



Evaluation of the Effects of a Demonstration Project for Restoring Bayside Sediment Processes at Sailors Haven Marina

Natural Resource Report NPS/FIIS/NRR—2016/1309



ON THE COVER

The beach west of Sailors Haven Marina, showing the fill placed in November 2011 (December 2011 photo) and the eroding shore after removal of fill by waves and currents (July 2013).

Photos taken by Karl Nordstrom

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Executive Summary

Shoreline erosion is often exacerbated by reduction of sediment inputs because of armoring of upland sources or interference with sediment transport alongshore by shore-perpendicular structures. Establishing a feeder beach to reinstate the sediment budget adjacent to a bulkhead is evaluated here as a solution for addressing future erosion problems along sandy estuarine shores. A feeder beach was created adjacent to Sailors Haven Marina in Great South Bay at Fire Island, New York, using sand obtained from the entrance channel. The fill was placed along a 75 m length of upland at a height similar to the eroding bluff. Topographic surveys were conducted before and after fill and at half year intervals for 18 months. Daily changes in wind and wave processes and beach change were evaluated during an instrumented time-series field study conducted during the storm season within the period 11 March to 7 April 2012. Sediment transport rates and directions were gathered using sand traps and dyed sand tracers. The beach is microtidal (mean range 0.21 m). Fetch distances for wave generation are <15 km. The bulkhead is a wooden sheet pile structure that projects about 115 m into the bay. The sides of the bulkhead are comprised of a series of segments with different orientations relative to shoreline trend, resulting in a complex pattern of wave reflection off the structure. The shoreline is characterized by segments of forested upland alternating with *Phragmites* marsh.

The quantity of fill placed was measured at 1,747 m³. Maximum shoreline advance due to fill emplacement was 20.7 m. The maximum volume placed at any transect was 28.6 m³ m⁻¹ of shoreline length. Erosion of the fill occurred rapidly, with formation and landward migration of a conspicuous scarp. The largest significant waves during the time series study were 0.30 m, associated with a mean onshore wind speed of 11.3 m s⁻¹ (maximum 18.2 m s⁻¹), which caused a foreshore volume loss of 0.9 m³ m⁻¹ of shoreline length. Sediment transport, monitored using a trap placed 55 to 62.5 m west of the bulkhead, was always to the west, away from the structure. The highest rate of measured sediment transport, 1.42 m³ h⁻¹, was associated with a significant mean wave height of 0.26 m and mean current velocity of 0.19 m s⁻¹.

The edge of the upland 18 months after the fill was placed in front of it had retreated up to 4.6 m farther landward than the edge of the upland prior to fill emplacement. Movement of sediment alongshore, downdrift of the fill, occurred as wave-like pulses, extending the active foreshore bayward, causing accretion of the inner low tide terrace, burying marsh peat outcrops on the foreshore and creating a higher and wider washover platform on the marshes. Nourishment as a point source caused landforms downdrift to undergo stages, from erosion (pre-nourishment) to accretion to stability (with throughput of sediment alongshore) to erosion again. The time of each stage can be related to nourishment periodicity and the significance of the stage, in terms of topographic change, can be related to the volume of sediment added.

Dredging of navigation channels can supply sediment and compensate for sediment starvation by structures built to protect marinas. At Sailors Haven, the presence of high quality beach sand in the channels and the requirement for periodic maintenance dredging provide a ready sediment source. The requirement to dredge makes losses in the dredged channel moot and provides a windfall benefit

to dredging. The similarity of fill sediment to native sediment helps reduce negative impacts on fauna. Burial of biota on the low tide terrace by direct placement of the fill is a short term effect that would also occur under natural conditions if overwash and inlet formation occurred. Delivery of sediment from the fill area to downdrift areas occurs through natural wave and current processes, allowing for adaptation by fauna. If maintenance nourishment could occur more frequently and in smaller volumes, burial of the low tide terrace and fluctuations in accretion-erosion cycles downdrift could be reduced.

Accretion or erosion of small volumes of sediment can result in substantial rates of shoreline change in low-energy environments. It may be difficult to restore and maintain coastal landforms and habitats to specific target states at a given location, but restoring the longshore sediment budget can allow those locations to undergo cycles of accretion and erosion, creating a variety of landforms and habitats where only erosional forms existed previously. Alternatively, nourishment could occur more frequently and in smaller volumes to reduce fluctuations in accretion-erosion cycles.

Acknowledgments

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Introduction

Availability of sediment is an important element in sustaining coastal landforms (Orford and Pethick, 2006; Cooper and McKenna, 2008; Morris, 2012), and sediment budget studies are a time-tested means of evaluating the relationship of sediment availability to coastal processes and landform size, morphology and tendency to accrete or erode (Kana, 1995; Rosati, 2005; Psuty et al., 2014). Estuarine shorelines often erode at high rates, despite relatively low wave energies (Singewald and Slaughter, 1949; Byrne and Anderson, 1977; Kraft et al., 1979; Ward et al., 1989). In many cases, erosion is caused or exacerbated by reduction of sediment inputs from updrift because nearby uplands are armored by shore-parallel protection structures and contribute no new sediment or because movement of sediment already in the beach system is interrupted by shore-perpendicular structures. On barrier islands and spits, shore protection projects on the ocean side can prevent sediment inputs to estuarine shorelines via overwash, inlet formation and migrating dunes.

The most common past response to erosion on estuarine beaches was construction of seawalls, revetments and bulkheads (Nordstrom, 1992). Bulkheads are especially common because they are affordable, provide protection in limited space, and need not alter the bay bottom (Nordstrom, 1992; Shipman and Canning, 1993; Macdonald et al., 1994; Douglass and Pickel, 1999; Taborda et al., 2009). Construction of bulkheads can result in (1) loss of the beach due to placement of the wall on it; (2) passive erosion, which is narrowing of the beach as the natural regional shoreline migrates landward; and (3) active erosion because of intensification of surf zone processes by wave reflection (Pilkey and Wright, 1988). Walls that extend out onto the beach or seaward of it can also function as groins (Kraus, 1988), trapping sediment on the updrift side and preventing it from nourishing beaches downdrift.

Shore-parallel structures that prevent delivery of sediment from the upland to the beach or interfere with throughput of sediment alongshore restrict natural long term evolution of the coast (Kraus and McDougal, 1996). Consequently, Basco et al. (1997) suggest that stakeholders who construct a wall could be required to artificially nourish the beach with a volume of sediment that represents a calculated annual loss. This action is rarely accomplished as a condition of bulkhead construction, but it remains a feasible option for future use.

One location where this kind of compensatory artificial nourishment may be feasible is near marinas, which are often protected by bulkheads and often extend out into the water, restricting sediment transport alongshore. Maintenance dredging provides an opportunistic source of sediment that can be used to counteract sediment imbalances (Silveira et al., 2011; Brutsché et al., 2015), including those caused by marina structures. Beach nourishment is now considered the principal means of shore protection in many countries, and case studies of projects on high energy shores are numerous (Hamm et al., 2002; Hanson et al., 2002). Documentation of volumes and purposes of beach nourishment and fates of fill sediment in estuaries, in contrast, is lacking (Nordstrom, 1992; Shipman, 2001; Jackson, et al., 2002; Jackson et al., 2010). Several differences between ocean and estuarine beaches occur due to the lower wave energies in estuaries. Rates of sediment transport on estuarine beaches are generally less than on exposed beaches; the landforms are likely to be lower,

narrower and have less volume; the landforms and habitats that characterize the shoreline are more heterogeneous because trees and marsh substrate can survive wave attack and provide a different land/water contact from the beach/dune contact that is ubiquitous on exposed sandy coasts; and the drift cells are shorter and more isolated because of the persistence of small topographic barriers such as trees and peat outcrops (Nordstrom, 1992). How these estuarine beach characteristics evolve after the addition of sediment in beach nourishment operations is unclear.

The purpose of this report is to evaluate whether establishing a feeder beach to reinstate the sediment budget adjacent to a bulkhead is a feasible solution for addressing future erosion problems along sandy estuarine shores. The questions addressed here are (1) how fast does the new fill move out of the placement area; (2) how does the transported fill change coastal landforms downdrift; (3) are the volume and frequency of emplacement that are required for maintenance of landforms related to dredging needs; and (4) can the configuration of the fill mimic natural environments and minimize adverse environmental impacts? This report addresses the physical changes to the shore. A companion report that will be produced after this one, evaluates the impacts of these change on biota.

The feeder beach was created at an eroding estuarine shore at Sailors Haven Marina within Fire Island National Seashore in Great South Bay (Figure 1a). The Seashore is managed by the National Park Service (NPS). The sediment was obtained from the navigation channel leading to the marina and placed on the west side of it. Topographic data were gathered periodically over an 18 month interval from 28 October 2011 until 29 April 2013 to determine the evolution of the feeder beach and its ability to function as a natural physical component of the shore system. Daily changes in wind and wave conditions and beach changes and sediment tracer and trapping experiments were gathered in a 24 day instrumented study conducted in March and April 2012.

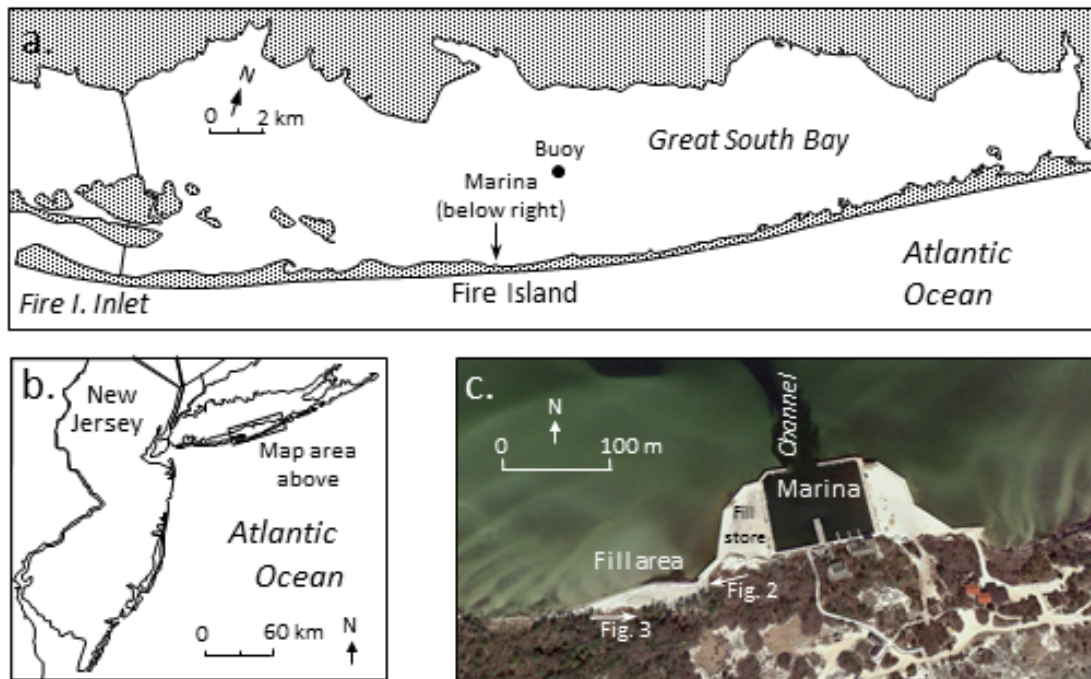


Figure 1. Sailors Haven study area, Fire Island, New York.

Study area

Site characteristics

Much of the bay shoreline of Fire Island is eroding, with an average long-term rate of about 0.3 m yr^{-1} and a maximum long term rate over 1.0 m yr^{-1} (Leatherman and Allen, 1985). Bluff erosion in a given year can be over 3 m (Nordstrom et al., 2009). Conspicuous evidence of erosion along the bayshore is seen in the accumulation of fallen trees and woody debris on the beach fronting forested uplands and outcrops of peat representing the remnants of former marshes in low-lying areas. The shoreline on the west side of Sailors Haven Marina is a conspicuous example of these conditions, where segments of eroding *Phragmites australis* marsh are separated by eroding woodlands (Figure 2). Erosion west of the marina has been causing loss of the Sunken Forest, a globally rare maritime holly forest (Edinger et al. 2014) managed as one of the principal visitor sites on the island.



Figure 2. The eroding upland (left) and *Phragmites* marsh (right background) west of Sailors Haven Marina, looking west in December 2014.

Fetch distances for generation of waves at the fill site are 12 km to the northwest and 15 km to the northeast. Mean tidal range is 0.21 m; spring tidal range is 0.24 m. Water depths in the bay are often less than 1.5 m within 1 km of the shoreline. The offshore zone is characterized by sandy sediments

organized into a series of transverse bars with an orientation (Figure 3b) that indicates they are primarily shaped by northwest winds during low water levels. The marina (Figure 1c) is protected by a wooden sheet pile bulkhead that projects about 115 m into the bay. The sides of the bulkhead are comprised of a series of segments with different orientations relative to shoreline trend. The landward bulkhead segment on the west side is built at a 30 deg angle to the shoreline to displace the location of wave scour farther west. The differences in orientation along the sides of the structure result in a complex pattern of wave reflection.



Figure 3. Characteristics of the Sailors Haven site in recent years. Panel b indicates locations of the long term profile lines singled out for detailed discussion in the text (Figure 8). The zero line for profiles was landward of the bulkhead near the east end of the eroding upland. The initial fill extended from the 0 m line to about the 75 m line.

A previous field study conducted several hundred meters west of this site provided insight to sediment mixing depths, longshore transport rates, and relationships between waves, winds and

beach profile changes (Sherman et al., 1994; Jackson et al., 1993 Nordstrom et al., 2003). Profile data from a study of annual erosion rates at selected bulkheads at Fire Island over the 4 yr period 2004-2008 (Nordstrom et al., 2009) reveal a an annual retreat rate of 1.3 m yr^{-1} of the top of the upland bluff just west of Sailors Haven marina (depicted in Figure 2) and a maximum one-year retreat prior to this study of 2.4 m, occurring 2004-2005.

Seventeen communities exist as developed enclaves within the Seashore. Most of the bay shore of these communities is protected by bulkheads. Most bulkheads were built on high ground that would normally erode and provide sediment to nearby beaches. Erosion problems on the bay are exacerbated by the lack of sediment input from the ocean side of the island via migrating dunes, overwash and inlets that have all been restricted by artificial construction or maintenance of dunes to protect oceanfront houses. Overwash can reach the bay shore in narrow portions of Fire Island that are managed as natural areas. Hurricane Sandy, occurring 29 October 2012, created an inlet 19 km east of Sailors Haven and delivered sediment to the bay, but no overwash reached the bay near the marina, where the island is about 300 m wide and has high dunes on the ocean side. NPS policy allows natural processes to occur where possible but allows intervention to redress erosion accelerated by human actions (NPS, 2006). The erosion problems at bulkheads are considered of sufficient concern to warrant human intervention.

Access to Fire Island by road is restricted, so marinas are critical to visitor use. Maintenance dredging of access channels is necessary to maintain them. Periodic dredging can supply sediment to use as beach fill, but New York State Department of Conservation (NYSDEC) regulations restrict placing beach fill below mean high water because it would cover benthic habitat. The perceived losses by burial have been identified as a reason for lack of categorical acceptability of nourishment projects in estuaries in other states as well (US Army Corps of Engineers Baltimore, 1980; US Army Corps of Engineers Seattle, 1986; Shipman, 2001). As a result, bulkheads built above high water have been the common response to erosion in developed communities on Great South Bay. The project evaluated here is thus the first project in the state to evaluate the feasibility of using a feeder beach to reestablish the sediment budget on an estuarine shore.

The fill design

The high rate of erosion on bay shores means that restoring new habitats to specific target states and maintaining them in a stable condition is not achievable as a permanent solution by implementing a single nourishment project. Theoretically, shorefront resources can be protected if the beach is maintained through subsequent nourishment projects. Reestablishing the sediment budget using a feeder beach next to a bulkhead is considered restoration of the process whereby a landform can be maintained. The concept of “permanence” then translates to providing the periodic sediment inputs that allow habitats to evolve, rather than maintaining the habitats as stable features.

Nourished beaches are often built to natural berm elevations to allow natural processes to form an equilibrium beach and prevent formation of the scarp that often develops when a higher beach fill erodes (Brutsché et al., 2015). The initial plan called for a design beach that would mimic the antecedent natural configuration of the eroding shore and was 200 m-long by 4 m wide and 1.5 m above the height of the low tide terrace. This design was intended to keep the fill close to the

bulkhead end and create a beach at about the height of a natural beach and narrow enough to allow swash uprush during storms to periodically reach the base of the bluff and deposit wrack on the backshore. In this way, the sediment deficit caused by the bulkhead could be compensated at the location most adversely affected, and the fill sediment could feed adjacent portions of the shore by natural processes, without allowing an exotic environment to evolve between the foreshore and the previously eroding upland. Emplacement of fill had to occur between the beginning of October and end of January to avoid impacts on threatened and endangered species and essential fish habitat.

The fill was emplaced by 14 November 2011. The project, as implemented, differed from the design in the length and height of the fill. NPS ownership of bottom lands extends only 100 m from the bulkhead end, so sediment was placed in a higher and wider fill with a short distance alongshore to maximize the amount of sediment placed within the limited length allowed (Figure 4).



Figure 4. The shoreline west of the fill site, looking east on 20 November 2011, just after fill placement and reshaping by bulldozers.

Subsequent events revealed that this method of placement was not worse than the original design because of the rapid rate of removal of the fill, as discussed below. Large woody debris was removed from the foreshore and inner low tide terrace to facilitate emplacement of the fill and its reworking by bulldozers. The general configuration of the fill mimicked an un-vegetated upland of about the same height as the previously eroding bluff. About 1,100 m³ of excess fill remaining from the maintenance dredging was stored inside the bulkhead west of the marina. The quantity of sand

emplaced on the shoreline was 1,747 m³ based on the pre-fill and first post-fill profile transects surveyed in October and December 2011.

Methods

Sediment samples were gathered before and after placement of the fill to determine whether the fill placed on the beach is similar to the native materials. Shore-perpendicular topographic profiles were monitored before placement and for 18 months thereafter to identify changes in beach morphology, quantify amounts of sediment removed from the fill area, and identify locations and volumes of deposition downdrift. The focus of this paper is on long-term changes (seasons and years), but a field study of daily changes in beach processes and responses conducted during the late winter/early spring storm season of 2012 provided insight to the relationship between daily changes and longer-term changes.

Sediment samples

Bulk sediment samples were taken to a depth of 50 mm at 20 m intervals for a distance of 100 m alongshore on the wave- reworked foreshore and inner low tide terrace prior to the fill on 28 October 2011 and the wave-reworked foreshore and the un-reworked fill on 22 December 2011. All sediment samples were washed, dried, split and run through a sonic sifter at 0.25 ϕ intervals, and mean grain size and sorting were calculated (Folk 1974).

Long-term topographic study

The topographic profiles were surveyed by rod and transit rather than GPS because the extensive tree cover in the uplands and *Phragmites australis* stalks in the marshes interfered with satellite signals. Profiles were monitored prior to fill placement (28 October 2011) and after passage of about 5 weeks (22 December 2011). This time period was selected to allow the bayward portion of the fill to equilibrate to wave conditions by forming a wave-reworked foreshore. The profiles were repeated about 5 months (5 April 2012), 12 months (17 October 2012) and 18 months (29 April 2013) after fill placement. Profiles were not conducted after April 2013 because all fill had left the placement area and the upland had eroded beyond the pre-fill position. Profile transects extended from a baseline landward of the limit of wave attack out onto the low tide terrace. The baseline was parallel to the regional trend of the shore prior to placement of the fill. Transects were spaced at 5-m intervals alongshore from a location within the portion of shore protected by the bulkhead to a distance of 160 m to the west (31 total profiles). A transect was added at 175 m on October 2012 (resulting in 32 total) when it was apparent that the accretion lobe from the fill was migrating to that location. At some location alongshore, the volume of sediment captured in profiles alongshore and across the shore is so limited its effect on morphology or significance for habitat is obscure. The number of transects and their lengths were based on the expected spatial limits of transport of the fill. These dimensions were selected to allow the field team to survey the sites in 1 to 2 days each deployment. Some of the sediment removed from the fill area was transported out of the monitoring grid to the west, but the shoreline beyond the end of the initial grid did not reveal accretion until 29 April 2013.

Measurements were taken across the shore at 2-m intervals on 23 December 2011 and at breaks in slope on other days. The shore within the study area is characterized by two wooded uplands alternating with two *Phragmites australis* marshes (Figure 3a). Four profile transects, identified by their distance alongshore (Figure 3b), were selected here as representative of topographic changes in

these four segments. Area changes between successive profiles were calculated and converted to volume, expressed as $\text{m}^3 \text{m}^{-1}$ of beach. Total volumes along the shore were calculated by assuming each profile represented change 2.5 m on each side of it. These volumes were plotted to reveal trends through time. Wind conditions during the 18 month period were taken from the Great South Bay Buoy Number 1, maintained by Stony Brook University in the middle of the bay (Figure 1a). These data are presented here as daily averages.

Time series of daily processes and responses

The time series study was conducted 11 March to 7 April 2012. This period was selected because wave energies are high at this time of year, and the beaches are relatively free of the wrack accumulations that can interfere with instruments. Wind speed and direction were monitored using a Gill 3-cup anemometer and microvane mounted on a mast at 2.65 m above the surface near the northwest end of the bulkhead but landward of it to avoid wave splash (Figure 5). Wave heights and water levels were monitored using five mini-pressure transducers (Druck PDCR1830) placed initially on the foreshore (Instrument Location 1, Figure 5); at the break in slope between the foreshore and low tide terrace (Location 2); on the low tide terrace 60 m from the baseline (Location 3), 100 m from the baseline (Location 4); and bayward of the end of the bulkhead 137 m from the baseline (Location 5). Currents were measured with four current meters co-located at Locations 1-3 and 5. The two inner current meters (Locations 1 and 2) were mini electro-magnetic current meters (Valeport 802) with a 3.2 cm discus sensor initially deployed 5 cm above the bed. The current meters placed farther offshore (Locations 3 and 5) were Acoustic Doppler Velocimeters (ADV) placed 15 cm above the bed. Most of the instruments were monitored along a main instrument line perpendicular to the shore and placed near the middle of the 100 m long fill. Location 5 was farther offshore and 25 m east of the main instrument line to better identify the likelihood of sediment moving into the navigation channel. Data were recorded at 8 hz in 20 min bursts on the hour on most days and as a continuous record when sediment traps and tracers were deployed. Visual observations of wave and current patterns were taken near the end of the bulkhead on 25, 26 and 29 March to determine the effect of the bulkhead on wave reflection during winds from the northeast, north and northwest.

Two micro-topographic grids (Figure 5) were established during the 28-day deployment to evaluate the small elevation changes that occur over daily and storm cycles and to evaluate whether the fill moved in lobes or as a continuous throughput with little change in form alongshore. The grids were placed right at the west end of the fill and 50 m west of the west end of the fill. The west grid was located where the upland had been eroding and fallen trees had accumulated on the beach. Each grid consisted of three transects spaced 5 m apart, with sampling points at 1 m intervals across the shore. Measurements were taken from the tops of 10 mm diameter steel rods driven into the sand. These rods enable measurement of changes in elevation to within 0.5 mm. A loose-fitting washer was placed over the rods to determine depth of sediment activation as described in Greenwood and Hale (1980) and Jackson and Nordstrom (1993).

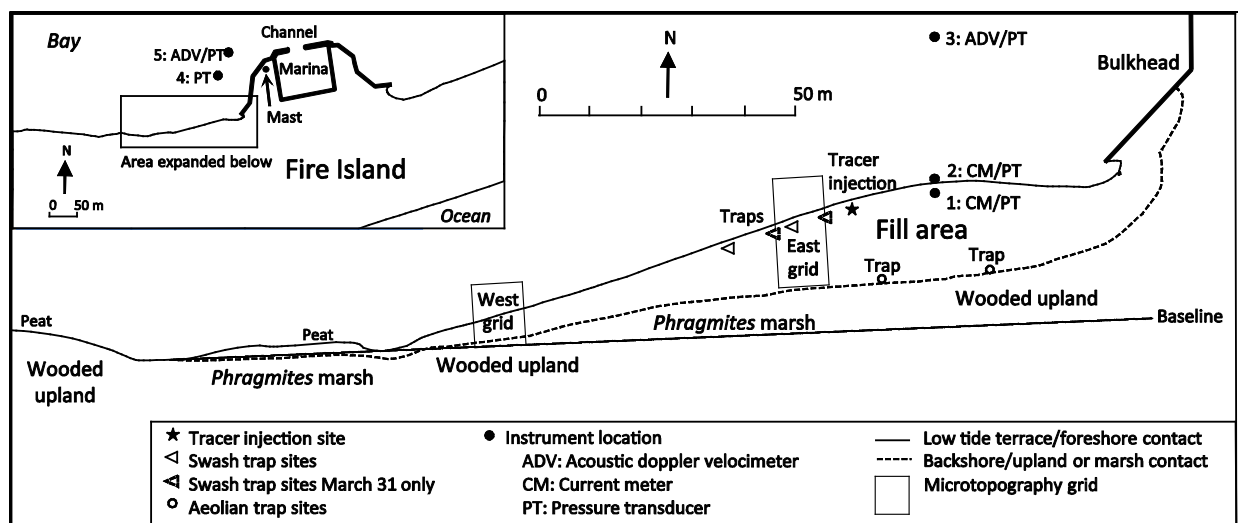


Figure 5. Locations of instrument sites 1-5, tracer injection sites, sediment traps and microtopography grids used during the time series study March-April 2012.

Measurements of the quantity of sediment in transport in the mid swash zone were made using a total load streamer trap. Trapping occurred on four high energy days (mean onshore winds $>6.0 \text{ m s}^{-1}$) on March 25 (two different time periods), 26, 31 and April 2. A trial run was conducted on March 24. Two of the trapping experiments were conducted when winds were from the northeast and dyed sand tracer was deployed. The other studies were conducted when winds were from the northwest, north and northeast. The trap was placed half way between the line of breaking waves and the upper limit of swash and was located downdrift of the main instrument line to enable correlation of currents with sand in transport. Offshore wave heights were derived primarily from the pressure transducer at Location 5 because that transducer provided the most complete record throughout all trapping periods. Longshore current data are primarily from the current meter on the upper foreshore (Location 1). The current meter near the break in slope (Location 2 was used if the upper current meter was not immersed. The trap was deployed at irregular times on the first two days and at 5 min intervals beginning the afternoon of 25 March. Ten waves were sampled on each deployment, and the number of deployments in a series varied from 8 to 17, yielding data for 80 to 170 waves per event. Trapping ceased when process conditions appeared to begin to change with drop in water level or shift in wind direction.

Streamer traps are hydraulically efficient and can provide reliable estimates of sediment flux in the surf and swash zones (Kraus and Dean 1987; Masselink and Hughes 1998; Wang 1998; Wang et al. 1998a, b). The mean error of this kind of trap is calculated as 10%, with a standard deviation of 9%, based on differences in trap weights of side-by-side measurements (Edwards 1997). The trap has a 0.1 m wide, 0.8 m high opening and a 1 m-long net composed of 0.1 mm nylon mesh. Trap height is higher than the depth of the swash, resulting in a complete sampling of both suspended and bed load the water column. Visual estimates of the distance between the breaker line and the upper limit of swash were taken periodically during trapping to characterize the width of the active swash zone. Locations of these upper and lower swash limits were evaluated over at least one minute using the 1-m stakes in the east microtopography grid (Figure 5) as reference points. Angle of breakers relative

to beach orientation in the trapping zone was determined using a compass to sight on the modal crest orientation of waves breaking over about a one minute period.

A previous comparison of trapping rates across the swash and surf zones of an estuarine beach (Lampe et al. 2003) revealed that rates in the turbulent breaker and swash zone can be 7-14 times greater than on the lower foreshore or nearshore, where the waves do not break, even when longshore currents are as fast in those other locations. Accordingly, trap data from the swash zone provide a rough estimate of the total quantity of sediment transported through the system. The quantity of sediment in traps in grams was multiplied by the width of the active swash zone and by the number of waves occurring in an hour (based on the wave period) to yield a transport value in g hr⁻¹ and converted to m³ hr⁻¹, where 1.0 m³ of beach sand = 1,529.2 kg.

Five kilograms of dyed sand were placed on the surface of the swash zone prior to trapping on 25 March (green tracer) and 31 March (red tracer) to provide insight to the way sand is dispersed alongshore. Sediment taken from the beach was washed, dried and coated with a mixture of fluorescent paint and toluene following the procedure in McArthur (1980). Results in Nordstrom et al. (2003) revealed that 5 kg of tracer is sufficient for deployment on this beach during storms with wind speeds up to 10 m s⁻¹. The tracer injection position was located 50 m from the end of the bulkhead (Figure 5). Trap distance from the injection point was 12.5 m on 25 March and 5 m on 31 March. Bulk samples of the former middle of the active foreshore were taken at 1 m intervals alongshore for a distance of 100 m downdrift of the injection location at low water following trapping to determine tracer concentrations within the beach. Samples were taken using 50 mm diameter tube cores. Visual tracer counts were made in the lab on core subsamples under an ultraviolet light. Relative amounts of sediment moved were determined by number of tracer particles per gram of sediment in the portions of cores corresponding to depths of sediment activation revealed by depth of activation rods in the nearby east micro-topography grid (Figure 5).

The effect of transport of the fill by wind was evaluated by (1) field mapping locations of accretion of wind-blown sand; (2) obtaining representative depths of accretion landward of the fill; and (3) installing vertical cylindrical sand traps at the landward margin of the fill (Figure 5) to quantify aeolian transport during a strong onshore wind. The limits of aeolian inundation landward of the fill were estimated and sketched with reference to the datum monuments on each profile line. Depths of accretion at representative sites were identified by digging from the surface of the aeolian deposits to the surface of the pre-fill upland. The former surface had a dense cover of vegetation and leaf litter, facilitating identification of the depths of accretion.

The aeolian sand traps have a trapping height of 0.37 m and width of 43.0 mm. Cylindrical vertical traps are a standardized method for measuring aeolian transport in the field and are portable and easily installed (Sherman et al., 1998). Field testing of these traps reveals that they are efficient when adjusted for scour over 10 min intervals (Jackson and Nordstrom, 1997) as done during this study. Two traps were placed at the landward edge of the fill for 50 min during strong onshore winds occurring 26 March. The emplacement and removal times of each trap were recorded individually and data were reduced to total values averaged as kg m⁻¹ hr⁻¹.

Results

Wind characteristics during the 18 month study

The shoreline trend at the site is nearly east-west (azimuth 86-266), and offshore winds from the south do not contribute to generation of large bay waves. For example, Hurricane Sandy, occurring 29 October 2012, caused extensive erosion on the southeast-facing ocean beaches but resulted in less erosion on the bayside than other storms that occurred that season. The strongest onshore winds over the 18 month period (Figure 6) were from the west and north. The relatively great frequency and magnitude of winds blowing at an acute angle from the west normally would be expected to contribute to longshore sediment transport to the east. This potential is rarely achieved near Sailors Haven Marina due to wave reflection off the bulkhead, as identified in observations conducted during the time-series study below. Strong winds blowing nearly directly onshore (from the north) undergo the least refraction, so their ability to generate relatively large waves is great.

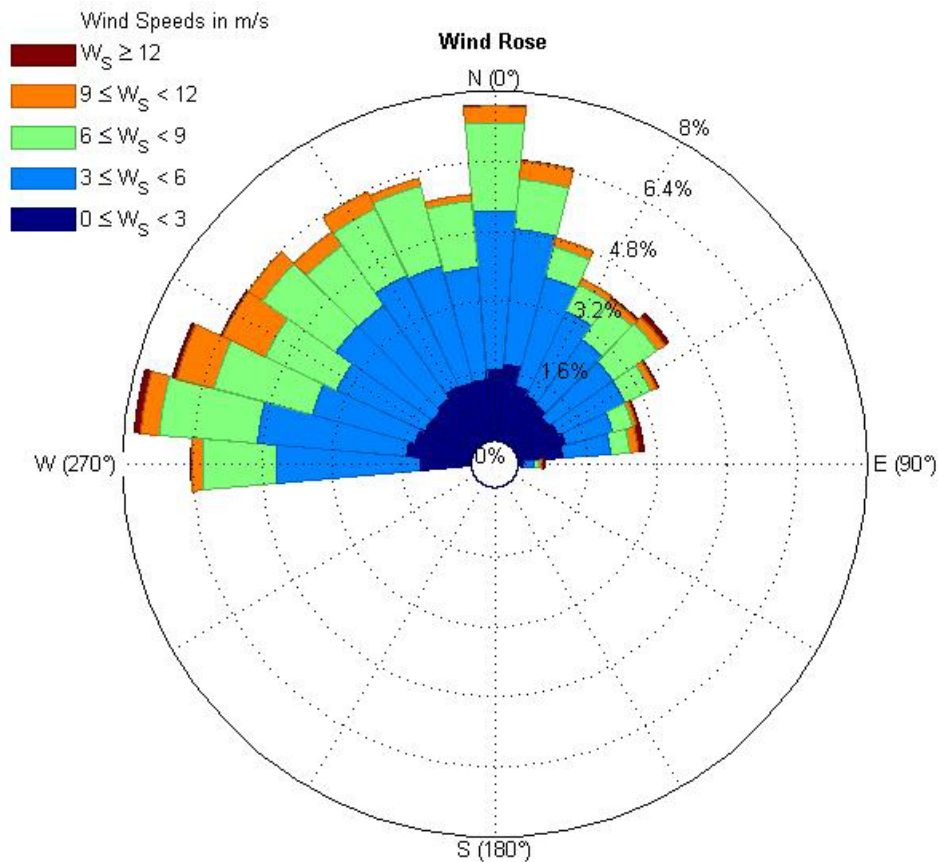


Figure 6. Wind rose for winds blowing onshore at Sailors Haven. Data are hourly averages from the buoy on Figure 1a for 1 November 2011 to 30 April 2013. The shoreline trend is azimuth 86-266.

Grain size differences

Mean grain sizes of sediment gathered on the foreshore before the fill was placed and sediment remaining 39 days afterward (Table 1) are similar because of winnowing of the fine fractions of the fill by swash action. Sediments in the fill are finer and better sorted than sediments on the active foreshore and are closer in size to sediments on the low tide terrace prior to fill. The sediments in the fill and on the low tide terrace may be similar to each other because the dredged channel is a sink for sediments moved along the low tide terrace.

Table 1. Mean grain size and sorting and range of values for the 5 samples taken along two cross-shore locations pre-fill (28 October 2011) and about a month after fill (22 December 2011). Statistics represent the means of the 5 samples (upper row) and the maximum and minimum value of individual samples (lower row).

Day/location	Pre-fill, low tide terrace	Pre-fill, foreshore	Post fill, foreshore	Post fill, top of fill
M _z (mm)	0.35	0.44	0.44	0.32
Range	0.40 to 0.29	0.51 to 0.33	0.50 to 0.38	0.36 to 0.29
S _i (□)	0.60	0.69	0.59	0.52
Range	0.74 to 0.50	0.96 to 0.52	0.68 to 0.50	0.59 to 0.34

Long-term changes in volume

The greatest increase in beach volume (Figure 7) between the time of fill placement (28 October 2011) and the first beach profiles (22 December 2011) is within the fill area (up to 29.0 m³ m⁻¹ at Transect 50). Accretion extended at least to the 125 m transect within Upland 2 by 5 weeks after the fill was placed, indicating rapid spreading. Volume loss occurred at Transect 130. Before the fill was placed, evidence of erosion was seen along the entire length of the shore, either in scarps in the upland or in the marsh peat, so it is possible that the fill diminished the pre-fill loss rate at Transect 130. The fill may have prevented overall losses at Transects 120 and 125 (Figure 7), but the ambient loss rate prior to the fill is unknown.

Transect volumes from 22 December 2011 to 5 April 2012 (Figure 7) reveal losses in the fill area, accompanied by gains in shoreline segments to the west, with the change in erosion/accretion trend alongshore occurring near Transect 80, just west of the original fill limit. Little or no increase in sediment volume occurred at or west of Transect 150, but it is likely that those transects would have lost sediment during the winter storm season and would have had volume loss without the new sediment inputs from the fill.

Sediment volumes in the fill area in October 2012 (Figure 7) were less than in April 2012, except in the portion of the shore sheltered by the bulkhead (Transects 10 and 15). The minimal change in beach volume in Transects 90-105 fronting Marsh 1 in the 6 months between April 2012 and October 2012 indicates that the beach was a transport surface for throughput of sediment to beaches to the west. The change in trend from relative stability to accretion over the six months shifted alongshore

to Transect 115 and throughout Upland 2, while a sediment balance was maintained at the two transects fronting Marsh 2 (Transects 155-160).

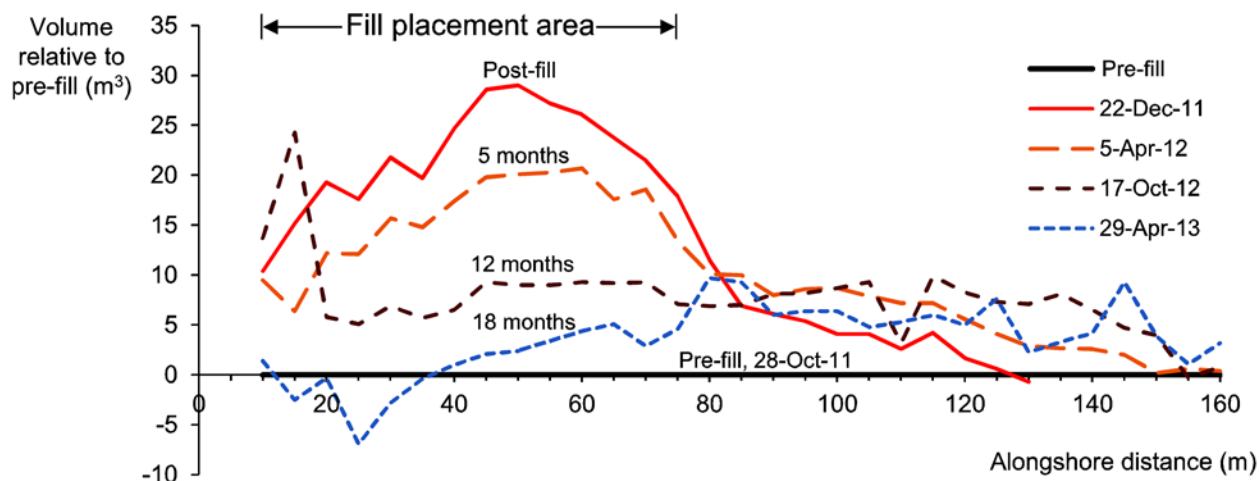


Figure 7. Alongshore differences in sediment volumes at 5-m transects relative to pre-fill conditions (zero line).

Sediment volumes in April 2013 were less than in October 2012 east of Transect 120, except for Transects 80 and 85, just west of the original end of the fill. No loss of original upland occurred west of Transect 40 by the end of the 18 month monitoring period. Transects closer to the bulkhead provided sediment to replace losses to the west, even when some of this sediment came at the expense of the original upland. Accretion or relative stability over this 6 month period occurred at and west of Transect 120 (Figure 7). Data gathered at Transect 175 on October 2012 and April 2013 (not plotted on Figure 7) reveal accretion of $9.4 \text{ m}^3 \text{ m}^{-1}$ at that location over this 6 month period. That volume is roughly comparable to what had previously occurred in Marsh 1 and Upland 2 and provides evidence of continued westward migration of the accretion lobe.

Some losses from the fill were due to onshore aeolian transport. By 16 March 2012, 4 months after the fill, a layer of wind-blown sand had penetrated up to 23 m into the forest along Upland 1 from the location of the pre-fill scarp in the upland. The deposits were commonly 1-3 cm deep, but local deposits 8-13 cm deep occurred on the rising upwind (north) sides of upland slopes, the falling downwind sides of slopes, at obstacles such as fallen tree trunks, and at lobes representing the downwind ends of sand sheets. The rate of transport was reduced in later months by the ever-diminishing width of the eroding fill. A rough estimate of volumes using these observations indicates that less than 50 m^3 of loss from the fill would have been accounted for by aeolian transport.

The reduction of the volume of sediment through time within the fill area can provide an estimate of the longshore transport rate. The bulkhead provides a complete barrier, enabling estimates using cross shore profiles. Transport rates cannot be estimated using profiles farther west because there is no barrier to accumulate sediment. Surveys conducted 22 December 2011 and 17 October at Transects 10 to 75, within the limits of the fill, reveal a mean rate of volume change of $1,053 \text{ m}^3 \text{ yr}^{-1}$.

Long-term changes in topography

The post-fill profile for 22 December 2011 within the fill area (Transect 25, Figure 8a) reveals a bayward advance of the foreshore of about 14 m at mid foreshore. Erosion of the fill after placement was accompanied by formation and landward migration of a conspicuous scarp. The scarp in the upland 18 months after the fill was placed was up to 4.6 m farther landward than it was prior to the fill at Transect 25, although the position of the foreshore was similar to where it was prior to the fill. These changes are similar to changes in profiles taken close to the bulkhead. Profiles from Transect 40 to the west end of the fill revealed rapid erosion of the fill, but there was no loss of the original upland by the end of the 18 month monitoring period. The differences in the east and west portions of the fill indicate that transects closer to the bulkhead provided sediment to help replace losses to the west, even when some of this sediment came at the expense of the original upland.

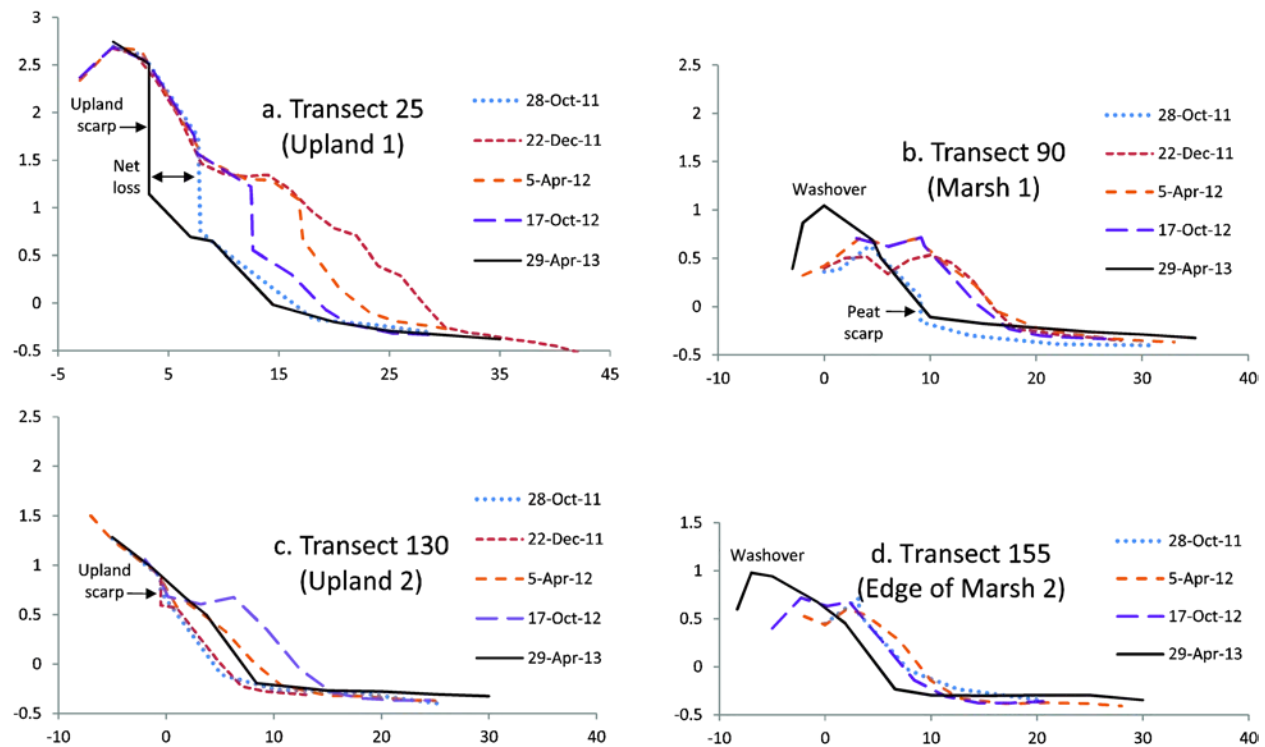


Figure 8. Representative profiles within the fill area (25 m transect), within Marsh 1 just west of it (90 m transect), Upland 2 to the west (130 m transect) and Marsh 2 west of it (155 m transect).

Profile transects along Marsh 1 just west of the fill indicate that the sediment that moved to that segment within the first two months covered the formerly exposed peat. Sediment from the fill continued to replenish losses through October 2012 (Figure 8b) and built up the height of the washover barrier. Storms during the winter of 2012-2013 built the barrier higher and drove it landward, leaving the foreshore in about the same location as prior to the fill but with a greater volume of sediment in the washover deposit and the low tide terrace. The upper surface of the barrier increased about 0.42 m over its pre-fill height at Transect 90 (Figure 8b) and 0.24-0.34 m at the other transects in Marsh 1. This upward accretion increased the effectiveness of the beach as a barrier against flooding and as a reservoir of sand against further erosion. The geomorphic effects of the

sediment throughput fronting Marsh 1 identified in Figure 7 are revealed in the pronounced deposition of the berm in Upland 2 and washover deposit in Marsh 2 to the west by October 2012 (Figure 8 c,d).

The accretion at Transect 130 between December 2011 and April 2012 (Figure 8c) indicates that more than 5 weeks was required for the fill to have a conspicuous effect as little as 55 m downdrift of the end of the fill. Foreshore advance during this period was about 3.5 m (Figure 8c), associated with a volume change of $3.6 \text{ m}^3 \text{ m}^{-1}$. Beach width increased through April 2012 and October 2012, but erosion occurred in the following 6 months. The foreshore in April 2013, 18 months after fill emplacement, was 2.4 m bayward of its location prior to fill at Transect 130 and up to 2.7 m along the shoreline of Upland 2. The upland was better protected against erosion by the sediment input, but the vertical scarp remained at the upper limit of the foreshore (Figure 8c) until it was covered by storm wave sedimentation between October 2012 and April 2013.

Change in the foreshore along Marsh 2 by April 2012 (Figure 8d) indicates that sediment from the fill reached this location within the first 5 months, but the foreshore accretion (1.7 m) was much less than sites to the east. The foreshore eroded back to the 2011 position in the first year. The influence of storms during the winter of 2012-2013 is indicated in the washover barrier revealed on the April 2013 profile, which is landward of the barrier prior to the fill but 0.27 m higher. Despite shoreline retreat during this period, the volume of sediment was conserved in the greater size of the washover deposit and the accumulation on the low tide terrace. The net result over the 18 months of monitoring at Transect 155 was volume gain of $1.1 \text{ m}^3 \text{ m}^{-1}$. This transect underwent conspicuous changes in shape and shoreline position, but it had the least volume change of all transects monitored (Figure 7).

Direct deposit of fill in the project area resulted in burial of the low tide terrace to an offshore distance corresponding to the width of the new backshore. Thereafter, little difference occurred in the elevation and shape of the low tide terrace in Upland Segment 1 as the foreshore eroded landward (Figure 8a). The elevation of the low tide terrace fronting the marsh segments was more variable, possibly because of variations in the permeability of the peat, its patchy exposure and the tendency of the peat to erode in layers. The variability is especially conspicuous in the Marsh 1 segment just west of the fill (Figure 8b), where the peat layer is lower in the intertidal profile and the sediment inputs from the fill are greater. Net accumulation on the low tide terrace was seen on 18 of the profiles and was most common just west of the west end of the initial fill. The greatest cumulative increase in elevation of the low tide terrace was about 0.16 m, which occurred within the marsh segment just west of the fill. The slopes of the zones of accretion on the low tide terrace indicate that the closure depth (where all profiles converge) appears to be about 20 m bayward of the location of the break in slope at the time of maximum foreshore accretion.

Wind and wave characteristics during the time series study

Wind characteristics measured at the vane and anemometer on the mast at the marina 17 March to 4 April (Figure 4) reveal a strong north-northwest component (Figure 9), reflecting the greater frequency of winds from this quadrant in this part of the year. The lack of strong offshore winds reflects the sheltering by the nearby topography and vegetation on Fire Island. The one second averages used to create Figure 9 result in wind speeds that are greater than the daily averages

portrayed in Figure 6. The high frequency of onshore winds during the time series provided great opportunity to monitor changes when wave heights, longshore transport and beach erosion were enhanced. Wave heights during this period (Figure 9) appear relatively low compared to ocean sites, but were high enough to cause conspicuous beach change at the site (Figure 10).

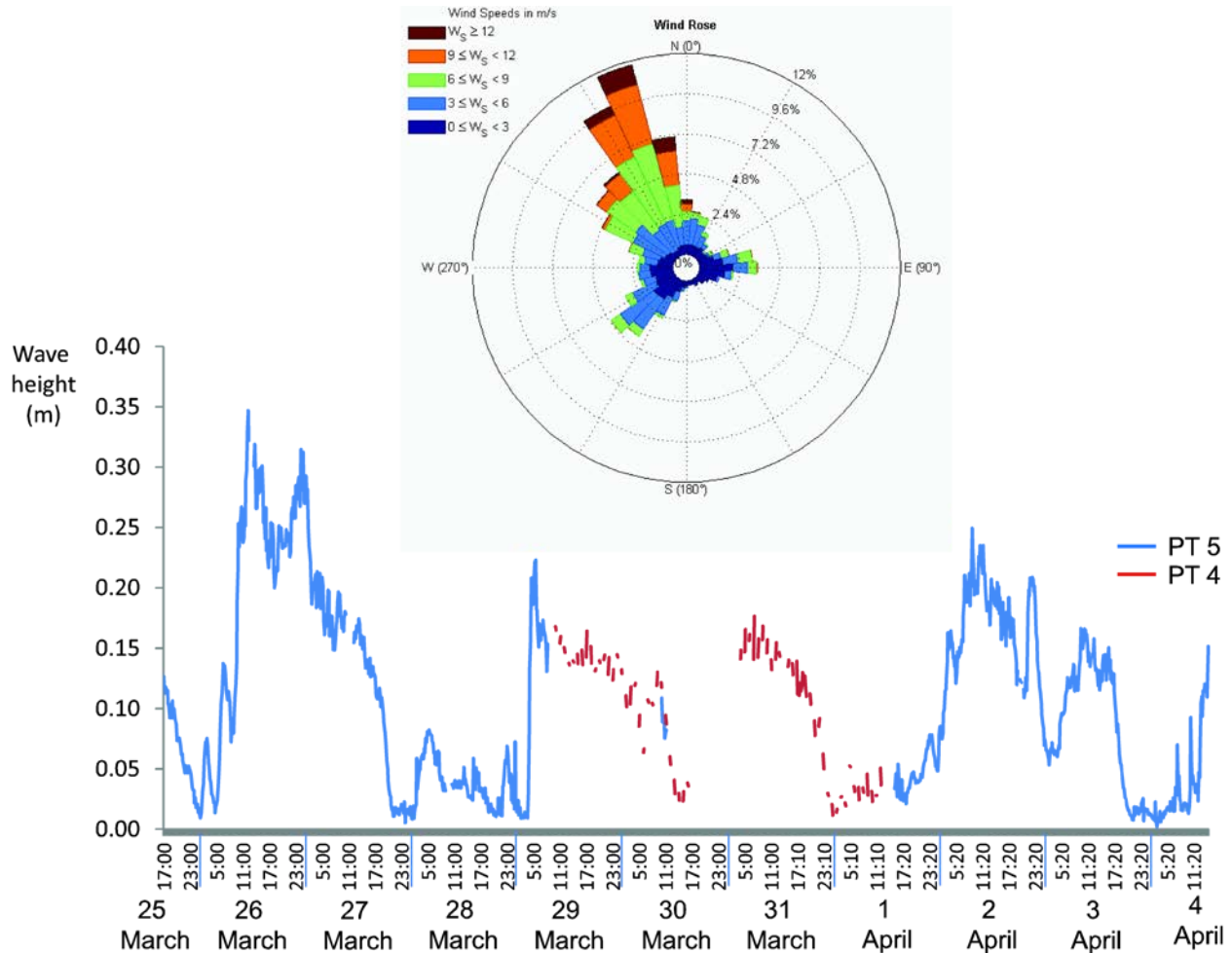


Figure 9. Wind rose and significant wave height from data gathered during the time series study March-April 2012. Wind data are one-second averages of data gathered at the anemometer and vane on the mast at the marina (Figure 4) from 17 March to 4 April 2012. Wave heights are 10-min averages from PT4 and PT5 (Figure 5) from 25 March to 4 April.

Visual observations of wave and current patterns near the end of the bulkhead during the time-series study reveal that the bulkhead contributes to net westerly transport under most high-energy conditions. Observations on 25 March when winds approached from east of shore normal revealed westerly transport right at the end of the bulkhead. Observations on 26 March, when winds approached from slightly west of shore normal, revealed a divergence in current direction, with easterly flow beginning about 14 m west of the west end of the bulkhead. Lower-energy wave conditions on 29 March, when winds approached from the northwest (44 deg west of shore normal) revealed a current divergence about 7 m from the west end of the bulkhead, with flow to the east of it

near the foreshore and a compensating current to the west in the deeper water right at the end of the bulkhead. Wave reflection off the shore-perpendicular portion of the bulkhead was conspicuous during days when winds approached from the north and northwest and contributed to westward flows on the foreshore. The wave and current patterns help explain the sequestering of sediment transported into the open end of the bulkhead (foreground of Figure 2) as revealed in the accretion on the 10 and 15 m transects in October 2012 (Figure 7), as well as the lack of conspicuous deposition just west of the end of the bulkhead.

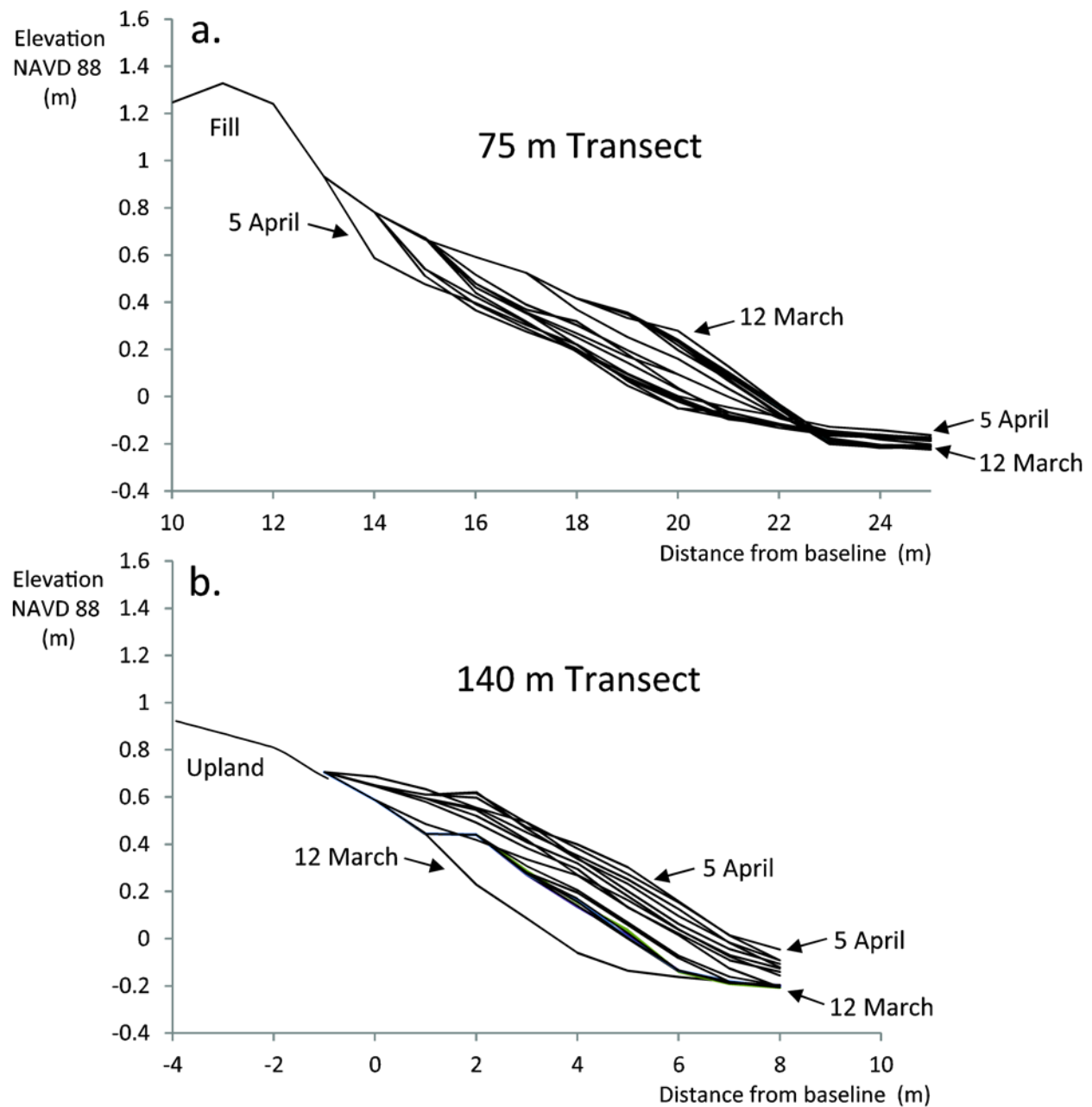


Figure 10. Daily changes in the beach surface measured at 1-m intervals within a representative transect of each microtopography grid 12 March to 5 April 2012.

Daily topographic changes

Measurements at the 75 m microtopography line near the west end of the fill area (Figure 10a) reveal erosion of 2.75 m at mid foreshore from the beginning to the end of the 24 days of monitoring. This amount of foreshore retreat was associated with a loss of 1.6 m^3 in sediment volume per meter of shoreline length. Erosion was greatest during the strong northerly winds (az. 352) on 26 March (1.27 m), resulting in loss of 0.9 m^3 of sediment. Mean wind speed between 14:00 to 14:20 on that day was 11.3 m s^{-1} with a max of 18.2; mean significant wave height at that time was 0.30 m at the pressure transducer at Location 5 (Figure 5). The elevation of the inner low tide terrace at the 75 m transect increased 0.062 m over the 24 day period, when large amounts of sediment were moving along the fill area and onshore winds were strong enough to cause conspicuous erosion of the upper foreshore. Burial of the low tide terrace from transport of sediment offshore from the fill during storms appears to be neither rapid nor deep at this location. Burial depths on the low tide terrace from direct deposit of the initial fill (Figure 8a) was considerably greater.

Measurements at transects within the west microtopography grid revealed deposition during the 24 days. Linear advance of the beach at mid foreshore was 2.95 m at the 130 m transect and 3.55 m at the 140 m transect (Figure 10b). The increase in foreshore width resulted in burial of the inner low tide terrace. This spreading of the fill by longshore transport is conspicuous over the long term (Figure 8b,c,d) and short term (Figure 10b).

Comparison of volume changes within microtopography grids through time (Figure 11) reveal variability of response over spatial scales of 5 m and temporal scales of days. Some evidence exists of pulses of sediment transport passing through the grid at the 5 m scale, revealed especially in the inverse trends of adjacent transects to the event of 4 April (Figures 9,11). Over temporal scales longer than a few days, the overall trends are similar.

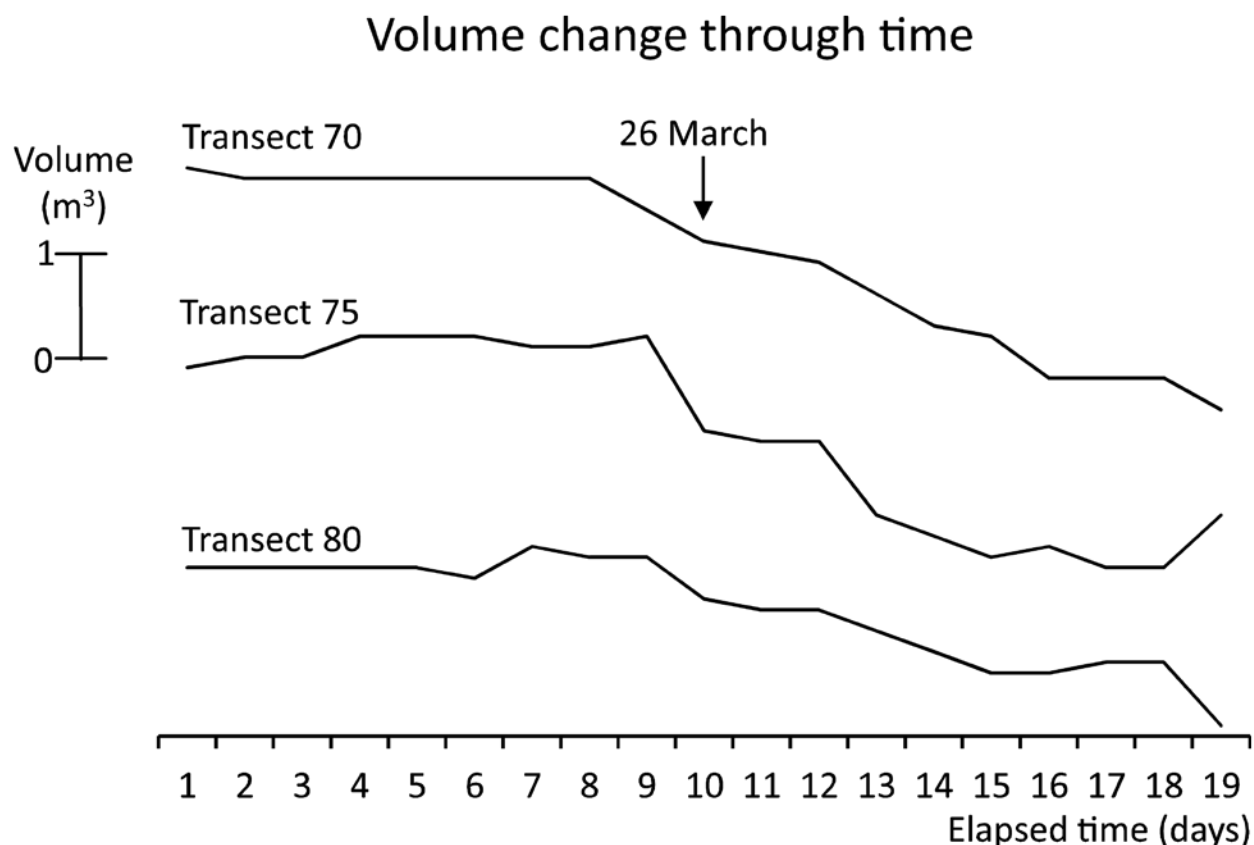


Figure 11. Change in volume within transects in the east microtopography grid 17 March to 5 April 2012.

Sediment trapping rates

Sediment trapping rates (Table 2) are greater than often occur on this beach because sampling days were intentionally selected to represent strong onshore winds with high water levels that allow waves to pass over the low tide terrace without losing much of their energy. The net direction of transport was to the west during all trapping times. The greatest amount of sediment trapped per wave was on 26 March, when onshore wind speeds, wave heights and wave periods were greatest. Considerable variability occurs in the amount of sand trapped throughout each deployment (seen in the standard deviations and coefficient of variation), but the mean weights are generally correlated with the mean wave heights for each trapping period.

Wave heights, in turn, are related to swash widths (wave runup distances) which define the active layer across which sediment is moving. Longshore current velocities were low relative to wave heights on 26 March and 2 April, perhaps because of wind approach that was slightly west of shore normal. The high rates of transport on that day relative to 25 and 31 March may be attributed to the higher wave heights, which could put more sediment in suspension for advection into the swash. The rates of transport are close to those for 26 March because of the greater number of swash events per hour.

Table 2. Wave characteristics and sediment amounts measured during trapping days.

Day and time	25 March 11:09-11:37	25 March 12:34-14:34	26 March 14:55-15:55	31 March 17:45-18:48	2 April 09:28-09:50
Processes during trapping					
Wind direction (az)	058	019	352	060	345
Wind speed (m s^{-1})	7.7	6.4	12.6	8.8*	9.2
Wave height (H_s in m)	0.12	0.12	0.26	0.12	0.19
Wave period (s)	2.6	2.1	3.1	2.4	2.6
Breaker angle (deg)	19	19	27	21	18
Swash width (m)	2.5	2.9	4.8	2.4	4.2
Longshore current (m s^{-1})	0.18	0.18	0.19	0.08	0.15
Trap data					
Number of trap deployments	17	25	12	12	8
Mean (g m^{-1}) per wave	182.4	186.4	345.5	156.5	329.2
Standard deviation (g m^{-1})	141.8	137.2	136.3	74.9	110.6
Coefficient of variation	0.78	0.74	0.39	0.48	0.34
Total transport across active swash zone					
Rate ($\text{m}^3 \text{h}^{-1}$)	0.413	0.606	1.220	0.368	1.252

Wind direction and speed are from the anemometer and vane at the marina (Figure 2). Wave heights and periods are from PT3. Breaker angle is from compass sighting along breakers. Swash width is from visual estimate of 10 significant waves. Each trap deployment represents 10 waves (e.g. 80 waves on 2 April).

*The anemometer was not logging during this experiment, so wind speed was taken from the Great South Bay Buoy (Fig. 1b).

The trapping rates are similar to transport rates gathered on the foreshore of this beach in the past using tracers (Nordstrom et al. 2003) and on other sheltered beaches using similar sand traps (Lampe et al. 2003). The volumes moved may appear small, but even small volume losses can result in conspicuous horizontal change. The rates of movement do not correspond directly to rates of loss in the nearby micro-topography grid because the traps and the grid are at the downdrift end of the fill area, and sediment inputs from updrift can compensate, in part, for losses. Erosion at a specific location alongshore resulting from an individual event can depend on where the apex of the downdrift-migrating lobe occurs (Figure 11).

Tracer results

The dispersion of tracers (Figure 12) is rapid due to their placement right on the surface of the beach. The relatively great quantities of tracer trapped at the beginning of the time series on 25 March (with sampling beginning 5 min after injection) could have been because of its location 12.5 m downdrift. The trap on 31 March was 5 m downdrift of the injection location, and it is possible that a sizeable amount of tracer passed the trap location in the 5 min prior to sampling. Part of the reduction in tracer trapping through time on both days is likely due to burial of the tracer at the injection site during subsequent swash uprushes. Evidence that pulses of tracer concentrations can occur through time is seen in peaks in the record at about 35 min after injection on 25 March and 24 and 55 min after injection on 31 March.

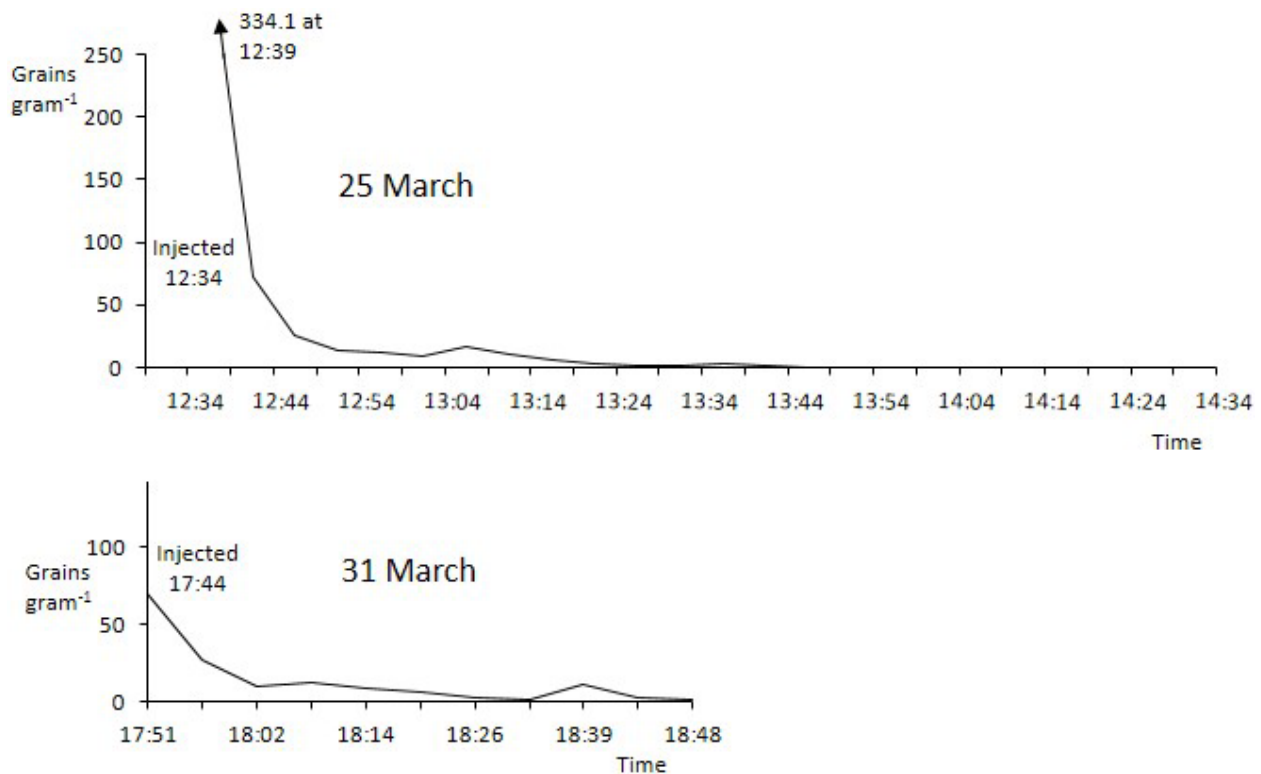


Figure 12. Tracer concentrations through time from trap samples placed at mid swash on 25 and 31 March.

Counts of tracer from cores taken on the exposed beach at mid foreshore after tracer deployment (Figure 13) reveal low peaks of tracer concentration alongshore. The concentrations following the 25 March event are less than following the 31 March event and gradually increase with distance from the injection point. The reason for the difference in recovery may be attributed to the time interval between tracer injection and recovery. Cores were taken beginning 2 hours after trapping on 25 March. Darkness fell just after trapping on 31 March, so trapping began the first daytime low tide after injection. More tracers within the sampling area on 1 April could be due to the greater amount of time for tracer to be mined from the injection point, combined with the low wave heights after the experiment (Figure 9), which would result in little dispersion or burial.

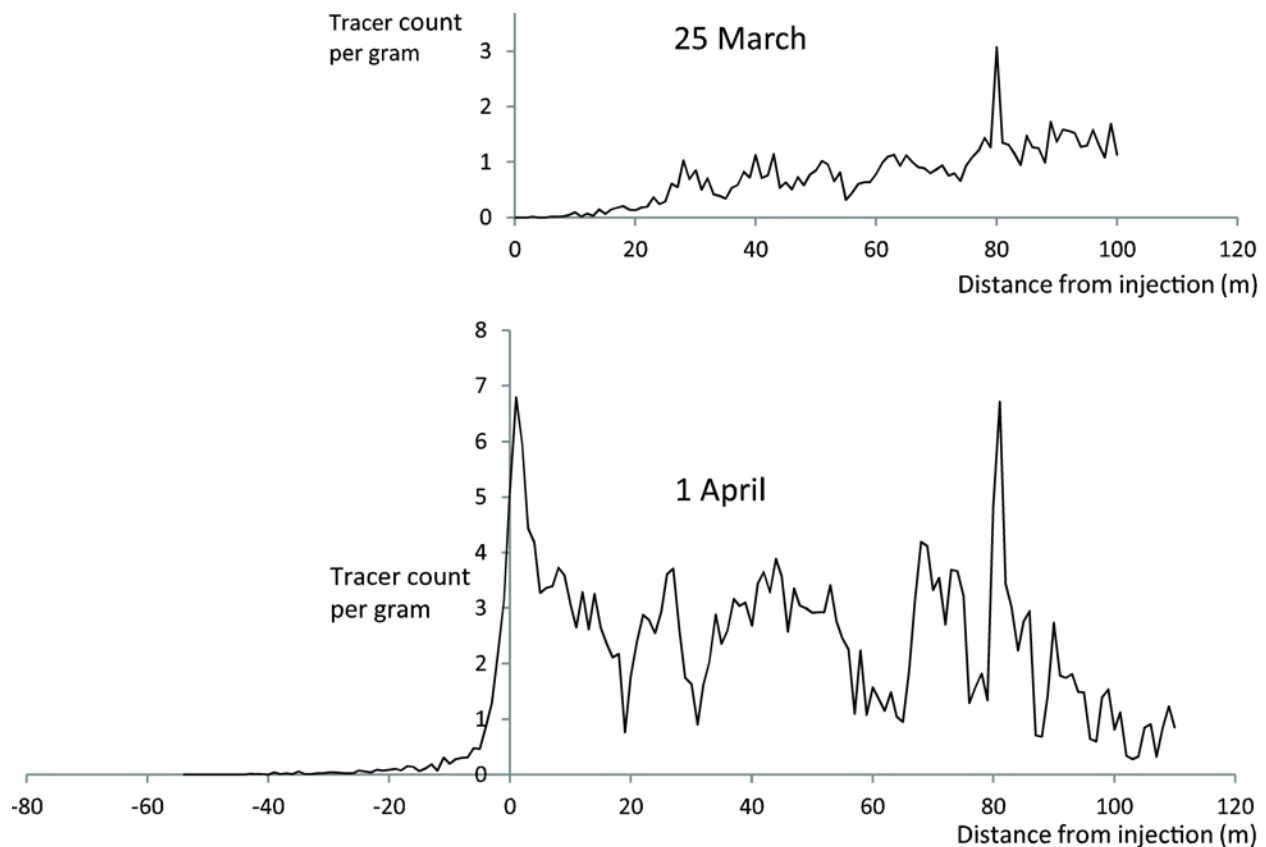


Figure 13. Tracer concentrations in foreshore cores taken after tracer deployments on 25 and 31 March. Positive values are to west. No cores were taken to the east on 25 March.

Aeolian transport

Aeolian transport rates were monitored during the strong onshore winds of 26 March 2012. The quantity of sediment in transport was $7.9 \text{ kg m}^{-1} \text{ hr}^{-1}$. The surface of the fill upwind of the traps had already developed a lag layer of coarser sand, but this lag layer did not prevent sediment entrainment. The rate of aeolian transport was relatively high for an estuarine beach because of the added width of the fill as a source for wind-blown sand. The subsequent rate of transport was reduced by formation of the beach scarp in the fill (Figure 8a), which prevented transport landward from the foreshore, and by the ever-diminishing width of the eroding fill.

Discussion

This discussion evaluates the initial effect of the deposition of fill, the rates of sediment movement from the fill area through the downdrift shoreline, and the way these rates contribute to changes in beach position. Alterations to the beach sediment budget are evaluated in terms of effect on maintaining physical habitats. The changes that differ from ambient erosional conditions include burial of the low tide terrace, increase in the volume of sediment covering marsh peat, burial of woody debris in the water and increased aeolian transport into the wooded upland.

Results indicate that the initial fill buried portions of the low tide terrace out to about 20 m, but rate of removal of fill was rapid, reinitiating erosion of the original bluff and reinstating the area of bay bottom in the fill area in less than 18 months. Sediment from the fill moved alongshore as anticipated, with a portion blown onshore to form a thin layer of aeolian deposition. The increased volume of sediment added to sites to the west created wider foreshores, caused accretion of the inner low tide terrace, buried marsh peat outcrops on the foreshore and created a higher washover platform on the marshes than existed prior to the fill.

The addition of the 1100 m³ of sediment stored landward of the bulkhead in 2011 would have helped address the sediment deficit but would not have overcome the losses before the next dredging project scheduled for December 2015, with an estimated volume of 1140 m³. The negative sediment budget cannot be overcome by channel maintenance alone, but the additional sediment can temporarily protect the pre-existing landscape in the fill area while increasing the sediment budget and levels of protection downdrift. Movement of the pulses of sediment through the system implies that shoreline changes will be periodic and temporary, and post-fill landforms and habitats landward of the beach will not be maintained in situ unless more frequent re-nourishment operations are conducted.

Rates of sediment movement

Previous studies indicate that rates of sediment transport on estuarine beaches are generally less than on exposed beaches, but rates of erosion can be high because the beaches are often lower, narrower and have less volume (Nordstrom 1992). Transport rates can be low in the absolute sense but are greater than rates calculated using existing formulas that may be more appropriate for non-estuarine beaches, where a greater proportion of sediment is transported in the surf zone rather than confined to the energetic swash zone under plunging breakers (Nordstrom et al. 2003).

The rates of movement do not correspond directly to daily rates of profile change in the microtopography grid (Figure 10) because sediment inputs from updrift can compensate, in part, for losses. Sediment throughput does not equate to sediment in residence. Erosion and accretion at a specific location alongshore resulting from an individual event can also depend on where the apexes of the downdrift-migrating lobes occur. Nevertheless, the net effect west of the bulkhead through time is erosion, aided by wave reflection off the bulkhead. The movement of sediment results in conspicuous horizontal change over periods of weeks. It is conceivable that the mechanically emplaced fill is more readily entrained than native material would have been, but the similarity in rates of transport with native material monitored at a site near the marina (Nordstrom et al. 2003) imply that ease of entrainment alone would not account for the high rates of movement.

The rates of transport measured by trapping cannot be directly correlated with the longshore transport rate using semi-annual cross shore profiles taken within the fill zone (Nordstrom et al. 2016), but the numbers can be compared to provide perspective on the magnitude of events monitored in this field study. The duration of events identified in Figure 6 is approximately 12 hours. Multiplying this value by the hourly rates measured on the 5 events in Table 2 and dividing the 1,053 m³ yr⁻¹ estimate from semi-annual profiles indicates that events of this magnitude would have to occur about every 3.7 days. This frequency is achieved in the late fall, winter and early spring. It is also likely that more severe conditions than those monitored can make up for the greater frequency of lower energy conditions in the rest of the year.

Re-establishing the sediment budget

High rates of longshore transport can thwart plans to use beach fill to protect target areas (Sedrati and Anthony, 2014). Rapid removal of fill is usually perceived as a problem because the justification for placement is to provide protection of the upland within the project area or provide recreational amenity (Houston 1996). The fill project at Sailors Haven was implemented to evaluate the effectiveness of a feeder beach for reestablishing the longshore sediment budget, not to create new habitat or recreation space. High rates of loss can be expected at a feeder beach, requiring frequent re-nourishment intervals (Roberts and Wang, 2012). Retention of some of the sediment in the fill area is a desirable outcome, but the ability to replenish sediment losses alongshore without creating excessive deposition in sensitive areas, such as the low tide terrace offshore or saltmarsh habitat downdrift is also important.

Sediment inputs from the ocean side via overwash and inlet creation can inundate bays landward of barrier islands, converting subaqueous habitat to intertidal and subaerial habitat (Lentz et al., 2013; Masselink and van Heteren 2014). Burial is thus a natural occurrence, but it can be relatively rare (many decades to centuries at a given location). Under present conditions at Sailors Haven, with little potential for new inlets to occur or overwash reaching the bay, subaqueous habitat is slowly expanding at the expense of subaerial habitat. The feeder beach helps redress the lack of sediment input to the estuarine shore but at a smaller scale and greater frequency than the storm-associated processes that result in cross-island transfers.

The addition of sediment to the system can be viewed as protection of existing habitat (conservation) or creation of new or more expansive habitat (restoration) depending on the amount of sediment added and the time allowed for colonization by vegetation and use by fauna. Periodic input of sediment at what is essentially a point source on a shore with a dominant longshore transport direction creates a progressive wave of sediment that causes downdrift shore segments to undergo stages proceeding from erosion (pre-nourishment) to accretion to stability (throughput) to erosion again, with the time spent in each stage related to the periodicity of nourishment and the significance of the stage related to the volume of material added. The volumes of fill emplaced at Sailors Haven and the speed at which the accretion lobes moved downdrift made the changes too small and brief to be of significance in restoring habitat, but existing landward habitat was conserved over the 18 months, except near the bulkhead, where the sediment deficit was greatest.

Long-term success of attempts to overcome a negative sediment budget requires periodic re-nourishment of the feeder beach. Nourishment can be done in conjunction with periodic maintenance dredging of the Sailors Haven channel, where dredging is required every 3 to 6 years and provides high quality beach sand. Losses in the borrow area can be a major environmental cost of beach nourishment operations (Paoli et al., 2013), but the requirement to dredge makes this constraint moot and provides a windfall benefit to dredging. The quantity of material supplied by maintenance dredging cannot overcome the overall sediment deficit, because input from the ocean side is lacking, but the fill can offset interference with sediment transport by the marina. Re-colonization of nourished beaches can be impeded if the texture of fill material is not well matched to local beach sand (National Research Council 2014; Peterson et al. 2014; Viola et al. 2014), but this problem does not occur at Sailors Haven because of the similarity of the fill to the in situ sediment.

The high rate of removal at the fill site indicates that the excess sediment placed landward of the bulkhead during the dredging operation should have been placed in the fill area. The best time to do that would have been soon after October 2012 to reduce upland erosion in the following winter storm season. Considering that dredging operations are often more costly than redistributing stockpiled sediment, future operations could deposit less sediment on the beach initially and move sediment in the stockpile to the beach more frequently and in smaller amounts. More frequent or smaller amounts have been suggested for nourishment operations, in general, to mimic natural sediment transfers and facilitate species recruitment (Bishop et al., 2006; Schlacher et al., 2012).

Changes on the low tide terrace, marsh shoreline and zone of woody debris

Net deposition occurred on the low tide terrace on some transects that were not initially buried by direct deposit of fill. The amount of deposition (0.16 m) is within the range of the 0.1 to 0.2 m elevation of the transverse bars common on the inner low tide terrace fronting sandy beaches at Fire Island (Nordstrom et al. 1996). Limited offshore transport during large storms is a characteristic of estuarine beaches (Nordstrom and Jackson, 1992a). The limited storm-induced deposition on the inner low tide terrace in the fill area during high energy events (Figure 10) and lack of long-term accretion there (Figure 8a) imply that little fill is moved offshore. The greater amount of sediment added to the low tide terrace at sites downdrift of the fill (Figure 8b-d) may be longshore smearing of fill from the bulge in the shoreline at the fill site rather (compare Figure 3b and c) than an offshore loss following foreshore accretion. The similarity in grain size characteristics of fill sediment and the sediment on the low tide terrace prior to the fill indicates that little potential for dramatic alteration of the sediment characteristics of the offshore habitat would occur due to the project.

Eroding marshes supply little sand-size sediment to the beach, and the resistance of outcrops of marsh peat to erosion can create local barriers in the longshore transport system that trap and restrict the small amounts of sediment moving alongshore and create isolated littoral-drift cells on estuarine beaches (Nordstrom 1992). An abundant sediment supply from updrift can convert an eroding marsh front to an active sand-rich beach and establish a pathway for transport alongshore, connecting adjacent drift cells. Some of the new sediment will be sequestered in the new and larger overwash platform resulting from the abundant supply of sediment. The initial formation of this deposit will remove some of the sediment transported from updrift (creating a local sediment sink), but the

increase in foreshore width at sites downdrift of Marsh 1 indicates that the volume of sand that passes will still be greater than the pre-fill rate. The rate of landward displacement along the marsh segments should diminish as the elevation of the new sandy foreshore builds up and restricts overwash. The new higher, wider foreshore helps reduce the rate of erosion of the marsh but will change the periodicity of flooding of the marsh and cover the marsh-peat outcrops, reducing the variability of intertidal habitat.

Changes to woody debris were caused by direct removal of large debris from the fill area prior to sediment emplacement, burial of remnants by direct deposit of the fill and burial of woody debris downdrift by sediment moved alongshore from the fill. Removal of the debris to facilitate depositing the fill represents a loss of wood that has no natural analog. Burial of wood remaining in place is a temporary loss that is reversed once the beach erodes after the sediment pulses move downdrift. Like the exposure of marsh peat, the presence of woody debris is a function of erosion of a portion of shore that had ample time to evolve in the past. Woody debris provides physical structure for habitat and is an important link between terrestrial and aquatic systems (Christensen et al., 1996; Marburg et al., 2006) and is considered an important ecological resource on estuarine shores (Zelo et al., 2000). The extent of woody debris and marsh peat are attributed to the sand-starved condition that has been increased in intensity by human action. The added sand may return the site to conditions that better represent an earlier stage when sediment was more available, but the more continuous sandy foreshore provides less variety of habitats than the eroding shore. Large woody debris can be temporarily removed to facilitate the fill operation but stored locally and replaced after the fill is deposited (Hummel et al. 2005). This procedure can be used in future operations to better reestablish pre-fill conditions if habitats more typical of an eroding condition are perceived to be of more value than habitats in early stages of development.

Wind-blown sand

Inundation of surfaces landward of nourishment projects on ocean shores is common and well documented (Draga 1983; Marqués et al. 2001). The degree of inundation of the upland at Sailors Haven was unanticipated because of the rarity of dunes forming from the bay side. Aeolian transport off a nourished estuarine beach is usually limited because (1) the quantities of fill used are small and (2) the sediments usually contain a sufficient amount of gravel and shells to develop a lag layer of coarse particles to armor the surface after finer sand is blown away (Jackson et al. 2010). The lag surface that formed on top of the fill reduced the amount of sand that could be blown off the beach but it did not eliminate it. The width of the fill as a source area diminished rapidly as erosion occurred, further reducing the amount of sand that could be delivered by onshore winds. Previous field studies indicate that rates of aeolian transport are negligible when dry, unvegetated foreshore widths are less than 8 to 10 m (Nordstrom and Jackson 1992b; Jackson et al. 1993). Eroding uplands are not subject to aeolian deposition under natural conditions due to limited beach widths. A change in surface habitat characteristics is thus possible where relatively wide beaches are placed in front of eroding uplands and the top elevation of the fill coincides with the top elevation of the bluff, facilitating inland transport. Inundation of the upland by wind-blown sand would not have been a problem if the 4 m-wide, lower beach in the original plan had been constructed, but it is now obvious that a beach of that size would have been eliminated within weeks and would have added little

sediment to the longshore sediment budget. Emplacing sand fences at the landward limit of fill is a common adjustment on ocean beaches, but this alternative would be of limited value on an estuarine site where a sizeable dune would be unrepresentative of natural conditions and where the fence would interfere with movement of fauna between upland and bay.

Conclusions

Dredging of navigation channels at marinas can supply sediment to nourish adjacent beaches starved of sediment by the protection structures built to protect the marinas. Pronounced unidirectional transport adjacent to the end of the structures can make the concept of a feeder beach appropriate because sediment will readily move downdrift from the fill area, but removal of fill and progression of sediment pulses alongshore will be rapid without reversals in transport direction to slow sediment residence time. Burial of the foreshore, inner low tide terrace and peat outcrops can change habitat characteristics. The significance of habitat changes is not clear, in part because the habitat value of rapidly-eroding previously-established coastal environments is poorly documented on estuarine beaches. Expansion of the low tide terrace and increase in the number and size of peat outcrops represent a sand-starved condition that has been increased in extent by human actions that reduce the bayside sediment budget. A portion of the low tide terrace was buried by direct placement of the fill, but burial would occur if the sediment were delivered from the ocean side by natural processes. Delivery of sediment from the fill area to downdrift areas is less problematic because it is through natural wave and current processes, allowing for adaptation by fauna.

An initially high volume of sediment can restore the dimensions of previous environments, but time is required for these environments to evolve into fully functioning woodland or saltmarsh. A lower volume can reduce erosion rates and help maintain the existing character of landforms and habitats. Rapid movement of fill implies that maintenance nourishment should occur more frequently and in smaller volumes to limit burial of the low tide terrace and reduce fluctuations in accretion-erosion cycles. Aeolian transport landward of the fill can also be reduced using smaller volumes of sediment emplaced more frequently, thereby reducing the fetch distance across which sediment can be entrained and transported.

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