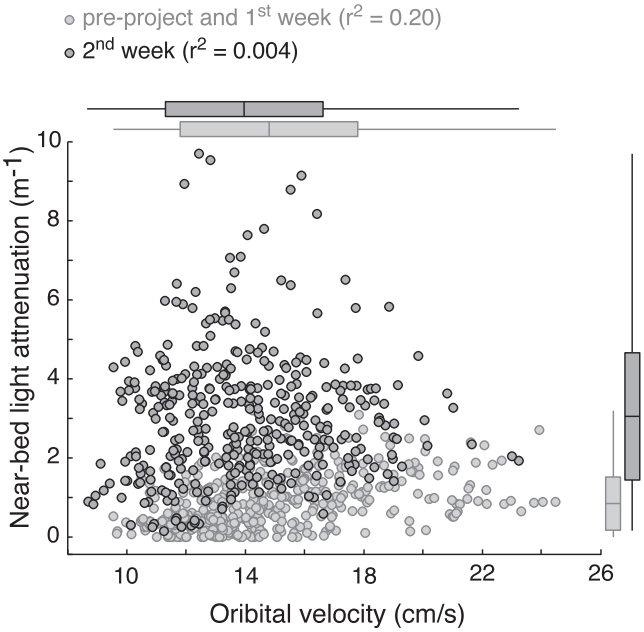

Figure 15. Comparison of the turbidity data from the northern tripod during the combined preproject and week 1 of the project as compared with those of the second week of the project. Light attenuation data provided from a transmissometer 1.5 m above the bed, orbital velocities are from the ADV. Box plots on the right and top of the figure show the mean, standard deviation, and range of each grouping of data. The two intervals of time are defined by September 15–24 and September 25–October 2. Linear regression correlation coefficients are shown with labels.

velocities ($r^2 = 0.20$; $p < 0.005$), whereas the higher turbidities of the latter interval of time were not correlated with wave orbital velocities ($r^2 = 0.004$; $p = 0.22$; Figure 15).

Thus, it appears that the near-bed turbidity measurements at the tripods were associated with suspended sediment advected from the direction of the beach within the lower portion of the water column. These elevated turbidities did not occur until several days after the start of nourishment. The greatest turbidities were measured after beach nourishment during the larger waves of October 4–5 (Figure 14).

Sedimentation on the Beach and Seafloor

The grain-size distributions of the beach and seafloor of the study site were generally coarsest in the swash zone and fined with depth offshore from the beach. During and following the beach nourishment project there was fining of both the beach and seafloor sediment. For example, in May 2008—before both of the 2008 and 2009 nourishment projects—the proportion of fines in the beach sediment averaged 0.12% (range = 0.01% to 0.46%; $n = 21$). During the 2009 project, the surface of the beach shoreface within the nourishment area (Station HT) had a fine sediment proportion of 2.1% to 5.3%. Fine sediment proportions of beach sediment were much lower for the beach stations outside of the nourishment site (Stations TJR, N2, N1, M, S1, and BF), which averaged 0.36% fine sediment by weight (range = 0.004% to 1.2%; $n = 82$) during and immediately following the nourishment project. No spatial or temporal patterns were observed in the grain-size results outside of the nourishment site.

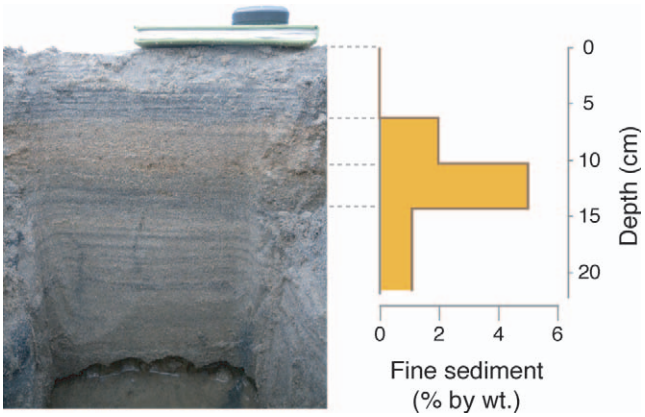

Figure 16. Sediment profile of the subaerial beach within the nourishment area on day 19 (October 9, 2009), which was 7 days after the end of nourishment. This subsurface deposit of fine sediment was observed throughout the intertidal swash area of the nourishment site on October 9–10, 2009, although it was absent when resampled on November 18, 2009.

Following the project, a subsurface layer of sediment with 1% to 12.2% fines by weight was observed within the nourishment site (Figure 16). Trenching and sampling throughout the project area suggested that this layer extended across the swash zone (~14 m across the beach) and within, but not beyond, the project site (~115 m along the beach; data available in Warrick *et al.*, 2012). A maximum thickness of 24 cm for this layer was measured from a trench dug across shore and through the center of the nourishment area; this thinned to 4-cm thick in the low tide swash zone. This layer was underneath 5 to 20 cm of sand with low proportions (0% to 0.5%) of fine sediment, which presumably had been winnowed by surf zone swash action. Integrated throughout the project area and using the depth-averaged fine sediment proportion of 5%, the total volume of fine sediment remaining in the beach 7–8 days after nourishment was equivalent to approximately 15 m^3, which is roughly 0.1% of the total volume of fine sediment placed on the beach. Upon resampling of the beach 5 weeks later (November 18, 2009) no fine sediment layers were found throughout the nourishment project area, and the average fine sediment proportion of the beach sand was 0.16%.

The fine sediment proportions of the surficial seafloor before the project averaged 4% at 8-m water depth and increased to 16%, 29%, and 39% at 10-, 12-, and 14-m depth, respectively (Figure 17a). These seafloor sediment grain-size distributions did not change substantially during the project, except for at C8, the station closest to the nourishment site and in 8-m water depth (Figure 17b). A time series of the surficial grain size at this station shows a fining with time largely from the increase of coarse silt (32–64 μm) fraction, which increased from 7% to 30% by weight (Figure 17c). Finer fractions, like medium silt (16–32 μm), initially increased from 2% to 11% during the nourishment project, but then decreased to 5% during the days following nourishment (Figure 17c). The greatest coarsening of

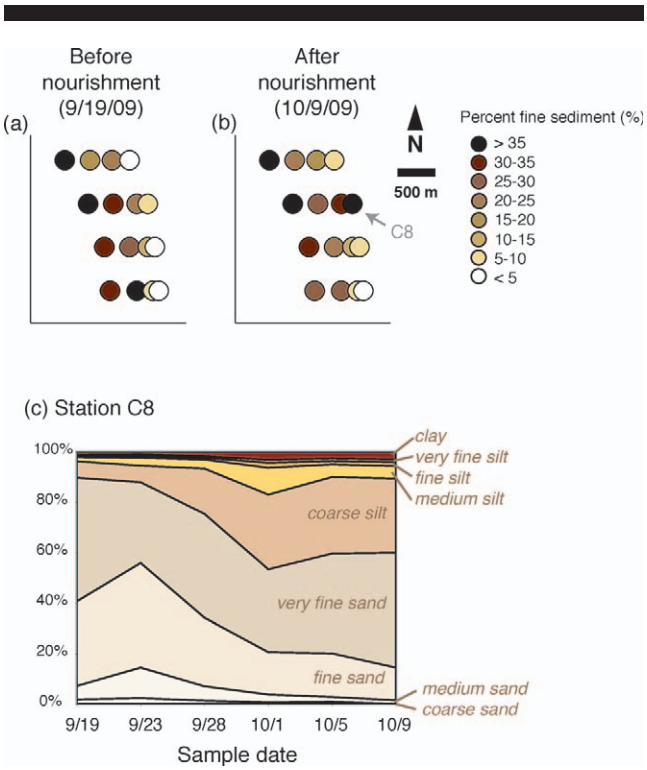

Figure 17. Patterns of seafloor surface grain size before, during, and after the nourishment project. (a) and (b) Percentage of surface sediment finer than 0.063 mm both before and after nourishment. Mapped stations within a box with the same geographical bounds as Figure 12. (c) The time series of grain-size distribution at Station C8 (highlighted in (b)), which was nearest to the nourishment site and experienced the greatest change in grain size during the project.

the sediment at Station C8 occurred between October 1 and 5, during which the largest waves of the project occurred (Figure 14c; *cf.* Figures 3c, 8, 12).

DISCUSSION

Pathways and Patterns of Fine Sediment Transport

Fine sediment from the nourishment project was observed to transport both alongshore and across shore from the project site, and the directions and patterns of this transport were related to wave and current conditions. Initially, the fine sediment was transported alongshore within the surf zone, and the direction of this transport related significantly to wave direction. Estimates of the volume of fine sediment within the surf zone can be made with the swash sediment concentration measurements, an original bulk density of sediment of 1300 kg/m^3, and a well-mixed assumption across the surf zone (*cf.* Feddersen, 2007). Integrating along the ~2-km long surf zone that was sampled between Stations TJR and BF and assuming the surf zone averaged 100 m in width and 1 m in depth, approximately 0.9 m^3 of fine sediment was in this surf zone on the day before nourishment. During days with active nourishment the sampled surf zone averaged 160 m^3 of fine sediment with a standard deviation of 52 m^3 and a range of 86–265 m^3, or roughly 200 times greater fine sediment than before nourishment.

Table 2. *Time scales of fine sediment transport processes observed during the 2009 nourishment project.*

Location	Residence Time (h)
Surf zone (~1 km long)	0.7–1.5
Rip cells	~0.3
Nearshore waters [a] (2 km^2)	~2
Nearshore alongshore current: surface	0.7–3
Nearshore alongshore current: near bed	14–200 [b]

[a] Calculated from the fine sediment residence time of the region sampled by CTD.

[b] Smaller value was calculated for the time between September 29 and October 3 when the net current was 3 cm/s toward the NW, larger value was calculated for the time between September 20–28 when there was no net current and low current amplitude (~5 cm/s).

These estimates of the volume of fine sediment suspended within the surf zone are useful for estimating average residence times of fine sediment within the surf zone. Assuming that fine sediment concentrations are at or near steady state after several hours of nourishment, the average residence time for fine sediment within the surf zone can be estimated by the ratio of the volume of fine sediment within the surf zone to the nourishment rate. The nourishment rate of fine sediment was approximately 140 m^3/h during the 10-hour workday, which suggests that the surf zone residence times for fine sediment through this ~2-km long beach averaged 1.1 (±0.4) hours (Table 2). If flux of sediment out of this sampled beach was dominantly through alongshore transport to the north, the average rate of alongshore fine sediment transport could be estimated by the ratio of the longshore distance of the beach (1000 m) to the average residence time (1.1 h), suggesting speeds of approximately 0.25 m/s, which is within the range of measured alongshore current speeds for similar beaches under similar wave conditions (Grant *et al.*, 2005; Inman, Tait, and Nordstrom, 1971; Spydell *et al.*, 2007). However, fine sediment flux and deposition was observed both alongshore and across shore from the sampled surf zone, suggesting that this calculated speed of alongshore transport is an overestimate. Nonetheless, these estimates of residence time suggest that once fine sediment was suspended, it moved, on average, through the sampled stretch of surf zone within hours of initial placement.

However, fine sediment concentrations of the surf zone did not return to background levels within hours, but rather within several days. This appears to be related to incomplete suspension of the fine sediment upon nourishment, as suggested by the measurable fine sediment on and within the beach face during and immediately following the nourishment project. Fine sediment remaining on and within the beach was winnowed over time, and fine sediment concentrations within the study area returned to preproject levels within 2–5 days. Initially, the rate of decrease in fine suspended-sediment concentrations was rapid. For example, after 24 hours of nourishment the median fine sediment concentrations were only 1.3% to 9% of those measured during nourishment (Figure 5). Assuming exponential-like decreases in concentration with time, this results in concentrations reducing by half every 1 to 4

hours. If fine sediment concentrations continued to fall at these rates, background concentrations (~10 mg/L) would have been realized within 40 hours of nourishment. However, because sources of fine sediment remained on and within the beach after nourishment (*e.g.,* Figure 16), fine concentrations were measurably above background levels for days longer than this simple exponential-like reduction model for the surf zone.

The across-shore transport of fine sediment from the surf zone to nearshore waters was important, as shown by observations of fine sediment in the water column and on the seafloor. Turbidity from the fine sediment was observed extending offshore of the surf zone in each of the nine remotely sensed ocean color images (Figure 4). Within this turbid region offshore of the surf zone, the water column was most turbid near the seafloor, suggesting that sediment particles were settling vertically toward the lower portion of the water column. A mass balance of sediment within these turbid rip cells can be estimated from the combined ocean color and CTD observations. For example, on September 28 an excessively turbid zone was observed ~100 m offshore of the surf zone from the nourishment site past the Tijuana River mouth (~1500 m distance; Figure 10). Fine sediment concentrations of the surface waters within this region averaged ~100 mg/L and near-bed concentrations were approximately twice these values. Assuming an average water depth of 4 m in this nearshore turbid region, approximately 60,000 kg of fine suspended sediment (or ~50 m^3 of the fines in the nourishment sediment) were present in these rips. Using the 140 m^3/h fine sediment nourishment rate reported above and assuming steady state, the average residence time of fine sediment in these rips on this day is calculated to be ~20 minutes (Table 2). Thus, these rips are found to rapidly export fine sediment from the surf zone, suggesting that these rips are key processes to the export of fine sediment from the surf zone to the inner shelf.

The amount of fine sediment suspended within the sampled inner shelf coastal waters averaged only about 100 m^3 above the prenourishment volumes (Figure 13). Compared with the influx rate of sediment coming from turbid rips, which, if assumed to be approximately constant in time during the entire day of nourishment, results in a rate of 58 m^3/hr, the average residence time of fine sediment in the sampled coastal waters was only ~2 hours (Table 2). This result, combined with the relatively steady volume of sediment in the coastal waters during a time when fine sediment was added continuously (Figure 13), suggests that fine sediment was moving out of the sampled waters either by vertical settling to the bed or near-bed (*i.e.,* below the ~0.5 m bottom range of the CTD sampler) or by lateral advection out of the sampled region.

To evaluate the potential for sedimentation within the sampled region, an estimate of the volume of fine sediment deposited upon the seafloor offshore of the nourishment site was established. This estimate was limited to sampling locations in which the grain size changed, although it may be noted that sedimentation would not have been detected if the deposited grain-size distribution was identical to that of the bed. A conservative assumption is that the region of fine sediment deposition extended 1000 m alongshore between Stations B8 and D8 (the approximate distance between stations with no deposition) and 100 m across shore (the distance between the surf zone and the 8-m isobath). With a thickness of 2 to 4 cm and 25% fine sediment by weight, a conservative estimate of 500 to 1000 m^3 of fine sediment was made, which is approximately 5% to 10% of the total fine sediment placed on the beach (Table 3).

There also may have been fine sediment suspended between the bed and the lower sampling limit of the CTD-mounted light transmissometer, which sampled to approximately 0.5 m above the bed. If the majority of the fine sediment from the nourishment project resided uniformly within this narrow layer across the ~2-km^2 sampled area, the average suspended-sediment concentration within this layer would be roughly 13,000 mg/L. It is not possible to evaluate whether these high suspended-sediment concentrations existed within this region, although if they did, there is a strong likelihood for the bottom boundary layer to have negative buoyancy with respect to the coastal waters, thereby inducing sediment gravity flows that would have transported fine sediment offshore (*e.g.,* Warrick *et al.*, 2008; Wright and Friedrichs, 2006).

Another reason that the mass of fine sediment sampled within the offshore survey stations was small compared with the mass introduced at the nourishment site may have been the advection of fine sediment out of the sampled region within either the surf zone or the nearshore coastal waters. A simple assessment of surf zone flux of fine sediment can be developed with the results of the swash suspended-sediment sampling. For example, on days of strong northward longshore currents in the surf zone, the maximum speed of these currents was estimated to be 0.25 m/s. On these days, the concentrations of fine suspended sediment at Station TJR, roughly 1 km away from the nourishment site, were 50–100 mg/L during active nourishment (Figure 5). Thus, using the same beach geometry reported above (100 m width and 1 m average depth), the fine sediment flux past the TJR station during the 10-hour nourishment workday was estimated to be 35–70 m^3. Assuming that concentrations reduced during the 14 remaining hours of each day toward levels reported in Figure 5, the total daily fine sediment flux past Station TJR is estimated to be 50–100 m^3/d during active nourishment. This flux is only ~5% of the total daily fine sediment nourishment rate (Table 3), which suggests that ~95% of the fine sediment placed at the nourishment site had moved offshore of the surf zone within 1 km of longshore transport in the surf zone.

Offshore of the surf zone, fine sediment may have left the sampled region of the nearshore waters laterally as suspended-sediment transport. The current velocities in the upper half of the water column were southward for the duration of the project with speeds of 10–40 cm/s and a mean low-pass speed of 15 cm/s (Figure 3e). For fine suspended sediment within the upper water column, the time to transport from the center to the southern limit of the sampled area—a distance of ~1 km—would have ranged between 0.7 to 3 hours with a mean of ~2 hours (Table 2). The volume flux of fine sediment within these surface currents can be estimated with these current speeds and water column samples. Suspended fine sediment concentrations of the upper water column were elevated by an average of approximately 10 mg/L across the sampled region during the nourishment project. Southward current velocities were observed in the upper 5 m of water, and using the mean low-pass

Table 3. *Fine sediment mass balance results from the 2009 nourishment project.*

Process	Fine Sediment Flux and/or Volume	Percentage of Nourishment	Notes
Beach nourishment	~1400 m^3/d; 14,000 m^3	100%	Daily rates varied
Beach sedimentation	15 m^3	0.1%	
Nearshore sedimentation	500-1000 m^3	5–10%	Centered at 8 m water depth
Longshore flux offsite (oblique waves)	50–100 m^3/d	3–7%	Flux estimated past Station TJR (1 km away from nourishment)
Longshore flux offsite (normal waves)	0 m^3/d	0%	
Lateral advection (surface waters)	500 m^3/d	36%	
Lateral advection (near bed)	200 m^3/d	14% of daily rate; 8% of total volume	This rate persisted for only 5 days (Sept. 29–Oct. 3)

current speed of 15 cm/s across the 1-km southern boundary of the sampled area, the flux of fine sediment is estimated to be 500 m^3/d, which is roughly one-third of the nourishment rate of fine sediment (Table 3).

In contrast to the upper portion of the water column, the currents within the lower water column had very little net movement (Figures 14d and e). Although these near-bed currents had amplitudes of 5–10 cm/s, the net distance of excursion related to these currents did not exceed 0.5 km across shore and 1 km alongshore during the first portion of the nourishment (September 20–28). This changed during September 29–October 3, when a measurable net current of 3 cm/s directed toward the NW was observed in ADCP records at both tripods and the near-bed ADV records (*e.g.,* Figures 14d and e). This northwesterly current was likely the cause in the coincidental decrease in beam attenuation at the southern tripod starting on September 29 (Figure 14b), because of the reduction of the nourishment sediment source upstream of this site. Using this current speed, the time to transport across the sampled area—from the center to the northwestern edge, a distance of ~1.5 km—was ~14 hours (Table 2). During the 5 days of this net near-bed current, lateral advection of fine sediment from the CTD-sampled study area can be estimated by the tripod measurements of flow and turbidity. The beam attenuation measurements at 1.5 m above the bed averaged 5 m^{-1} during these 5 days (Figure 14a), which was equivalent to a fine suspended-sediment concentration of ~30 mg/L. Assuming that this concentration was fairly constant over the lower 3 m of the water column (*cf.* Figure 11b), approximately 200 m^3/d of fine sediment was transported offshore and north of the study area along this ~1-km northwestern boundary during these 5 days (Table 3).

Mass Balance and Conceptual Model of Nearshore Fine Sediment Transport

Combined, the calculations above can provide the basis for a fine sediment mass balance from the nourishment project (Figure 18; Table 3). Of the fine sediment placed onto the beach, the vast majority was suspended within the surf zone within days of placement, resulting in very little sedimentation on the beach (Figure 18; Table 3). Longshore transport of fine sediment within the surf zone occurred during the oblique wave angles that occurred during this project (*e.g.,* Figures 4 and 7). However, the net flux of fine sediment from the surf zone to coastal waters primarily through rips was substantial: approximately 95% of the fine sediment flux in the surf zone was lost to offshore waters after 1 km of alongshore transport in the surf zone during oblique waves (Figure 18; Table 3). During normally directed waves, this rate of loss was likely greater. Thus, the transfer of fine sediment from the beach to nearshore waters was efficient, even during significant longshore currents in the surf zone.

Once fine sediment was transported offshore of the surf zone to the nearshore waters, downward settling of particles resulted in convergence of fine sediment toward the seafloor. This was most evident from the increased turbidity of the near-bed waters and sedimentation directly offshore of the nourishment site. The latter effect could account for 5–10% of the total fine sediment budget (Figure 18; Table 3). However, the greatest nearshore loss of fine sediment was from lateral advection by currents (Figure 18; Table 3). Although suspended-sediment concentrations were generally higher near the bed, greater advection of fine sediment from the study area was observed in the surface waters, largely owing to the strong net southward currents observed in these surface waters (Figure 14). The remaining fine sediment (Figure 18; Table 3) could have deposited on the seafloor within the study or resided in or transported within thin layers along the seafloor (*cf.* Wright and Friedrichs, 2006), neither of which could be detected with the methods used here.

Implications for Fine Sediment Transport and Nourishment

A compilation of time scales computed here for fine sediment movement conveys the rapidity of sediment movement through this coastal system (Table 2). The average time that fine sediment resided within the combined surf zone, rips, and nearshore waters was only 3–4 hours. Therefore, it is important to have rapid sampling of these pathways during future fine sediment investigations. Nonetheless, there are a number of locations that fine sediment moved much more slowly. For example, sedimentation on and within the beach was partially responsible for elevated turbidity in the surf zone for several days following the nourishment project (Figure 8). To avoid similar multiple-day turbidity effects and the potential environmental impacts they may induce during nourishment projects, better initial suspension of sediment within surf zone waters would be required. Nephloid layers near the seafloor of the inner continental shelf were also locations of fine suspended sediment persistence (Table 2). It is possible that some of this fine sediment settled to the seafloor within the study area, although at locations that natural

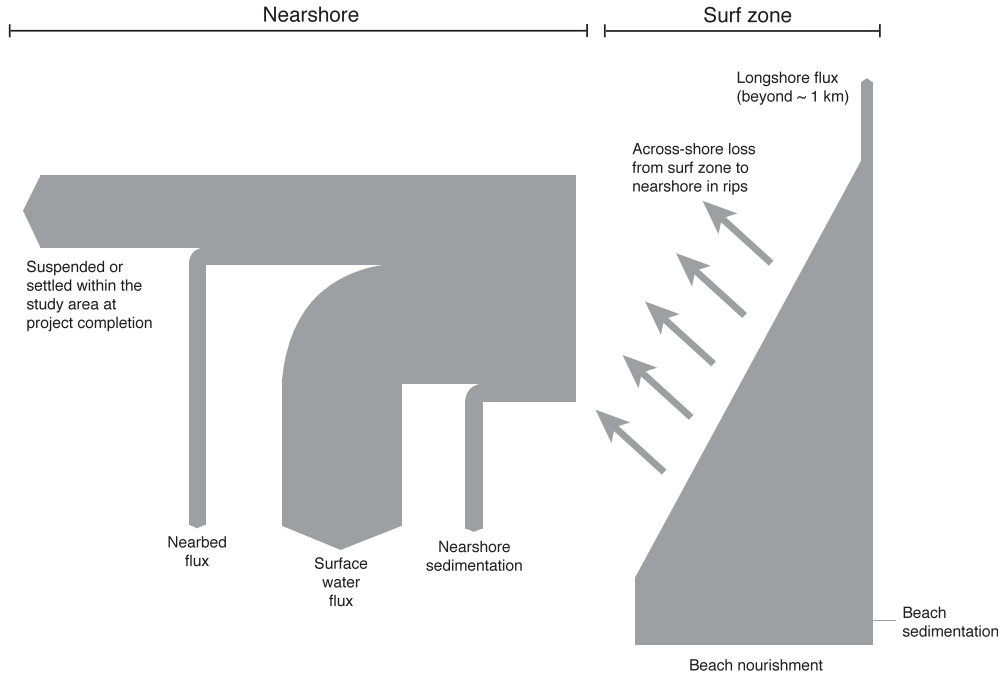

Figure 18. Schematic diagram of the mass balance of fine sediment from the beach nourishment project. The thicknesses of the lines are proportional to the approximate fluxes along the labeled pathways. See Table 3 for a summary a flux values.

seafloor grain-size distributions were already significantly fine grained. This near-bed and seafloor fine sediment most likely contributed to the large resuspension event on October 5, 2009, that coincided with the largest waves of the monitored record (Figures 12, 13, and 14).

The wave event of October 5, 2009, resulted also in a coarsening of the seafloor at Station C8, the only location of measurable fine sedimentation from the nourishment project (Figure 17). Because wave events such as these are important to the suspension and transport of sediment across coastal margins (Harris and Wiberg, 2002; Hill *et al*., 2007), it is invaluable to compare the wave conditions observed during the nourishment project with other times of the year. The nourishment project was conducted in late summer, which generally has the lowest wave heights of the year (Adams, Inman, and Graham, 2008). The timing of this late summer project missed the opportunity to use the larger waves of the fall and winter, which during 2009 had mean, median, and maximum wave heights substantially greater than those during the 2009 nourishment project and sampling (Figure 19). These wave conditions during the 2009 winter are very similar to those measured at CDIP Station 155 during the previous years (see the "Study Area" section). Thus, future projects may want to take advantage of the larger wave conditions that occur during the fall and winter (Adams, Inman, and Graham, 2008), which will likely encourage fine sediment transport to greater depths and extents than those observed here.

These results suggest that although fine sediment is incorporated into the swash zone in a tracer-like manner, this tracer-like behavior does not persist throughout or beyond the rip cell circulation. This is consistent with the theoretical calculations highlighted in the "Theoretical Considerations" section above, and it is in direct contrast to the assumptions and conceptual models of Inman, Tait, and Nordstrom (1971),

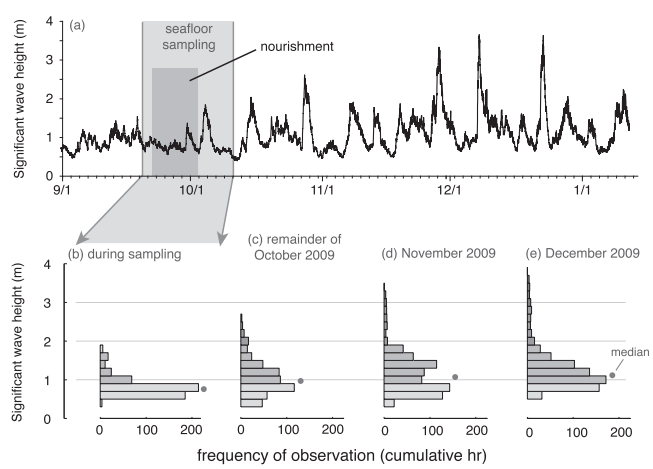

Figure 19. Significant wave heights at CDIP Buoy 155 during and after the sediment sampling of the seafloor for this project. (a) Significant wave height time series with the timing of the seafloor sampling and active beach nourishment identified with shading. (b–e) Histograms of significant wave height during (b) the interval of seafloor sampling, (c) the remainder of October 2009 following sampling, (d) November 2009, and (e) December 2009. The median of each histogram distribution is shown with a dot.

which could be easily revised in light of this by including sediment settling behaviors. The rapid removal of fine sediment from surf zone waters from rips (*cf.* Figure 18) provides evidence of the importance of rip cell circulation to fine sediment behavior in the nearshore. Unfortunately, our observations were not concentrated within this important zone of sediment exchange, and future investigations will be needed to build a more thorough understanding of the sediment dynamics within rip cells.

CONCLUSIONS

The placement of nourishment sediment with a high portion of fine sediment into the swash of a southern California beach provided an ideal opportunity to measure and track fine sediment dispersal processes and pathways. Although fine sediment was rapidly and efficiently transported within the surf zone, it was not observed to be tracer-like because of the substantial loss of the fine sediment flux to across-shore transport within rips. Subsequent transport of fine sediment was related to wave resuspension and current speeds and directions, the latter of which was observed to have substantial vertical shear at this study site.

Within the surf zone rips and water column of the study area, fine sediment was observed to have residence times that were of the order of an hour. Although these time scales suggest rapid movement of fine sediment through these systems, there are areas of longer residence times, including sedimentation on the beach and inner shelf seafloor, which was observed to persist for days to weeks. The pathways and rates of suspended-sediment transport were directly related to both the wave heights and directions and the current velocities. Therefore, it is suggested that careful application of predictive techniques may prove to be successful as long as the complex processes of the surf zone and nearshore waters (*e.g.,* Grant *et al.*, 2005; Kirincich, Lentz, and Barth, 2009; McMahan, Thornton, and Reniers, 2006; Noble and Xu, 2003; Spydell, Feddersen, and Guza, 2009) are incorporated. One important area of across-shore exchange of fine sediment is the rip current circulation cells, and further research is needed to better understand the hydrodynamics of this exchange and the potential influences of wave heights, directions and intervals, tidal conditions, and bathymetric properties on these processes.

ACKNOWLEDGMENTS

This work was funded by the California Ocean Protection Council, the California Coastal Conservancy, the U.S. Army Corps of Engineers, California Department of Boating and Waterways, and the USGS Coastal and Marine Geology Program. The nourishment project was managed by Karen Bane of the California Coastal Conservancy and Clay Phillips of the Border Field State Park with assistance from the staff of the Tijuana River National Estuarine Research Reserve, the Southwest Wetlands Interpretive Association, Border Field State Park, Nordby Biological Consulting, Moffatt & Nichol, and Diamond Lane Contractors. Special thanks are given for assistance from Mayda Winter, Jeff Crooks, Chris Peregrin, Chris Nordby, Brian Leslie, Clif Davenport, Chris Webb, and Megan Johnson. Field and laboratory assistance was provided by Ian Miller, Joanne Ferreira, Josh Logan, Kurt Rosenberger, Meg Rippy, Angela Lam, Mike Torresan, and Clif Davenport.

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