Environmental Earth Sciences (2018) 77:680
https://doi.org/10.1007/s12665-018-7826-3

ORIGINAL ARTICLE

Protecting natural landforms and habitats by nourishing an eroding estuarine beach

Karl F. Nordstrom[1] · Nancy L. Jackson[2] · Alana M. Rader[1] · Emir S. Garilao[2]

Received: 12 April 2018 / Accepted: 8 September 2018 / Published online: 26 September 2018

Abstract
An important issue facing coastal managers is how natural coastal habitats can be protected against wave erosion by human action. An assessment is made of attempts to protect a rare maritime forest on the bay side of a barrier island at Fire Island, New York, USA using artificial beach fill. The sediment deficit is caused by human attempts to stabilize the island by restricting inlet formation, overwash, and dune migration, and it is exacerbated by a nearby marina bulkhead. A total of 1099 m^3 of sand dredged from the navigation channel was placed near the bulkhead. Loss of fill was 5.54–7.87 m^3 m^{-1} in the first 6 months. The fill was gone 18 months after placement. Sediment moving out of the fill area caused almost 4 m of shoreline advance 40 m downdrift after 6 months (gain of 3.28 m^3 m^{-1}), followed by retreat of about 5 m at that location over the next 12 months (loss of 5.51 m^3 m^{-1}). These results reveal how small changes in volume of microtidal estuarine beaches can cause great shoreline displacement rates. The amount of fill from maintenance dredging is insufficient to replenish erosion losses. Placing additional fill sediment on the bayside to create artificial washover fans can mimic natural landforms and overcome loss of sediment inputs caused by stabilizing the ocean shore. Mechanical placement may be preferable to natural processes, which would deliver sediment across the island and through pre-existing stable habitat, eliminating some of the features that take long to form.

Keywords Beach nourishment · Bulkhead · Erosion · Maintenance dredging · Habitat loss · Sediment budget

Introduction

Most decisions about the advisability of using human actions to prevent coastal erosion and flooding focus on protecting buildings and other infrastructure. Natural landforms and habitats with human use and intrinsic value are also subject to erosion. Sustaining natural coastal features is becoming more difficult given increasing rates of sea-level rise, magnitudes of shoreline retreat, and lack of coastal sediment (Orford and Pethick 2006; Anthony et al. 2014; Roman 2017). Erosion is not considered a threat to the most dynamic landforms and habitats, such as beaches and foredunes and their early-colonizing species, which re-establish rapidly after storms, if sediment and space are available landward or alongshore (Cooper and McKenna 2008). Erosion is more critical for habitats that require stability and time to evolve and have achieved status as rare or endangered. These locations raise the interesting question of whether slow-evolving natural habitats now threatened by coastal erosion should be protected against natural processes by human actions and, if so, which alternatives are most compatible?

Determining appropriate actions for eroding natural areas include identifying the causes of erosion and alternatives to overcome restrictions in sediment and space. This paper provides an assessment of attempts to address erosion of the Sunken Forest, a globally rare maritime holly forest (Edinger et al. 2014) on an estuarine shoreline at Sailors Haven in Great South Bay, New York (Fig. 1a). The forest is west of a marina built to provide access to Fire Island National Seashore, a park managed by the U.S. National Park Service (NPS). The marina is protected by a sheet pile bulkhead that projects about 115 m into the bay.

NPS policies allow natural processes to occur unimpeded, but also allow intervention against natural processes threatening important natural resources if there is no other

✉ Karl F. Nordstrom
nordstro@marine.rutgers.edu

1 Rutgers The State University of New Jersey, New Brunswick, USA

2 New Jersey Institute of Technology, Newark, USA

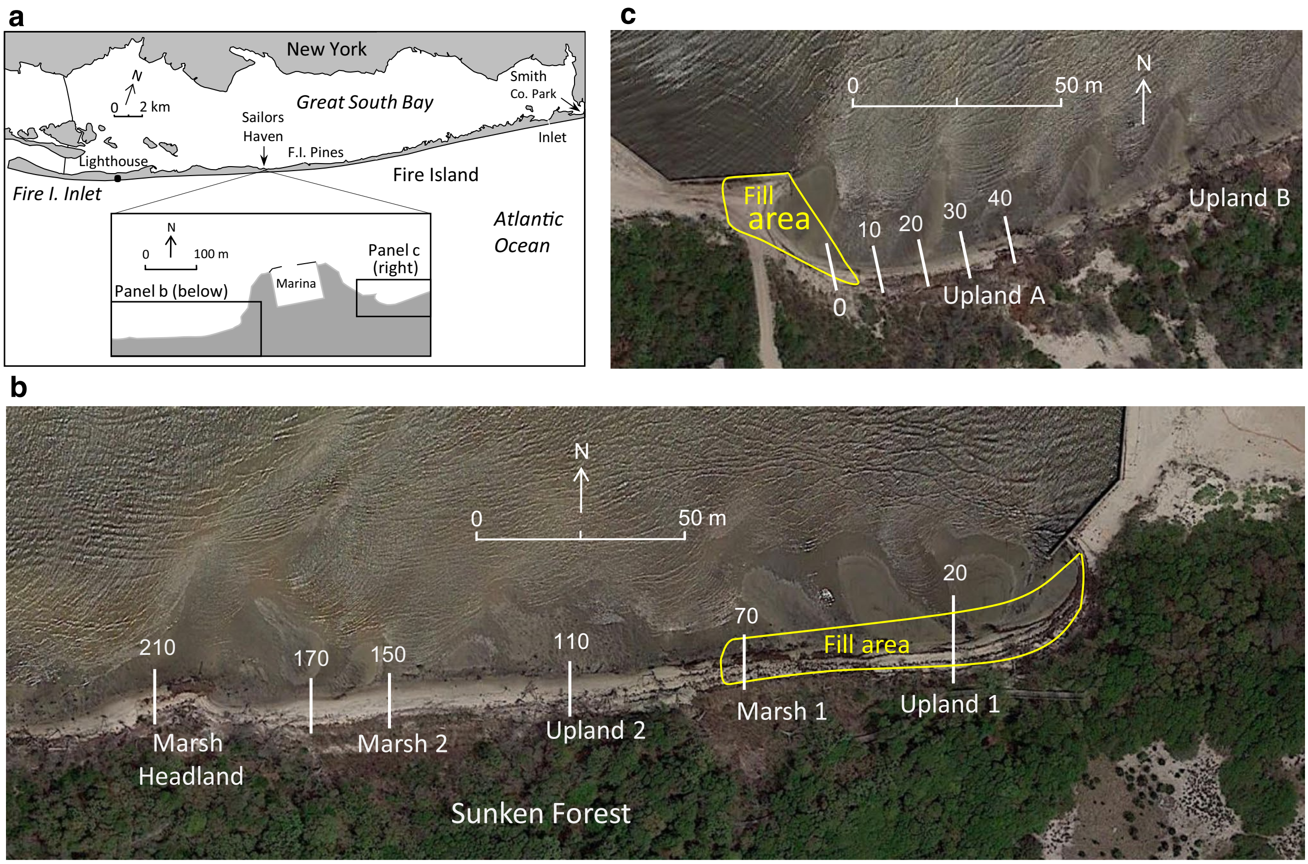

Fig. 1 Study site. Transects depicted are those discussed in detail in the paper. Fill area delineation is approximate. Imagery from Google Earth May 2015

feasible way to protect the resources (NPS 2006). NPS has attempted to mitigate erosion at Sailors Haven using sediment dredged from the navigation channel leading to the marina in beach nourishment projects conducted in November 2011 and December 2015. The focus of beach nourishment is usually on protecting human facilities and providing recreation space (Dean 2002; Gómez-Pina et al. 2004; Reid et al. 2005). Less attention is placed on ways the fill sediment is incorporated into existing landforms and habitats, with the potential to change their form and function (Nordstrom et al. 2011). Beach nourishment can protect resources directly landward of where it is placed, but it can also function as a feeder beach, supplying sediment downdrift. Thus, evaluation of nourishment projects should include the fate of sand in the project area and on adjacent shores (de Schipper et al. 2016).

Nordstrom et al. (2016) and Jackson et al. (2017) assessed the 2011 dredge and fill project to identify whether the fill sediment was similar to native material; how the fill sediment moved downdrift; how beach morphology changed with the added sediment; and whether the volume of sediment added from ongoing maintenance dredging would be sufficient to prevent long-term shoreline retreat. The present study assesses the 2015 dredge and fill project while addressing aspects not considered in the previous studies. These new aspects include placing fill in a lower, narrower, and longer configuration to be more compatible with natural beach and upland characteristics; monitoring a greater length of shoreline that included a prominent marsh headland to the west; placing fill on the east and west sides of the marina to identify the feasibility of mechanically bypassing sediment across it; and providing alternatives to using only the fill made available from maintenance dredging. Case studies of beach nourishment projects on estuarine beaches exist (Shipman 2001; Jackson et al. 2007, 2010), but they are few in number and focus on protection of cultural features or restoration of beach habitat. Insight is needed for implementing protection projects, where natural features landward of beaches are threatened by interruptions in longshore sediment transport.

Study area

The irregular orientation of the Fire Island bay shore is inherited from the past episodic additions of sediment delivered from the oceanside by inlets, storm-wave overwash, and dune migration. Sediment delivered through inlets forms substrate for new saltmarsh; storm-wave overwash results in deposits over the inner existing saltmarsh surface or, less frequently, into the bay; dunes that migrate from the ocean side or form near inlets provide a sediment source that can be delivered by bayside erosion (Leatherman and Allen 1985). Dune building processes on the ocean side have been enhanced by beach nourishment, beach scraping and deployment of sand-trapping fences (Lentz and Hapke 2011). These efforts to protect homes have reduced sediment inputs across the island, contributing to bayside erosion. The average long-term rate of erosion on the bayside is about 0.3 m year^{-1} (Leatherman and Allen 1985), with annual rates exceeding 3 m year^{-1} in places (Nordstrom et al. 2009). Shoreline segments fronted by marsh now occupy low land between segments of higher forested upland. The bayward sides of the marsh segments have a veneer of sand overlying salt marsh peat and correspond to the marsh barriers in the Rosen (1980) classification.

The central portion of the bay shore of Fire Island is exposed to waves generated locally within Great South Bay across fetch distances of 12–15 km. Water depths in the bay are often less than 1.5 m within 1 km of the shoreline. The shallow depths and low tidal range (mean of 0.21 m) result in low wave heights during strong onshore winds, e.g., root mean square breaking wave heights of 0.19–0.28 m during mean winds speeds of 9.2–12.6 m s^{-1} (Jackson et al. 2017). As a result, beaches are low and narrow, with foreshore widths < 10 m. The low tide terrace bayward of the foreshore is sandy and covered in places by transverse bars with a predominately northeast/southwest orientation that indicates that they are shaped primarily by northwest winds during low water levels. Northeast winds create higher water levels and pronounced westerly longshore transport on the upper foreshore.

The Sunken Forest (Fig. 1b) is on a sequence of relic inlet beach ridges landward of a shore-parallel secondary dune that protects the forest from overwash and salt spray from the ocean side (Leatherman and Allen 1985). The shoreline west of the bulkhead at Sailors Haven is characterized by forested upland interspersed with marshes colonized by *Phragmites australis*. Fallen trees and woody debris on the beach fronting forested dune uplands and outcrops of peat fronting marsh provide conspicuous evidence of ongoing bayside erosion. The shoreline east of the bulkhead is on a former washover deposit and is vegetated by maritime shrubs interspersed with marsh outcrops colonized by *P. australis*. Marsh substrate is more resistant to erosion than unconsolidated sand in adjacent uplands because of the extensive rhizome systems serving as a framework for the finer grained sediment in the matrix (Rosen 1980). As a result, segments of marsh peat protrude bayward from the general shoreline orientation, with the marsh headland near Transect 210 in Fig. 1b being especially prominent.

The fill operation

US Army Corps of Engineers data indicate that 1099 m^3 of fill was dredged from the navigation channel between 18 November and 4 December 2015, with 90% designated to go on the west side of the marina and 10% on the east side. The fill placed on the west side was initially shaped to create a backshore about 15-m-wide fronting the upland near the bulkhead (Fig. 2a) and ranged from about 0.75 to 0.95 m

Fig. 2 West of Sailors Haven Marina December 16, 2015, just after placement of the fill

above NAVD88, with an average elevation of about 0.65 m. The highest fill elevations were roughly the height of the washover ridge over the marsh (Fig. 2b) and represent the elevation of natural storm-wave uprush. The fill extended west from a sheltered location within the western extension of the bulkhead to near Transect 70 (Fig. 1b). In contrast, the fill placed in 2011 was 1.2–1.4-m above NAVD88, essentially creating an unvegetated upland at a height similar to the previously eroding bluff and higher than the washover ridge over the adjacent marsh. The 2011 fill was too high to be overtopped by waves, resulting in a prominent scarp in the foreshore that had not achieved an equilibrium slope as late as 5 months after fill placement (Nordstrom et al. 2016).

The small volume of fill placed on the east side of the marina in 2015 was designed to fill the erosional reentrant landward of the eastern extension of the bulkhead (Figs. 1c, 3) and provide a diagnostic for the way fill would move in a larger operation. The bayshore near the bulkhead (Upland A) is a remnant of a washover deposit delivered from the ocean side. This deposit is vegetated by grasses and low shrubs, with *P. Australis* marsh landward of Transect 0 (Fig. 1c). The shore to the east (Upland B) is a relic dune that formed when an inlet existed here.

Methods

Shore perpendicular topographic surveys were taken to determine changes in beach morphology and volume 2 weeks after placement of the fill (16 December 2015) and 6, 18, and 24 months after placement (28 June 2016, 28 June 2017, and 18 December 2017, respectively). Ground surveys were conducted in preference to determining changes using aerial imagery, which cannot reveal volumes or changes at the beach/upland contact that are obscured by the tree canopy. The topographic surveys were conducted at 10-m intervals alongshore for distances of 230-m west of the western terminus of the marina bulkhead and 40-m east of the eastern terminus using a Leica RTK GPS system. A Leica total station was used to survey the surface under the landward vegetation canopy. The 3DCQ error for the GPS system was < 0.037 m, which is considered acceptable, given the conspicuous changes that occur over 6-month intervals. Five profiles are not represented for the first 6 months, because three profiles surveyed in December 2015 (Transects 80, 90 and 100) were found incomplete after data were reduced, and the two transects farthest from the bulkhead (Transects 220 and 230) were added only after the fill reached Transect 140 by June 2016.

Areas between successive profiles were converted to volumes by assuming each profile represented the area 5 m on each side of it. These volumes were plotted to reveal alongshore trends through time. Five representative profiles on the west side of the marina and all five profiles from the east side (Fig. 1) were analyzed to reveal how foreshore change is related to gains or losses to the landward bluff or washover barriers.

Bulk sediment samples were gathered on the beach to a depth of 50 mm just after fill placement (16 December 2016) and 24 months later (18 December 2017) to determine compatibility of fill with wave-reworked sediment. Samples were gathered at 20-m intervals alongshore for a distance of 160 m from the west end of the bulkhead and 40 m from the east end. Samples west of the bulkhead in December 2016 were taken from the middle of the wave-reworked foreshore and the middle of the backshore. Beaches lacked a backshore on the east side during both sampling periods and on the west side in December 2017. Un-reworked fill is represented by the backshore samples on the 0-, 20-, and 40-m transects west of the bulkhead and samples designated as 1 and 2 from the fill area east of the bulkhead. The samples were washed, dried, split, and run through a sonic sifter at 0.5 ϕ intervals. Mean grain size and sorting were calculated using graphical measures (Folk and Ward 1957).

Aerial images available from Google Earth were used to determine the potential for sediment delivery to the bay by natural processes. Overwash penetration distance, area of deposits, island width, and length of gaps in dunes, where overwash occurred were measured from images taken 5 days after and nearly 1 year after the most recent large storm—Hurricane Sandy occurring 29 October 2012. Storm deposits at Sailors Haven, where overwash did not reach the bay, are compared to deposits, where sediment was transported to the bay at the eastern end of Fire Island, and at Fire Island Pines (Fig. 1a), the bay deposit closest to Sailors Haven.

Measurements were made using the Google Earth measuring tool from images at 1:1000 scale.

Fig. 3 East of Sailors Haven Marina December 16, 2015, just after placement of the fill

Data on hourly observations of wind speed and direction were derived from a meteorological station (elevation of 25.6 m) at the Islip MacArthur Airport (Lat 40.7939°, Long-73.1017°), located 14.9-km north of the field site (NOAA 2018) and used to assess conditions between topographic surveys. Waves in the central portion of Great South Bay are locally generated within the bay, so wind data provide perspective on potential wave energy. Onshore wind speeds at the beach are expected to be greater than at the airport because of the lack of topography, vegetation, and infrastructure, but the primary interest here is in relative directions and strengths of winds.

Results

Wind data

Winds from the northwest quadrant were dominant during the study period (Fig. 4). Winds from the northeast occurred less frequently, but the strongest speeds (> 9 m s^{-1}) occurred nearly as frequently. The 6 months between the topographic profiles taken in June and December 2017 included less of the winter storm season and the winds were less strong and more frequently shore-normal (Fig. 4c).

Sediment characteristics

All but three of the 30 sediment samples for all sites during both sampling periods fall within the range of medium sand. The other three samples are only slightly coarser. Mean size

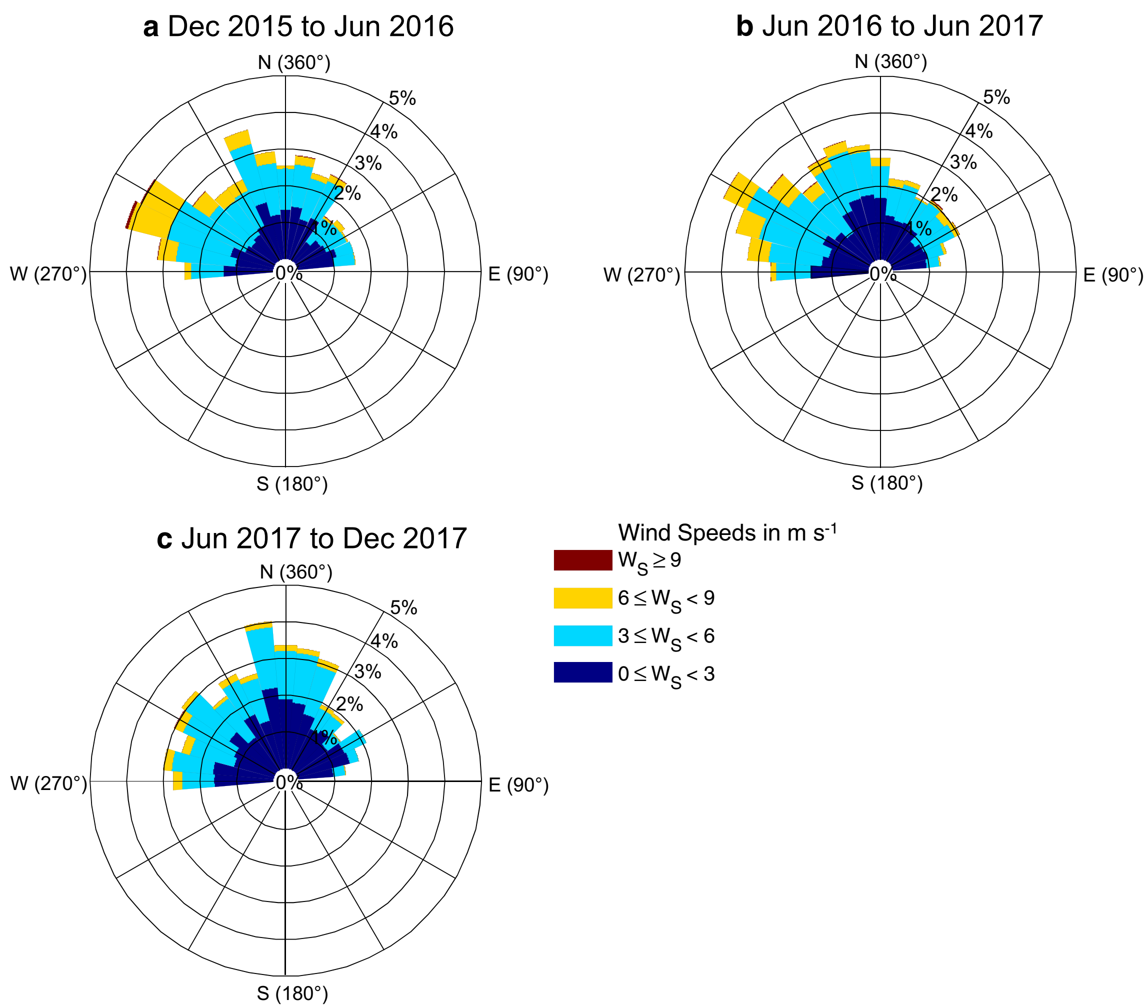

Fig. 4 Wind roses for data from the Islip MacArthur Airport, separated by elapsed times between topographic profiles. The shoreline trend at the site is nearly east–west (azimuth 86–266). Offshore winds do not contribute to generation of large bay waves and are omitted from the diagrams

of fill sediment west of the bulkhead in December 2015 (1.59 ϕ) is only slightly finer than sediment on the foreshore at the eight sites west of the bulkhead at that time (1.55 ϕ). Mean size of foreshore sediment west of the bulkhead 2 years after fill was placed is 1.28 ϕ, similar to the 1.18 ϕ mean prior to the 2011 fill, which represents the native sediment unaffected by nourishment (Nordstrom et al. 2016). The two sediment samples in the fill east of the bulkhead in 2015 are slightly finer than sediment on the foreshore at the nearby sites at that time but similar to foreshore sediment in 2017 (Table 1). Problems can occur with re-colonization of nourished beaches by biota if the texture of fill material is not well matched to local beach sand (National Research Council 2014; Peterson et al. 2014), but the overall similarity in size of foreshore sediment through time indicates that the fill sediment is compatible.

Beach volume changes

Sediment losses from the fill area west of the bulkhead (Fig. 5a, right side) were persistent in the first 18 months after emplacement. The movement of fill sediment toward the west in the first 6 months appears to have contributed to a gain in volume as far alongshore as Transect 140. Transects west of 140 were relatively stable until the final 6-month interval, when transects downdrift of Transect 160 revealed slight erosion. The relative stability west of Transect 140 may be at least partially attributed to the fill, because the portion of the shore had been erosional prior to the fill operation.

The amount of sediment loss at all of the transects within the 70-m-long segment, where fill was placed west of the marina was similar alongshore in the first 6 months, varying between 5.54 and 7.87 $m^3\ m^{-1}$. Greater longshore variability in erosion or accretion within the placement area occurred through time. Less sediment was removed from this 70-m-long segment between June 2017 and December 2017, after the bulk of the fill moved west and the bluff and marsh were subject to direct attack by waves and swash. The reduction in removal rate could be attributed to the lower wave energy at this time, revealed in the lower wind speeds (Fig. 4). Local differences in the height of the bluff, which provides sediment to the beach, and in bluff and marsh vegetation, which dampens wave energy and traps sediment (Fig. 6) could also have contributed to less erosion in the former fill area during the last 6 months. The local differences in shoreline characteristics may account for the greater longshore variability revealed in the cumulative volume changes at the end of the 24-month period (Fig. 5b).

Volume changes east of the marina (Fig. 5, left side) reveal persistent loss near the bulkhead but at a rate far less than west of the marina. Cumulative losses east of the marina over the 24 months (Fig. 5b) were no greater than 7.1 $m^3\ m^{-1}$ (at Transect 0). Cumulative volume changes reveal a progression similar to those occurring west of the marina, where loss in or near the bulkhead and placement area is accompanied by greater stability downdrift. In this

Table 1 Grain sizes on backshore, foreshore, and fill areas at Sailors Haven taken post nourishment 16 December 2015 and 2 years later on 18 December 2017

Location alongshore								
	0 m	20 m	40 m	60 m	80 m	100 m	140 m	160 m
West side								
Foreshore 2015								
Mean (ϕ)	1.54	1.90	1.82	1.82	1.71	1.30	0.96	0.97
Sorting (ϕ)	0.54	0.37	0.40	0.38	0.51	0.54	0.46	0.48
Backshore 2015								
Mean (ϕ)	*1.62*	*1.48*	*1.67*	1.64	1.65	1.44	1.41	1.62
Sorting (ϕ)	*0.55*	*0.61*	*0.56*	0.62	0.42	0.30	0.33	0.43
Foreshore 2017								
Mean (ϕ)	1.46	1.47	1.77	0.78	1.27	1.19	1.28	1.16
Sorting (ϕ)	0.37	0.37	0.43	0.27	0.40	0.54	0.40	0.35
East side		20 m	40 m			Fill 1	Fill 2	
Foreshore 2015					Fill 2015			
Mean (ϕ)		1.30	1.50		Mean (ϕ)	*1.61*	*1.88*	
Sorting (ϕ)		0.53	0.39		Sorting (ϕ)	*0.62*	*0.50*	
Foreshore 2017								
Mean (ϕ)		1.94	1.85					
Sorting (ϕ)		0.46	0.43					

No sample was taken on the west side at Transect 120, where an eroding shrub thicket covered the foreshore and backshore in 2015. Numbers in italic represent un-reworked fill sediment

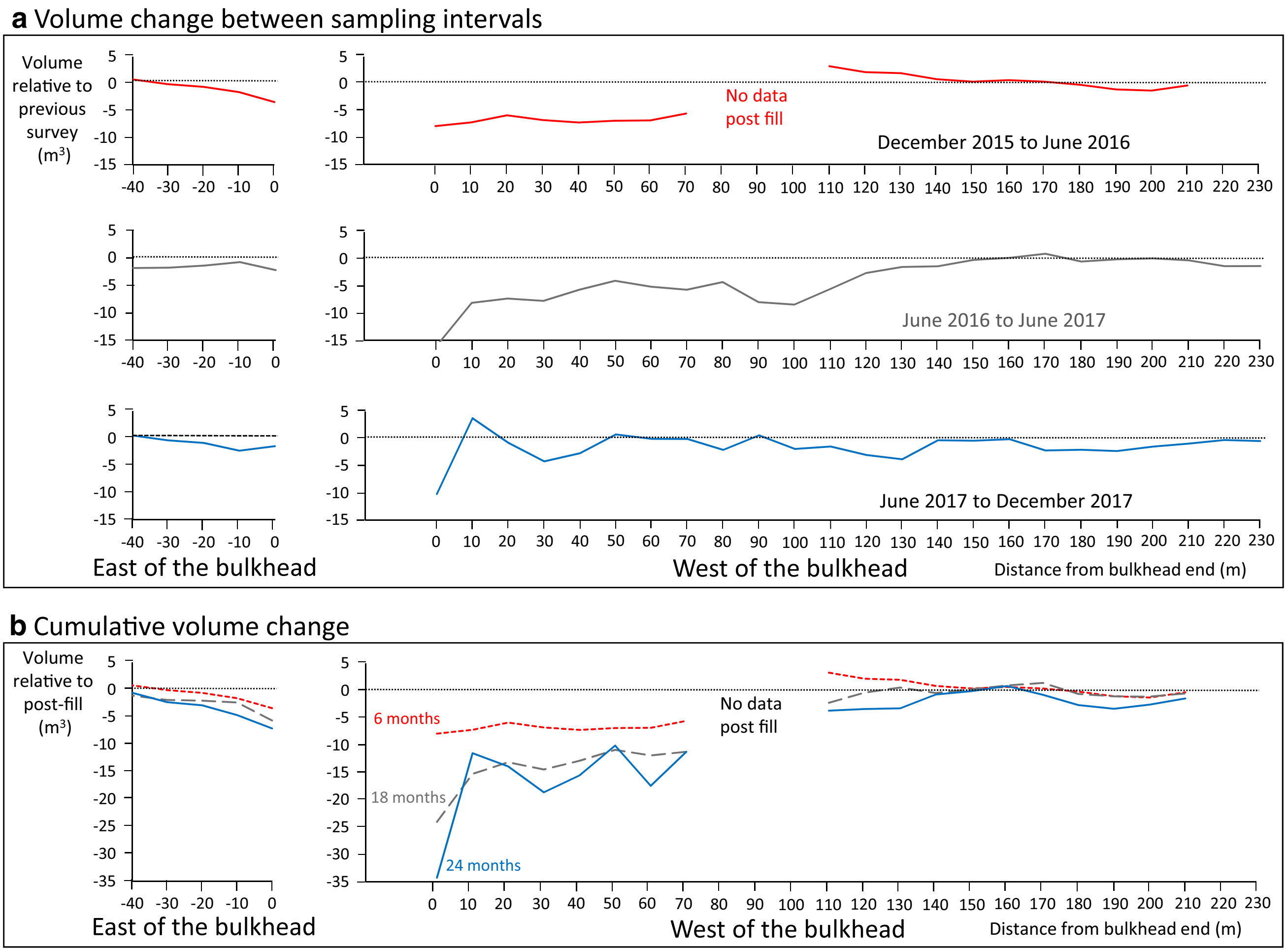

Fig. 5 Alongshore differences in sediment volume change. The dotted line at zero volume in Panel **a** represents the condition of each transect at the end of the previous survey. The dotted line in Panel **b** represents the condition just after the fill was emplaced

Fig. 6 Looking west from Transect 0 (west side) June 2017, showing pronounced longshore differences in shoreline conditions when coastal formations are exposed to wave erosion without a fronting beach fill

case, sediment transport away from the bulkhead is to the east, and the magnitude of change for a given distance from the bulkhead is less than on the west side.

Topographic changes

Beach profile lines west of the marina (Fig. 7) show that much of the sediment placed in the fill area (represented by Transects 20 and 70) was removed in the first 6-months, but a portion was also delivered higher on the profiles. Considerable foreshore retreat occurred at these sites in the next 24 months, followed by little change in the shorter and less windy 6-month interval between June and December 2017.

The ramp that formed seaward of the upland at Transect 20 by June 2016 is nearly 1 m higher than the elevation of the active foreshore and appears to have occurred primarily by aeolian transport off the widened backshore surface, driven by the strong winds from the west-northwest (Fig. 4). This deposit initially protected the bluff from erosion but

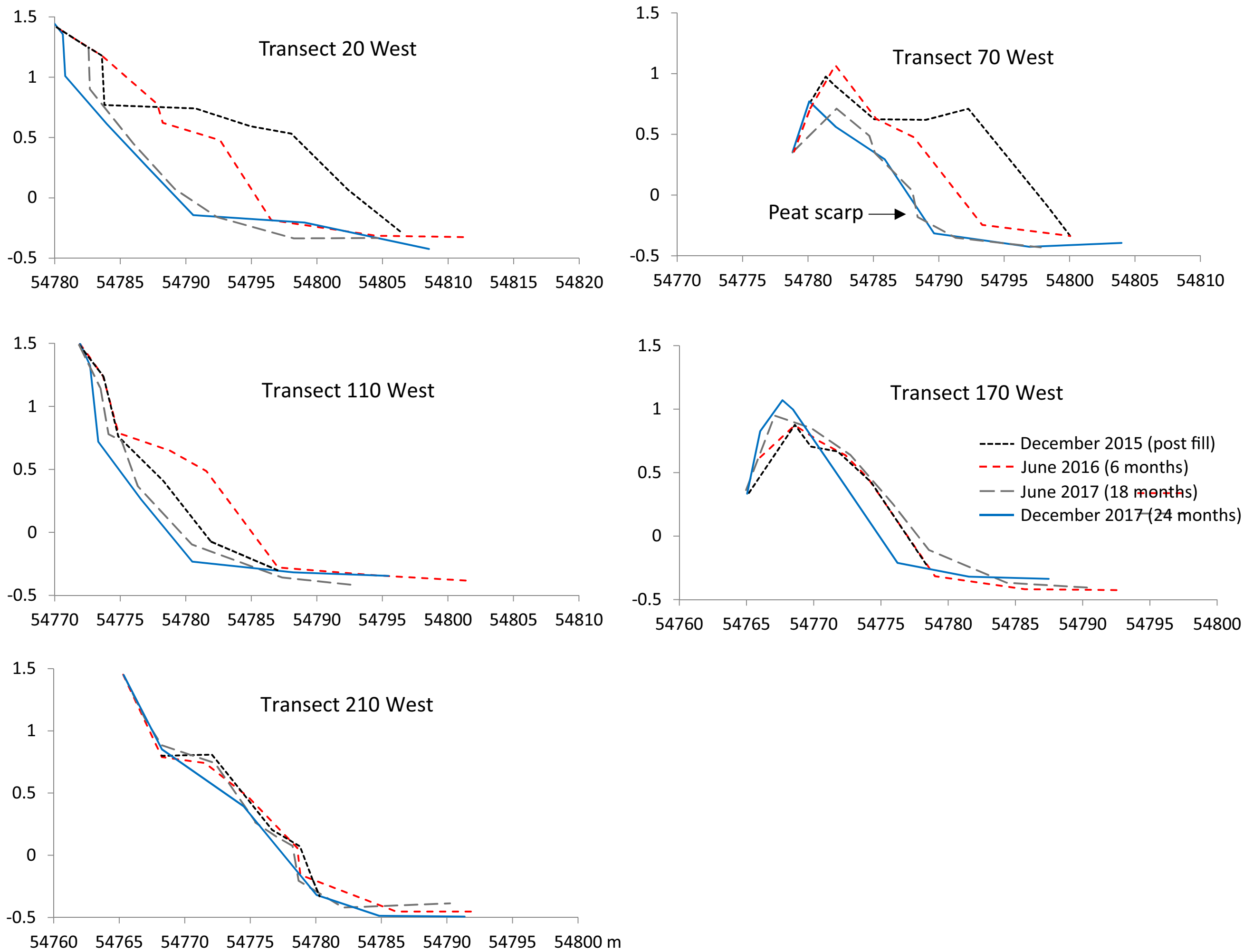

Fig. 7 Selected beach profiles monitored west of the marina 16 December 2015, 27–28 June 2016, and 28 June 2017

was eliminated by June 2017, and the scarp in the upland at Transect 20 was farther landward at that time than it was just after the fill. The contribution of sediment from erosion of the bluff after June 2016 may have contributed to the relative stability of the foreshore in the last 6 months. The contribution of bluff sediment to the active beach was even greater closer to the bulkhead. At the 0-m transect, the bluff retreated 2.4 m between June and December 2017, representing a release of 2.12 m^3 m^{-1} of sediment to the beach.

The lobe of sediment moving downdrift (west) of the fill area resulted in almost 4 m of shoreline advance at 0-m elevation at Transect 110 by the end of the first 6 months (Fig. 7) associated with a volume contribution of 3.28 m^3 m^{-1} (Fig. 5). Retreat of about 5 m occurred on the foreshore at Transect 110 over the next 12 months associated with a volume loss of 5.51 m^3 m^{-1}, and the beach and upland were landward of the post fill position 18 months after fill placement. Retreat of the foreshore and upland was much slower in the last 6 months.

The small difference in foreshore position at Profile 170 in the first 6 months after the fill (Fig. 7) implies that any sediment that arrived from the fill did not greatly increase beach width, although sediment passing through may have reduced the erosion that would have occurred there in the absence of the fill. A small amount of sediment was supplied to the beach at Transect 170 by June 2017, but conspicuous foreshore retreat occurred in the next 6 months.

Sediment covered the surface of the marsh peat on Transect 210 by 6 months after the fill (but not the scarp on the bayward side of the peat layer). The surface of the marsh peat was completely exposed 18 months after the fill, and erosion of the peat outcrop, foreshore and upland occurred in the last 6 months. Erosion of the peat outcrop at Transect 210 and the reduction in its effect as a barrier to longshore transport coincided with conspicuous erosion updrift at Transect 170 (Fig. 7) and volume loss between Transects 170–190 (Fig. 5). Linear shoreline retreat was 2.0 m at Transect 170 and 2.6 m at Transect 180 during this period.

East of the marina (Fig. 8), the greatest amount of initial foreshore retreat was within the fill area (Transect 0). Foreshore retreat in the 24 months after the fill was placed decreased alongshore east of the bulkhead, likely because of delivery of sediment from the fill area (at and west of Transect 0) by longshore transport. Profile 40, underwent net gain in the first 6 months, but erosion of the upland occurred by 24 months after fill placement. The foreshores of all other sites east of the marina revealed progressive erosion in the 24 months following the fill, although the crest of the washover deposits did not change in the last 6 months.

Effects of storm-wave overwash

Hurricane Sandy created new gaps in foredunes or widened existing gaps and created washover deposits in numerous places along Fire Island. Sediment was deposited directly into the bay in four locations–through a 60-m-wide gap at Fire Island Pines (Fig. 9c), through a 60-m-wide gap just west of Smith County Park (Fig. 1a) and through gaps of 883 and 558 m just east of the access bridge to Smith County Park. Sediment deposited bayward of the 883-m breach evolved into salt marsh. The 558-m breach included a temporary inlet, and a sandy barrier formed over the marsh that evolved on the inlet flood tide delta, creating a beach up to 94-m bayward of the pre-inlet bay shoreline. A higher washover deposit near the inlet evolved into a new upland extending up to 30 m farther into the bay than the previous shoreline. A new inlet that remains open was created just west of Smith County Park (Fig. 1a). A new marsh is likely to evolve on the flood tide delta of this inlet.

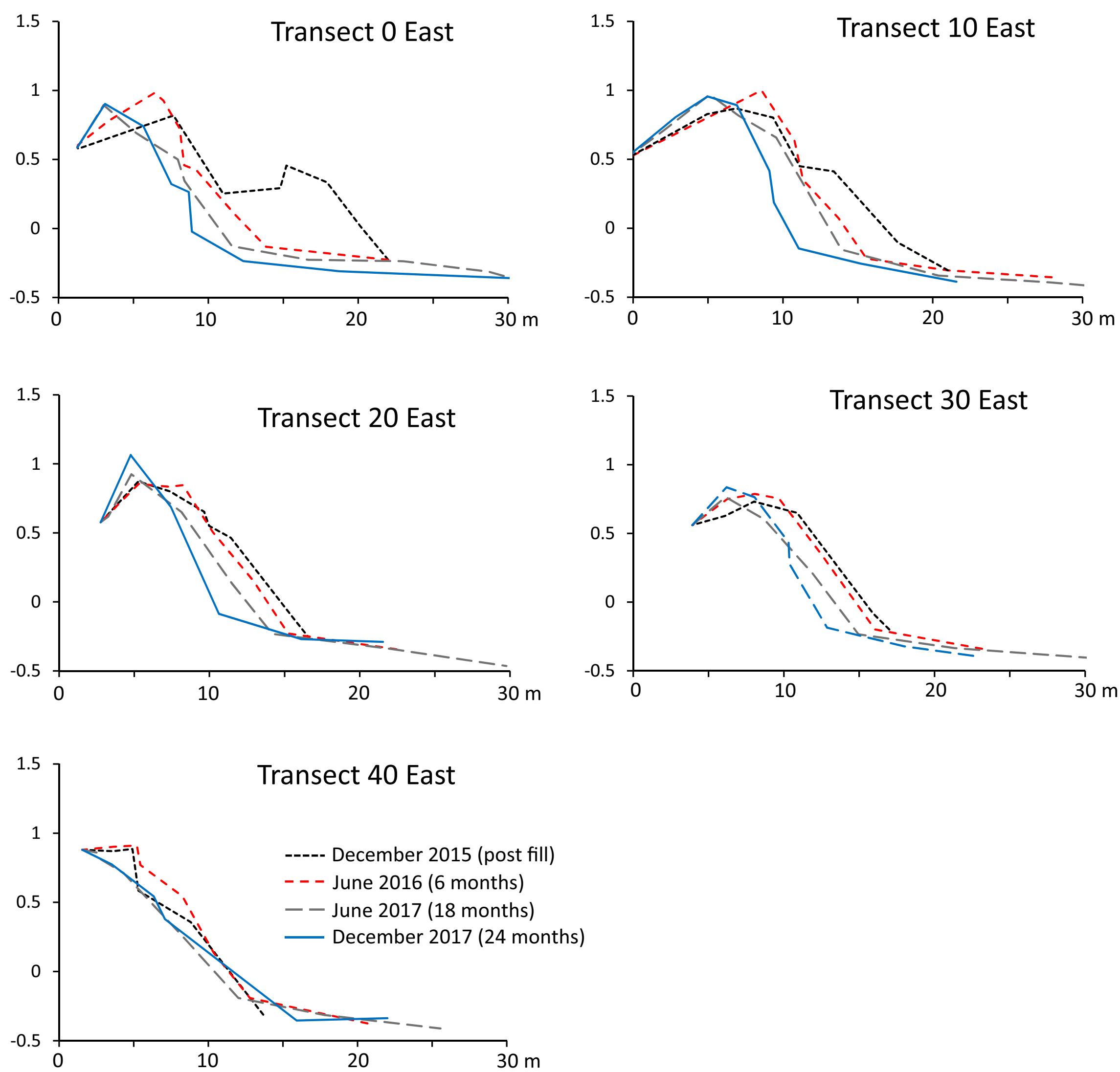

Fig. 8 Beach profiles monitored east of the marina 16 December 2015, 27, 28 June 2016, and 28 June 2017

Fig. 9 Overwash areas created during Hurricane Sandy east of Sailors Haven (**a** and **b**) and Fire Island Pines (**c** and **d**)

The only overwash through the dune near Sailors Haven during the storm (Fig. 9a) deposited sediment to a distance of 80-m landward of the seaward face of the dune. The deposit covered 4560 m^2 of the upland surface, and its shape did not change by September 2013 (Fig. 9b). Island width east of the bulkhead at Fire Island Pines (Fig. 9c) was narrower, and overwash extended 60 m farther into the bay than the former shoreline. The deposit in the bay was 2820 m^2. This deposit moved onshore and alongshore by September 2013, creating a 10–12-m-wide beach to a distance of 120 m east of the bulkhead (Fig. 9d). This beach was gone by May 2016.

Discussion

The rates and volumes of change associated with the 2015 fill are more subdued than after the 2011 fill because of the smaller fill volumes (62.9% of the 1747 m^3 emplaced in 2011). This investigation of the 2015 fill indicates that (1) placing the fill at a lower elevation than the upland (but similar to the natural berm elevation) reduces aeolian transport landward; (2) marsh outcrops can reduce foreshore erosion, contribute temporarily to cross-shore shoreline stability, and, when large, reduce longshore transport; (3) fill placed bayward of marsh outcrops and trees expedites longshore sediment transport; and (4) sediment movement is away from the marina on both sides of the structure. These new findings are elaborated in the subsequent discussion that includes addressing alternatives to relying solely on use of sediment from channel dredging to protect the Sunken Forest.

Results of this project substantiate some of the findings of the investigation of the 2011 beach fill (Nordstrom et al. 2016; Jackson et al. 2017), namely (1) the dredged sediment is compatible with native material; (2) the landforms undergo stages, including erosion (pre-nourishment), accretion, stability (with throughput to downdrift sites), and erosion again; (3) small changes in beach volume can result in relatively great shoreline displacement rates; and (4) the volume of sediment added from maintenance dredging is sufficient to slow but not prevent long-term shoreline retreat.

Placing fill in a lower and narrower configuration

Placing fill at an elevation that corresponds to natural bayside storm-wave uprush allows for natural interaction between the foreshore and backshore and between the backshore and landward habitat (Jackson et al. 2010; Brutsché et al. 2015). The lower fill placed in 2015 provided less of a disturbance to the pre-nourishment character of the shore than the 2011 fill, reduced the likelihood for development of an erosional scarp in the beach, and restricted the amount of aeolian sediment reaching the forest floor in the upland while allowing for wave overwash onto the marsh landward of where fill was placed. The fill placed in front of the marsh in 2011 was too high to allow overwash to occur (Nordstrom et al. 2016).

Beach fill creates a wider beach that initially provides a more effective source for aeolian transport (Helewaut and Malherb 1993; van der Wal 1998). Estuarine beaches are characterized by narrow widths with limited backshore development, so the potential for aeolian transport can greatly increase with only small amounts of fill. Aeolian transport from the surface of the 2011 fill into the forested upland resulted in a 10–30-mm-deep layer of deposits, with local vertical accretion up to 130 mm (Nordstrom et al. 2016). These deposits introduced an unvegetated upland that would not otherwise have occurred. The amount of aeolian accretion on the upland after the 2015 fill was barely conspicuous. The 2015 fill surface was 0.4–0.8 m lower than the upland surface, and the scarp in the upland provided a trap for sand blown onshore.

Effect of marsh outcrops and trees

Narrow beaches on estuarine shores contribute to conspicuous rates of shoreline advance and retreat with removal and addition of relatively small volumes of sediment (Freire and Andrade 1999; Freire et al. 2007; Jackson et al. 2017). Resistant marsh headlands, trees, and tree roots exposed to wave uprush can have a pronounced effect on beach change by providing barriers to longshore and cross-shore transport. This effect is revealed in changes within the upland and marsh in the fill area after the fill was removed and changes updrift (east) of Transect 210. The headland at Transect 210 retreated through time (Fig. 7), reducing its effectiveness in protecting the foreshore landward of it and retaining sediment updrift of it.

Saltmarsh-peat outcrops on the foreshore that do not extend out far enough to provide barriers to longshore transport can still play a role in reducing rates of erosion landward of them (Rosen 1980). Burial of peat outcrops by direct deposit of fill or movement of fill to them from updrift temporarily eliminates the exposed peat as a component of the natural intertidal habitat and converts the marsh barriers to more readily erodible permeable beaches. This conversion is temporary, because the fill sediment moves through the system (e.g., at Transect 70, Fig. 7). The peat does not extend above about 0.17-m elevation and does not armor the beach at higher levels. The scarp can trip the waves when water levels are just above scarp height, reducing, but not preventing change on the beach above it.

The effect of trees in altering transfers of sediment across and alongshore is more difficult to assess than peat outcrops using transects spaced at 10 m, because locations of fallen trees and exposed roots are not as uniform for appreciable distances alongshore. Longshore differences in losses and gains when fill remained in the placement area were less conspicuous than after the fill was removed (Fig. 5b). The fill sediment smooths the shoreline, facilitates longshore transfers and allows for a more balanced distribution of sediment alongshore through time, but sediment losses from the placement area appear to exceed losses in the absence of fill.

Alternatives for addressing erosion in the future

Removing the marina and bulkhead would provide sediment to nourish the adjacent beach, thereby providing greater protection to the Sunken Forest. This option does not seem justified, given the loss of visitor access, the cost of removing the structure and the economic and environmental costs of creating access elsewhere. Bulkhead removal would not prevent long-term erosion of the Sunken Forest, because the bay shoreline in this portion of the island would continue to erode, although at a lesser rate.

Allowing the Sunken Forest to erode is a potential option. Erosion of the upland and marsh would provide sediment to help retain a narrow beach, so beach habitat is not threatened as long as a sediment supply and space to migrate exist. The Sunken Forest cannot replace itself readily, and it has stature as a human-designated resource, which argues for protecting it in place. The erosion problem is exacerbated by a prior human action, which justifies active mitigation (NPS 2006).

Bulkheads are a common response to erosion on low energy shores in the USA, because they are affordable, provide protection in limited space, and need not alter much of the offshore bottom (Nordstrom and Jackson 2012). Bulkheads are allowed in the developed communities in Great South Bay, but NPS policies severely restrict use of new shore protection structures. A human structure would sever the connection between the natural bay habitat and the natural habitat inland, and the static structure would contribute to total loss of beach in only a few years. Addressing erosion of the Sunken Forest using beach nourishment is a more compatible alternative, in that it would allow for existing uses of the marina while addressing the erosion problem adjacent to it in a more environmentally compatible way. Sources of fill include sediment dredged from the navigation channel, sediment bypassed from the east side of the marina, and sediment brought in from outside the bay system. Using sediment dredged from the ecologically productive bay bottom outside the navigation channel is not allowed by existing state regulations.

Obtaining sediment for future nourishment projects

Sediment bypassing across navigation channels and use of dredged sediment from external sources as beach fill are recommended practices for addressing sediment imbalances at inlets modified by structures (Dombrowski and Mehta 1993; Montague 2008; Castelle et al. 2009; Rodríguez and Dean 2009; Keshtpoor et al. 2013). Use of sediment from navigation channels is desirable to save the costs of using external sources (van de Graaff et al. 1991; Frihy et al. 2016). Continued use of sediment dredged from the channel leading to the marina appears warranted, because the sediment is well matched to native material. The amount of sediment placed adjacent to the bulkhead in 2011 and 2015 was not enough to prevent ongoing erosion of the upland close to the structure. The rate of fill removal west of the marina in 2011 (Nordstrom et al. 2016) indicates that about 1200 m^3 $year^{-1}$ would be necessary to replenish annual losses just to keep pace with erosion. Maintenance dredging during the 6 years that elapsed between the 2011 project and the December 2017 surveys provided only 2846 m^3 (474 m^3 $year^{-1}$). Maintenance dredging is not currently projected for the navigation channel. If beach fill is selected as the best alternative for addressing erosion, additional sediment would have to come from a mechanical bypassing operation or from an external source.

Sediment bypassing is effective, where accretion rates updrift of structures are similar to erosion rates downdrift, the quantities bypassed are adjusted to these rates, and bypassing continues through time (Keshtpoor et al. 2013). At Sailors Haven, net movement is away from the bulkhead on both sides, so mechanical bypassing does not appear to be a viable method for overcoming the detrimental effects of the marina on the longshore sediment budget.

The lower rate of beach loss on the east side of the marina than on the west side implies that the net direction of longshore transport in the absence of the marina would be from east to west in this portion of Fire Island. Easterly transport on the east side of the bulkheads at Sailors Haven and Fire Island Pines indicate that those bulkheads partially counteract westerly transport during easterly winds, at least close to the structures. Wave and water level data gathered on the west side of the Sailors Haven bulkhead (Jackson et al. 2017) indicate that wave interactions with the structure induced westerly transport during westerly winds. Westerly transport also occurred during the present study despite the dominance of westerly winds (Fig. 4). The flow counter to wind approach was attributed to wave reflection off the bulkhead or compensating flows from setup near the structure as revealed by lower frequency energy in the velocity spectra on those days (Jackson et al. 2017). These mechanisms for flow reversal may occur on the east side during easterly winds.

Sediment delivery from inlet formation, storm-wave overwash and dune migration has not been prevented (Fig. 9), but it has been greatly restricted by beach nourishment, dune building and dune stabilization projects on the ocean shore. Bulkheads constructed on the bayside within the developed communities on the island have also reduced sediment inputs to the beach. Erosion is pervasive all along the bay shore in the central portion of the island, not just adjacent to bulkheads (Nordstrom et al. 2009). This problem of sediment starvation on estuarine shores is common on developed barrier islands, where cross-shore sediment transfers are prevented (Jarrett 1983). Creating artificial fans by placing fill sediment on the bayside but not on the marsh would be a creative way to mimic incipient natural landforms. The extent of overwash on the east side of the marina during Hurricane Sandy indicates that overwash could reach the bay in a storm of greater magnitude or duration. The marina would likely occupy part of the footprint of a large overwash fan, and the bulkhead at the marina would interfere with natural westerly transport of the bulk of the sand residing in a fan east of the marina. Accordingly, placement of sand west of the marina appears to be warranted in any project to create an overwash fan near the marina. A sand bypass operation would have no value now, because there is so little sand moving from the east, but that condition would change dramatically if an artificial overwash fan is created east of the marina, where overwash is now favored (Fig. 9).

Placing fill at widths and elevations that exceed the dimensions of natural beaches is commonly done to increase protection to landward facilities, provide space for adjustment of the fill to a natural profile and reduce the mobilization costs of more frequent small-scale operations (National Research Council 1995), but oversize projects greatly alter natural processes and functions. The small 2011 and 2015 operations were practical, because the need to dredge the channel made mobilization costs moot, and the small volumes of sediment supplied did not dramatically alter the character of the shore. Large scale nourishment projects would alter more of the bay bottom and likely increase the potential for aeolian transport into the forest and marsh. The area of bay bottom greatly exceeds the area of beach and maritime forest, making bay bottom habitat less threatened under current conditions. Vegetation plantings may be required on artificially created washover deposits to reduce the potential for aeolian transport into the maritime forest.

Nourishing beaches bayward or updrift of critical natural landforms and habitats that need time to evolve provides a way of protecting those features while allowing natural processes to prevail. The environment subject to wave reworking would be the beach and washover fans. The long-evolving marine forest habitat would remain unaffected by erosion, but remain in place in the ecological gradient. The advantage of restoring sediment via human action, rather than natural processes, is that the fill can be directly placed to mimic the incipient stages of natural landforms. Natural inlet, overwash and dune processes, if allowed to occur unfettered by human action would deliver sediment across the island, over and through pre-existing stable habitat, eliminating some of the features that take so long to form.

Conclusions

Placing fill at the elevation of the natural storm berm allows for natural interaction between the beach and landward habitat, reduces the likelihood for development of an erosional scarp in the beach and restricts the amount of sediment transported inland by wind. Placement of fill bayward of peat and eroding trees enhances movement of sediment downdrift. Return to marsh barrier systems and eroding uplands with trees and tree roots exposed occurs as the fill passes through, reducing rates of transport alongshore. Large peat headlands can trap sediment updrift and reduce longshore transport rates but allow sediment to pass when peat is eroded. Under present conditions, sediment bypassing and maintenance dredging do not provide sufficient sediment to counteract local erosion. Adding fill material on the bayside to mimic artificial fans can deliver sediment alongshore in a way that replicates the erosional stage of the fans without replicating the natural depositional phase that would involve storm-wave overwash and be accompanied by loss of pre-existing upland or marsh habitat.

References

Anthony EJ, Marriner N, Morhange C (2014) Human influence and the changing geomorphology of Mediterranean deltas and coasts over the last 6000 years: From progradation to destruction phase?. Earth Sci Rev 139:336–361

Brutsché K, Wang P, Rosati JD, Beck TM (2015) Evolution of a swash zone berm nourishment and influence of berm elevation on the performance of beach-nearshore nourishments along Perdido Key, Florida, USA. J Coastal Res 31:964–977

Castelle B, Turner IL, Bertin X, Tomlinson R (2009) Beach nourishments at Coolangatta Bay over the period 1987–2005: Impacts and lessons. Coast Eng 56:940–950

Cooper JAG, McKenna J (2008) Working with natural processes: the challenge for coastal protection strategies. Geogr J 174:315–331

de Schipper MA, de Vries S, Ruessink G, de Zeeuw RC, Rutten J, van Gelder-Maas C, Stive MJF (2016) Initial spreading of a mega feeder nourishment: observations of the Sand Engine pilot project. Coast Eng 111:23–38

Dean RG (2002) Beach nourishment: theory and practice. World Scientific Publishing Company, Singapore

Dombrowski MR, Mehta AJ (1993) Inlets and management practices: southeast coast of Florida. J Coastal Res SI18:29–57

Edinger GJ, Evans DJ, Gebauer S, Howard TG, Hunt DM, Olivero AM (eds) (2014) Ecological Communities of New York State, 2nd edn. State Department of Environmental Conservation, Albany, NY, A revised and expanded edition of Carol Reschke's Ecological Communities of New York State. New York Natural Heritage Program

Folk R, Ward WC (1957) Brazos river bar: a study in the significance of grain size parameters. J Sediment Petrol 27:3–26

Freire P, Andrade C (1999) Wind-induced sand transport in Tagus estuarine beaches – first results. Aquat Ecol 33:225–233

Freire P, Taborda R, Silva AM (2007) Sedimentary characterization of Tagus Estuarine Beaches (Portugal). J Soils Sediments 7:296–302

Frihy OE, Deabes EA, Helmy EF (2016) Compatibility analysis of dredged sediments from routine pathways and maintenance of harbor's channels for reuse in nearshore nourishment in the Nile Delta, Egypt. J Coastal Res 32:556–566

Gómez-Pina G, Muñoz-Pérez JJ, Fages L, Ramírez JL, Enriques J, de Sobrino J (2004) A critical review of urban beach nourishment projects in Cadiz City after twelve years. In: Coastal engineering 2004: proceedings of the 29th international conference. American Society of Civil Engineers, New York, pp 3454–3466

Helewaut M, Malherbe B (1993) Design and execution of beach nourishments in Belgium. In: Hillen R, Verhagen HJ Coastlines of the Southern North Sea. American Society of Civil Engineers, New York, pp 258–266

Jackson NL, Smith DR, Tiyarattanachi R, Nordstrom KF (2007) Use of a small beach nourishment project to enhance habitat suitability for horseshoe crabs. Geomorphology 89:172–185

Jackson NL, Nordstrom KF, Saini S, Smith DR (2010) Effects of nourishment on the form and function of an estuarine beach. Ecol Eng 36:1709–1718

Jackson NL, Nordstrom KF, Farrell EJ (2017) Longshore sediment transport and foreshore change in the swash zone of an estuarine beach. Mar Geol 386:88–97

Jarrett JT (1983) Changes of some North Carolina barrier islands since the mid-19th century. In: Coastal Zone 83. American Society of Civil Engineers, New York, pp 641–661

Keshtpoor M, Puleo JA, Gebert J, Plant NG (2013) Beach response to a fixed sand bypassing system. Coast Eng 73:28–42

Leatherman SP, Allen JR (eds) (1985) Geomorphic analysis: fire Island Inlet to Montauk Point. Reformulation Study. U.S. Army Corps of Engineers, New York, Long Island

Lentz EE, Hapke CJ (2011) Geologic framework influences on the geomorphology of an anthropogenically modified barrier island: assessment of dune/beach changes at Fire Island, New York. Geomorphology 126:82–96

Montague CL (2008) Recovering the sand deficit from a century of dredging and jetties along Florida's Atlantic Coast: a reevaluation of beach nourishment as an essential tool for ecological conservation. J Coast Res 24:899–916

National Oceanic and Atmospheric Administration (NOAA) (2018) Quality controlled local climatological data. National Centers for Environmental Information, Washington

National Park Service (NPS) (2006) National park service management policies. U.S. Government Printing Office, Washington

National Research Council (1995) Beach nourishment and protection. National Academy Press, Washington

National Research Council (2014) Reducing Coastal Risks on the East and Gulf Coasts. National Academy Press, Washington

Nordstrom KF, Jackson NL (2012) Physical processes and landforms on beaches in short-fetch environments in estuaries, small lakes and reservoirs: a review. Earth Sci Rev 111:232–247

Nordstrom KF, Jackson NL, Rafferty P, Raineault NA, Grafals-Soto R (2009) Effects of bulkheads on estuarine shores: an example from Fire Island National Seashore, USA. J Coast Res SI56:188–192

Nordstrom KF, Jackson NL, Farrell EJ, Rafferty P, Tengwall C (2016) Restoring sediment to compensate for human-induced erosion of an estuarine shore. Geomorphology 262:37–46

Orford JD, Pethick J (2006) Challenging assumptions of future coastal habitat development around the UK. Earth Surf Proc Land 31:1625–1642

Peterson CH, Bishop MJ, D'Anna LM, Johnson GA (2014) Multi-year persistence of beach habitat degradation from nourishment using coarse shelly sediments. Sci Total Environ 487:481–492

Reid J, Santana GG, Klein AHF, Diehl FL (2005) Perceived and realized social and economic impacts of sand nourishment at Piçarras Beach, Santa Catarina, Brazil. Shore Beach 73(4):14–18

Rodríguez EL, Dean RG (2009) A sediment budget analysis and management strategy for Fort Pierce Inlet, Florida. J Coastal Res 25:870–883

Roman CT (2017) Salt marsh sustainability: challenges during an uncertain future. Estuaries Coasts 40:711–716

Rosen PS (1980) Erosion susceptibility of the Virginia Chesapeake Bay shoreline. Mar Geol 34:45–59

Shipman H (2001) Beach nourishment on Puget Sound: a review of existing projects and potential applications. Puget Sound Research 2001. Puget Sound Water Quality Action Team, Olympia, pp 1–8

Van de Graaff J, Niemeyer HD, van Overeem J (1991) Beach nourishment, philosophy and coastal protection policy. Coast Eng 16:3–32

van der Wal D (1998) The impact of the grain-size distribution of nourishment sand on aeolian sand transport. J Coast Res 14:620–631