

Article

# Sediment Budget and Geomorphological Evolution of the Estuarine Dune-Beach System on Three Nourished Beaches, Delaware Bay, New Jersey

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**Abstract:** Beach nourishment was applied at three fetch-restricted sites along the estuarine margin of Delaware Bay, New Jersey. Evaluation of geomorphological performance of the nourishment project was conducted through seasonal monitoring to track linear features (shoreline, dune crest, peat edge) and to create digital elevation models (DEMs). Comparisons of the DEMs yielded sediment budgets of the updrift, fill area, and downdrift zones as well as the spatial and temporal evolution of the tidal flat, beach, and dune features within the zones. Through four years, Moore’s Beach lost all of the emplaced fill as well as an additional  $-5446\text{ m}^3$  from the fill area. The shoreline position shifted inland  $-12.78\text{ m}$ , and the foredune crest shifted inland  $-9.23\text{ m}$ . The fill area at Pierce’s Point lost all of the fill and an additional  $-3810\text{ m}^3$ . The shoreline and dune crest shifted inland  $-7.35\text{ m}$  and  $-1.17\text{ m}$ , respectively. The Reed’s Beach study area benefited from beach fill updrift that more than offset the losses in the fill area, a net gain of  $2107\text{ m}^3$ . There was a major contrast in volumetric change between the updrift and downdrift portions. Sediment budget calculations established alongshore transport was an important factor in the fetch-restricted estuarine environment driving the variable geomorphological responses in the updrift, fill, and downdrift zones.

**Keywords:** metrics of change; digital elevation models; alongshore transport; performance evaluation; barrier island rollover

## 1. Introduction

Hurricane Sandy struck the New York–New Jersey area in late October 2012 with record storm surge and vast coastal erosion [1]. In the aftermath of Hurricane Sandy, a variety of efforts associated with beach nourishment were applied to re-build the beach and dune system and to re-create its geomorphological character and accompanying habitats. Subsequently, in 2016, the National Fish and Wildlife Foundation (NFWF) funded several proposals to assess the outcomes of beach nourishment projects that were conducted to assist in the recovery [2]. This is a study from one of the NFWF-funded projects: detailing the methodology applied, the metrics derived, and the evaluation of the nourishment products at three beaches in the Delaware Bay estuary, New Jersey (Figure 1).

Estuarine beaches in sites of restricted fetch are especially vulnerable to storm impacts because of a lack of a continuing input of sediment supply to buffer episodic sediment loss [3,4]. Estuarine beaches are also prone to a stepwise displacement that may result in the loss of beach and dune features as well as components of the habitat because of negative sediment budget at the local scale. Attempts at modifying sediment budget through beach nourishment offer an opportunity to re-establish the beach and dune features and their associated habitats. However, the continued retention of the morphological

features remains dependent on the spatial sediment budget and the temporal evolution of the site. This study provides metrics on the morphological characteristics of sites of three estuarine beaches in New Jersey that were eroded during Hurricane Sandy, received post-Sandy nourishment to improve horseshoe crab and red knot habitat, and have evolved under the post-Sandy drivers of limited sediment availability, fetch-restricted incident wave energy, local sediment budget, and long-term impacts of sea-level rise [5,6]. A comparative analysis of the sites at four different points in time is derived through the construction and compartmentalization of digital elevation models of recovery, retention, and displacement of the offshore tidal flats, beaches, and dune features at the three sites.



**Figure 1.** Location of study sites monitored within Delaware Bay. Inset has the location of the sites within the east coast of the United States.

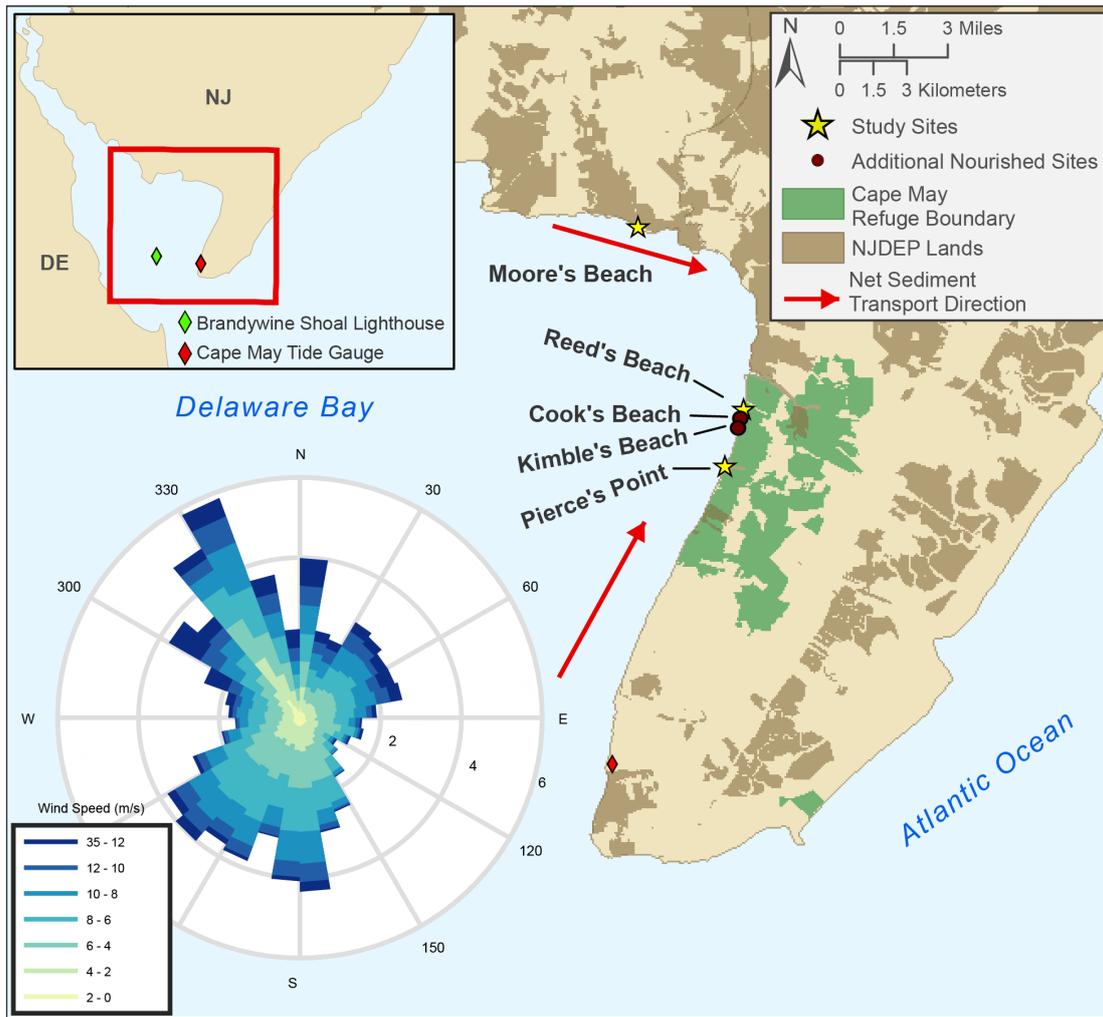
In the US, a long history of placing sediment on beaches to balance the local sediment budget has resulted in reviews of the efficacy of such action as well as the arguments that sediment placement both restores habitats and provides additional buffering to the anthropogenic development inland of the nourished beaches [7–13]. Estuarine beaches have become the sites of increased interest for sediment placement as development pressures and management issues have increased [3,14–18]. The expanded interest has also been augmented by the relatively recent creation of National Estuarine Research Reserves at 29 sites within the USA that incorporate a variety of projects intended to reduce the effects of erosion and to promote the regeneration of the habitats in this reduced energy environment [19]. Among this site-specific interest in estuarine beaches, there is a concern for the temporal and spatial connection between actions and the resulting impacts expressed as an element in evaluation of performance in coastal restoration attempts [4,20], incorporating a need to consider the impacts of outcomes as well as the achievement of goals.

As a means to provide evaluation of the geomorphological vectors of change at the local level, Sherman [21] and Rosati [22] have indicated that the most informative metric is sediment budget, the spatial-temporal measure of sediment input and output at the scale of several kilometers. Cooper and Pethick [23] and Marchand et al. [24] indicate that sediment budget is appropriate to management decision-making because the scales of application are similar. This attribute is linked to the portrayal of

sediment budget and outcomes as net conditions at the temporal scale rather than a focus on individual events [25–27]. Therefore, the data gathering thrust in this study is directed toward a collection of datasets on a seasonal basis that represent steps in the vectors of change to generate metrics of net sediment budget and evolution of geomorphological features associated with the beach nourishment.

### *1.1. Local Drivers*

A primary driver of shoreline response is the incident wave record that establishes the net direction and magnitude of inshore sediment transport. Whereas there is no long-term record of the waves present along these three estuarine locations in Delaware Bay, a wind record does exist at a buoy located in the bay [28] (Figure 2). These data indicate major wind directions are from the northwest and from the southwest, thereby having considerable effect on the New Jersey side of Delaware Bay. However, the southwest winds (and associated waves and currents from the southwest) are dominant at the study sites because of the sheltering effect of the landmass to the north of the three sites. The result is a net dominant flow and alongshore transport to the north at Pierce's Point and Reed's Beach, and a net dominant flow and alongshore transport to the east at Moore's Beach. Furthermore, the restricted-fetch environment limits the potential for incident waves to interact with the offshore sediments, thereby reducing the opportunity for cross-shore transport [29–32]. The result is a relative concentration of sediment transport along the beach face and nearshore by alongshore processes and interaction with natural and anthropogenic features in the vicinity of the shoreline.



**Figure 2.** Wind rose from Brandywine Shoal Lighthouse data [28], with net alongshore transport direction at the study sites. Inset has location of lighthouse and Cape May tide gauge within the Delaware Bay.

A secondary driver affecting morphological development at these sites is relative sea-level rise. The record at the nearby Cape May tide gauge indicates a rate of 4.57 mm/year [33] (Figure 3). Coupled with a negative or balanced sediment budget, the morphological effect in this barrier island environment is the variable rate of inland displacement of the beach and dune features that migrate over an adjacent wetland and result in outcrops of peat in the beach profile in a rollover mode [23,34] (Figure 4). As the beach feature migrates inland, the exposed peat feature will erode as well. However, it may be displaced at a different rate due to it not eroding as individual grains, but as larger masses of peat. Locations of tidal channels, overwash deposits, inland topography, and local sediment supply will determine the location and extent of peat exposures at the shore and the extent of the subaerial and nearshore sand features.

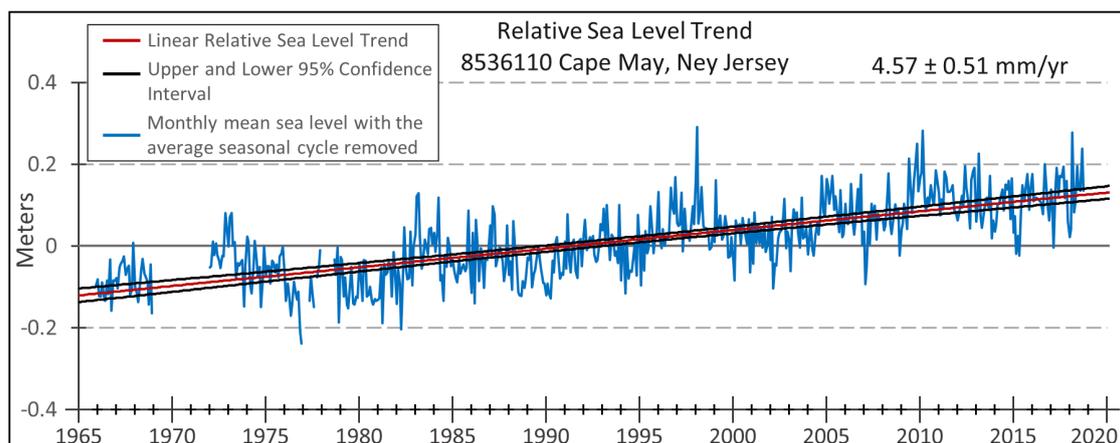


Figure 3. Record of mean sea level position adapted from [33], Cape May, New Jersey, tide gauge #8536110.

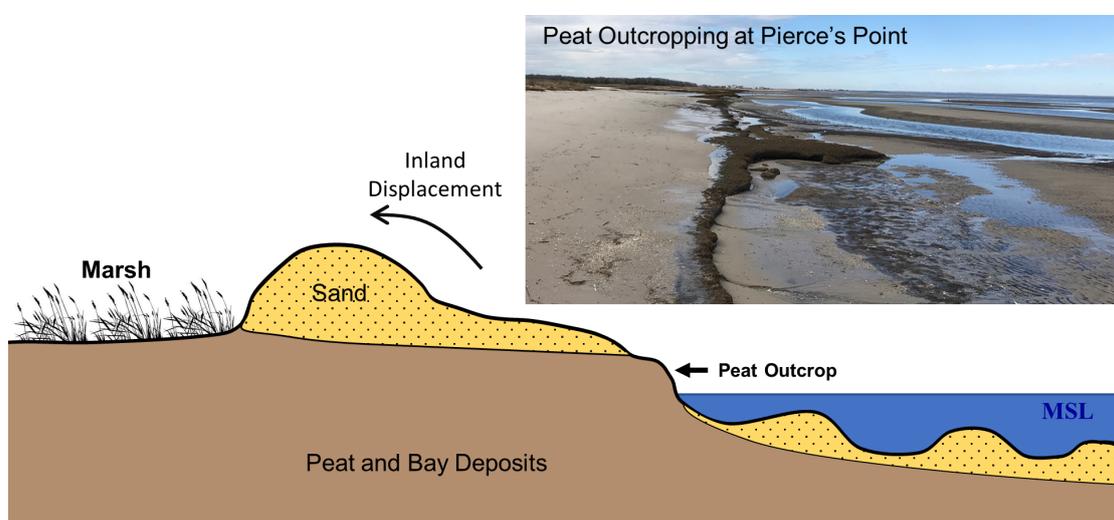


Figure 4. Conceptual relationship of inland displacement of beach topography associated with negative sediment budget and sea-level rise. Subaerial beach and dune forms migrate inland over marsh to result in peat outcrops lower in the beach/dune profile. Peat may be thin or thick layers dependent on scale of negative sediment budget and rate of sea-level rise. Photo by N. Psuty, 3 March 2017.

## 1.2. Site Locations

In general, the estuarine beaches along the New Jersey portion of Delaware Bay occur along narrow barrier spits and barrier islands separated from the mainland by a wetland [35], a classic barrier island scenario. Several small streams drain the mainland but do not transport sufficient sediment to create deltaic forms at their mouths nor contribute much to alongshore transport. As a result, most of the estuarine coast is characterized by short tidal creeks with small shoals at the creek mouths, and a suite of subaerial geomorphological features that accompany the inland transgression of the barrier island across the adjacent marshland. The presence of groins and jetties on the shoreline alter the alongshore transport processes, and bulkheads associated with housing impact the resulting beach and dune geomorphologies at the local level.

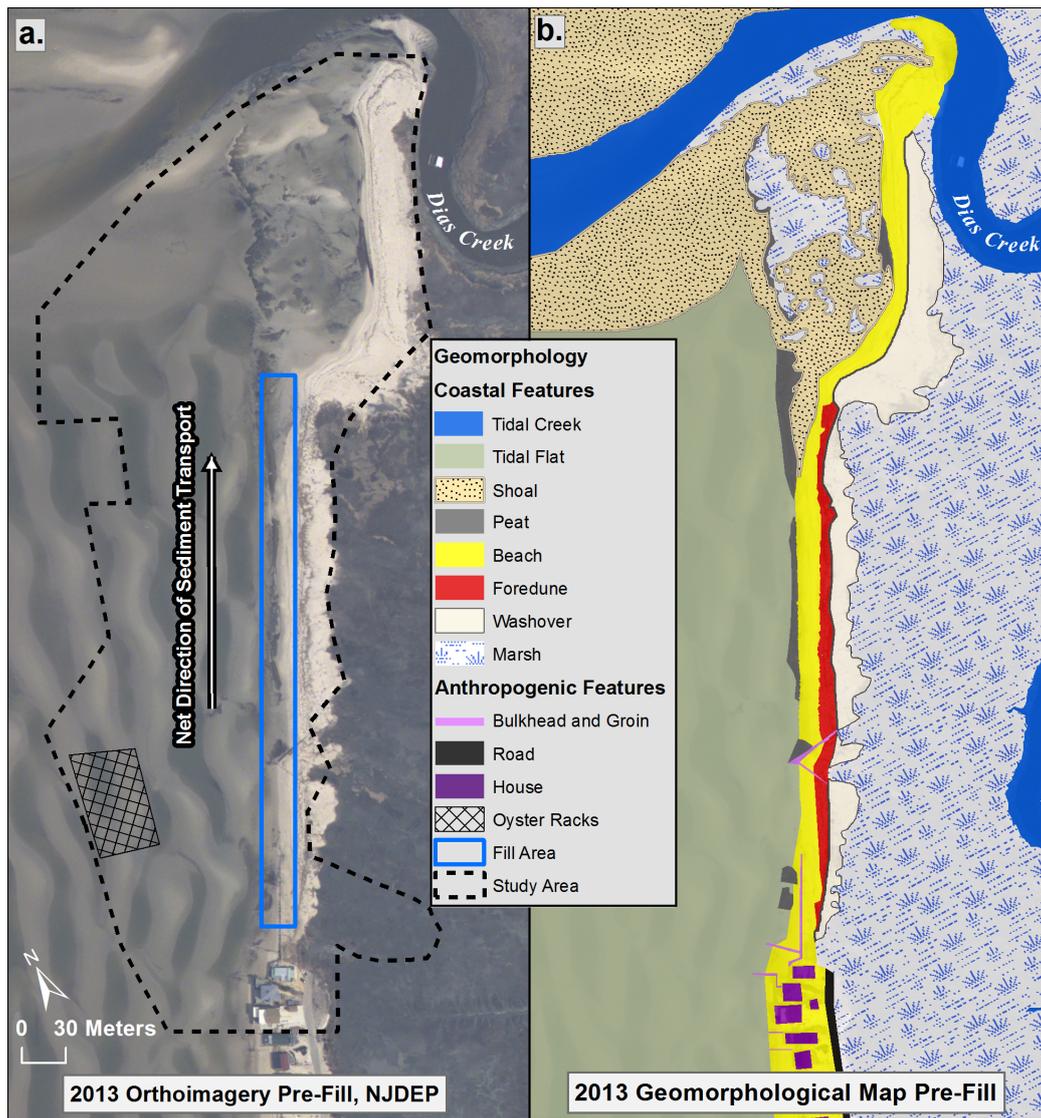
### 1.2.1. Pierce's Point

This study site extends northerly alongshore from a cluster of houses to Dias Creek for 670 m and cross-shore for about 250 m (Figure 5). The houses had bulkheads and short wooden groins on their seaward margin and the presence of a beach-dune morphology was absent for most of the housing development. Prior to the placement of sediment on the beach starting in mid-2013, (Figure 5),

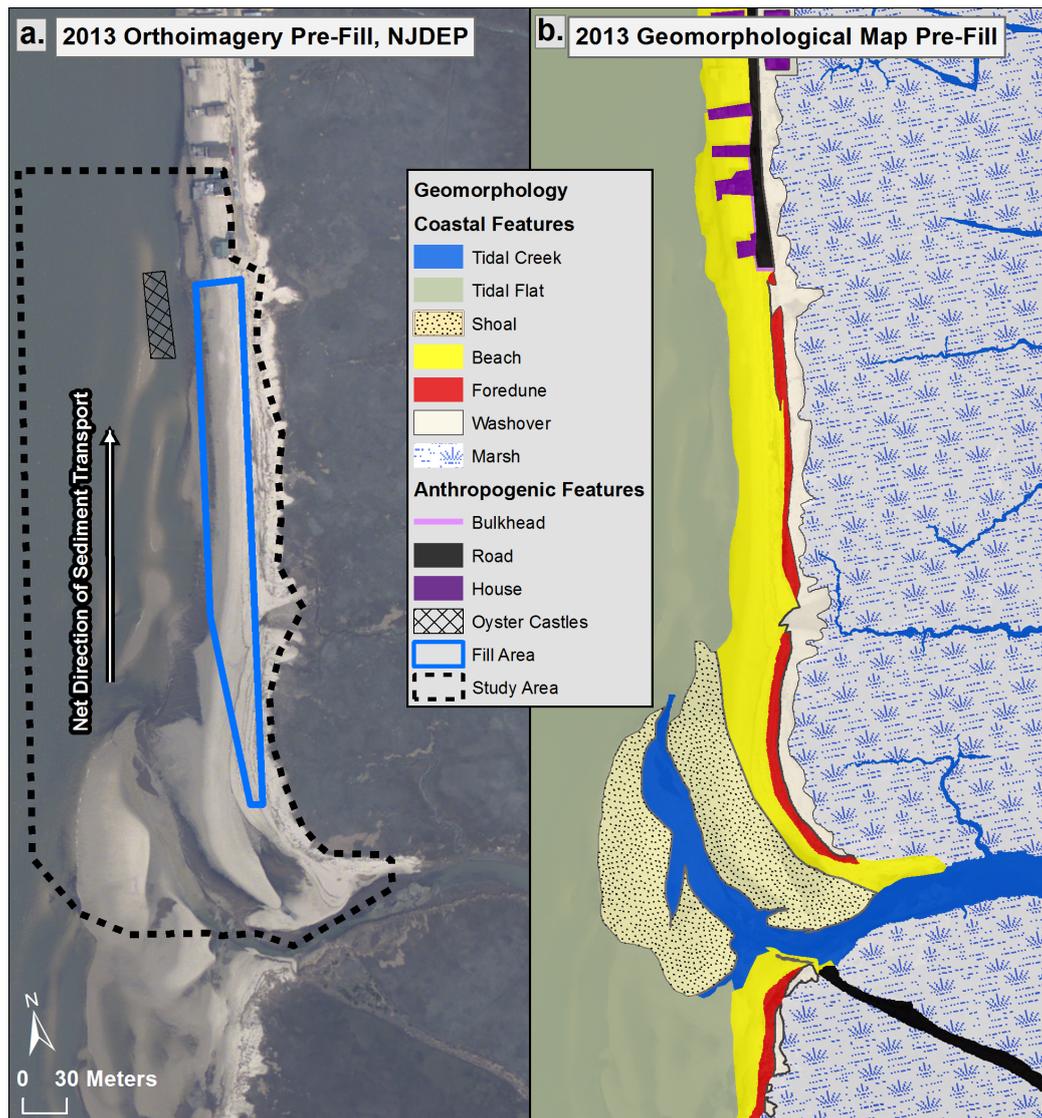
the beach-dune system incorporated variable morphology north from the cluster of houses to Dias Creek (Figure 5). Immediately north of the housing, a deteriorating bulkhead occupied the sandy beach for a distance of 70 m, and a v-shaped bulkhead was present in the beach approximately 130 m north of the housing. Approximately 80 m offshore, there was an active aquaculture site with several rows of oyster racks. North of the housing, the beach was migrating landward, indicating the results of the net direction of the alongshore transport and a negative sediment budget interacting with the impact of the structures. North of the deteriorated bulkhead, overwash and eolian transfers extended the dune feature into the adjacent wetland. Erosion of the beach zone resulted in an inland displacement and exposure of the marsh peat at several locations in the study area. The northerly alongshore sediment transport caused the buildup of a small beach feature into the creek mouth at Dias Creek, in the vicinity of exposed peat and active marsh in the beach zone. Several shoals developed near the mouth of Dias Creek, and patches of sediment accumulated on the marsh surface in the vicinity of the creek mouth. The shoals further mark the boundary of the interaction of the tidal creek flows with the northerly alongshore transport. In 2013 and 2014, 7651 m<sup>3</sup> of sand were trucked into the site and placed over a length of 360 m north of the development (Figure 5).

### 1.2.2. Reed's Beach

The study area has an alongshore length of 520 m and a cross-shore width of 120 m. This site is located at the southern margin of a zone of accumulation updrift of the jetty at Bidwell Creek, approximately 1.3 km to the north. The beach-dune system at this site in 2013 (Figure 6) extended south of housing to a tidal creek. The entire group of housing was lined by a bulkhead on its seaward margin. There was no subaerial beach-dune system seaward of the housing, the high tide swash line reached the bulkhead. The coastal dune feature was displaced inland in the area to the south of the housing, with no apparent seaward accumulation associated with the net south to north sediment transport direction. There were a few breaks in the dune feature where sediment in the form of washover fans had been transported inland to the marsh. The dune form had a well-defined ridge line in the northern portion of the site and was less well-defined to the south. There were no peat outcrops in the beach face. There were sand shoals exposed at the margin of the creek at low tide. A narrow series of shore parallel bars and troughs were present on the tidal flat at this site. In addition to the sediment placement of 3204 m<sup>3</sup> directly on Reed's Beach in 2013 (Figure 6), two beaches immediately to the south received trucked sand as well. Cook's Beach was the recipient of 3053 m<sup>3</sup> and 12,120 m<sup>3</sup> was placed at Kimble's Beach. In the post-fill period, two rows of oyster castles, mounds composed of recycled oyster shell, were installed approximately 20 m offshore in the northern portion of the site in an attempt to reduce wave energy and alongshore transport.



**Figure 5.** (a) 2013 Pre-Fill orthoimagery of Pierce’s Point from the New Jersey Department of Environmental Protection (NJDEP) [36]. Beach nourishment was accomplished to the north of the housing for an alongshore distance of 360 m. (b) Geomorphological map of the Pierce’s Point site prior to placement of sand on the beach, based on air photo interpretation of (a) together with field validation carried out in 2017. Features incorporate the inland displacement of the beach, dune, and washover fans migrating over the wetland to the interior and causing peat to be exposed in the beach zone.

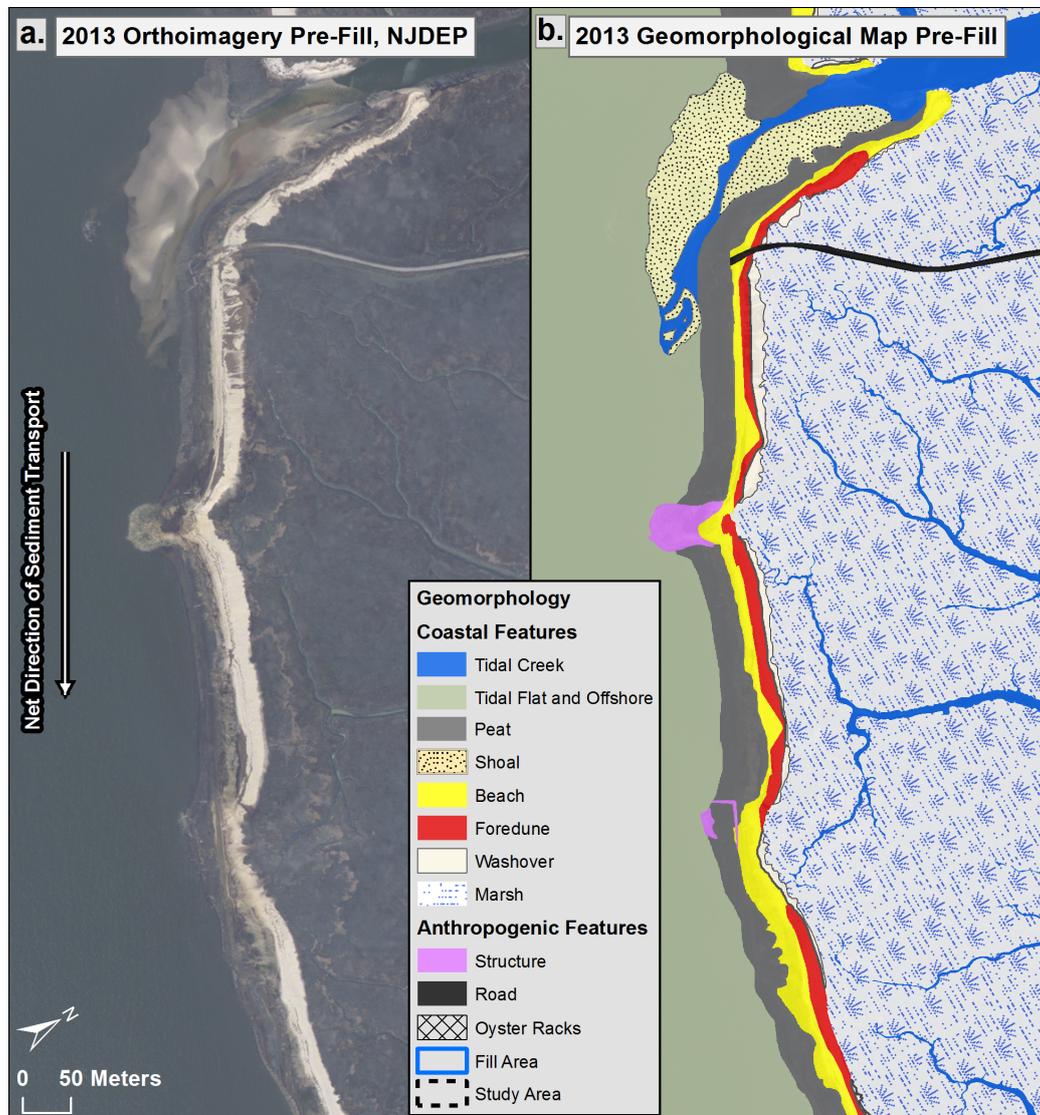


**Figure 6.** (a) 2013 Pre-Fill orthoimagery of Reed's Beach [36]. Beach nourishment was accomplished to the south of the housing for an alongshore distance of 360 m. (b) Geomorphological map of the Reed's Beach prior to placement of sand on the beach, based on air photo interpretation of (a) together with field validation carried out in 2017. Features represented the inland displacement of the beach, dune, and washover fans migrating over the wetland to the interior. The creek mouth was the site of a shoal on the tidal flat and a narrow beach along the northern bank. Few bars and troughs were on the tidal flat.

### 1.2.3. Moore's Beach

The beach-dune system at this site (Figure 7) extends for 1.1 km from a tidal creek at the western margin to a major re-entrant in the shoreline configuration at the east. The study area has a general width of 125 m, tapering to the east. Sediment transport is from west to east. There was a shoal at the creek mouth and a narrow beach along the eastern margin of the creek. Approximately 100 m offshore, the shoal was the site of an active aquaculture project incorporating several rows of oyster racks. A number of foundations of former buildings were in the beach face and on the tidal flat. There was a seaward projection of the shoreline at the location of the cluster of remains of foundations located about midway along the site, and another seaward projection associated with building remains at the eastern margin. Several levels of peat deposits outcropped in the beach face and lower on the profile into the tidal flat. Peat exposures occurred along the entire site in the beach face and into the tidal flat. There were few bars and troughs exposed on the tidal flat. Most of the tidal flat was beyond the depth of the

lower boundary of the survey effort. The foredune area was overwashed at numerous locations and fan-shaped sand deposits extended inland over the adjacent marsh. The trucked sediment, amounting to 17,720 m<sup>3</sup>, was placed on the beach in 2013 and 2014 over a distance of 690 m.

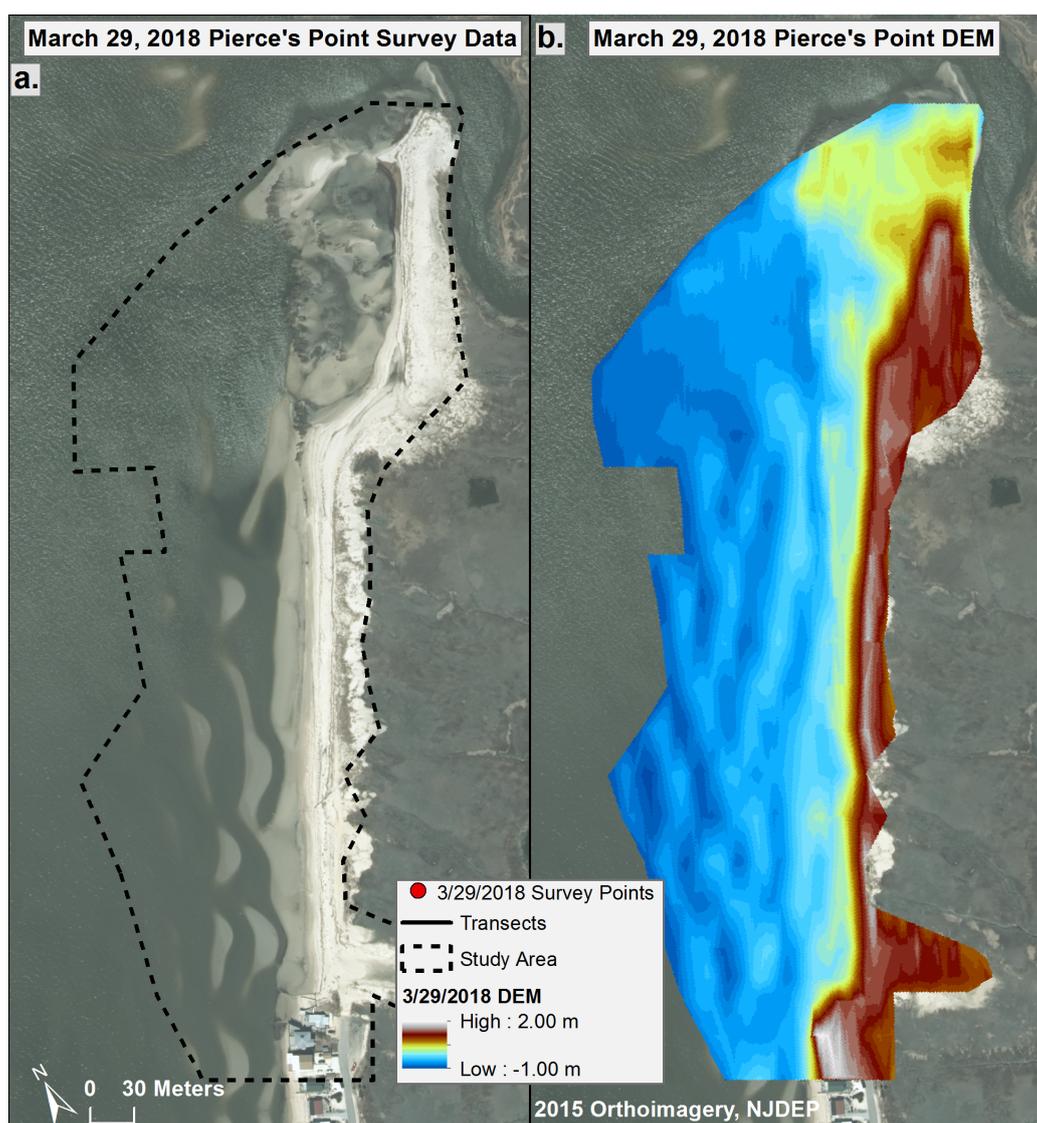


**Figure 7.** (a) 2013 Pre-Fill orthoimagery of Moore’s Beach [36]. Beach nourishment was accomplished in 2013 and 2014 for an alongshore distance of 690 m. (b) Geomorphological map of the Moore’s Beach prior to placement of sand on the beach, based on air photo interpretation of (a) together with field validation carried out in 2017. Features represented the inland displacement of the beach, dune, washover fans migrating over the wetland to the interior. The creek mouth had a narrow shoal on the tidal flat and narrow beach at the eastern bank. Few bars and troughs were on the tidal flat.

## 2. Methods

The basis for the temporal and spatial comparison of vectors of morphological change was the creation of digital elevation models (DEMs) from field surveys [37–40]. Field topographic surveys were conducted with geodetic GPS equipment in real-time kinematic mode along cross-shore transects. Surveys were collected in a time sequence incorporating: (1) GPS survey in 2013, prior to beach nourishment in the post-Sandy period; (2) GPS survey in 2014 post the beach nourishment; and (3) a series of more recently acquired GPS surveys in 2017 and 2018. The timing of these surveys allowed for the characterization of the study site immediately pre- and post-fill. The pre- and post-nourishment

survey dataset was collected by the Richard Stockton Coastal Research Center [5]. Their 2013 and 2014 surveys had a variable transect spacing ranging from 15 m to 120 m; we supplemented their surveys with 2014 LiDAR data where there were gaps in data due to transect spacing [41]. The surveys conducted in 2017 and 2018 were a part of an ongoing monitoring effort to collect spring and fall surveys annually through 2022 [6]. The 2017 and 2018 transects had a spacing of 30 m. An example of the point collection is provided for the 2018 survey at Piece's Point illustrating the concept of using consistent transects to generate a DEM from the interior wetland, across the dune and beach topography, into the tidal flat (Figure 8).



**Figure 8.** (a) Distribution of survey points collected in March 2018 survey at Pierce's Point on 2015 orthoimagery [42]. Transects were spaced at 30 m intervals and points were collected at each break of slope or at 1 second intervals in areas of planar topography. Repetitive seasonal surveys were collected along identical transects. (b) DEM created from March 2018 point data.

DEMs were created by using Delaunay triangulation to interpolate the elevations of the unsurveyed areas between the survey transects [40]. The creation of the DEMs permitted the quantification of resulting forms and the total volume under the produced surface form. Subtracting two DEMs created from different survey periods yielded rasters of elevation change and allowed volumetric change to be quantified. Given these DEMs, they were used to develop dimensional

analyses of sediment budget, characteristics of beach, dune, and tidal flat features, spatial associations, vectors of change, and comparisons of the three sites.

### 2.1. Derived Metrics

**Spatial volume and Sediment Budget:** Values of spatial volume were derived from the full DEM and divided into the several geomorphological feature categories. Geomorphologically, the DEM had elevation zones with the dune feature incorporating elevations above 1.2 m and the beach feature at elevations between  $-0.3$  and 1.2 m. The tidal flat encompassed elevations between  $-0.3$  m to  $-1$  m at Pierce's Point and Reed's Beach, and between  $-0.55$  m to  $-1$  m at Moore's Beach. Sediment budget was derived by comparing volumes in each of the feature categories in the study area. Sediment budget was also calculated for alongshore compartments of the site, at 30 m intervals, and further subdivided into the portion of the site where fill was placed, as well as updrift and downdrift of the fill zone. The elevational basis was a bit more complex at the northern end of Pierce's Point, where the salt marsh existed on the seaward side of the beach in the elevation assigned to the beach feature. In this instance, the area occupied by the saltmarsh was classified as beach because of elevation and morphological position for purposes of volume comparison.

The sediment volumes were determined for each of the compartments at the three sites based on the DEMs for March 2013 (prior to initiation of fill), April 2014 (following completion of the fill at the three sites), April 2017 (initiation of this project), and March 2018 (completion of an annual cycle), and separated into an updrift zone, fill zone, and downdrift zone of the study areas. Gaps in the tables were created when surveys did not overlap, and absences of uncertainty values occur when comparable survey points were missing in a compartment. Volumes were assigned to geomorphological features based on elevation and relative position.

**Linear Features and Displacement:** Additionally, surveyed transects were analyzed to generate traces of the several topographical features from each survey period. Two linear features were determined on the DEMs and tracked through the period of survey: (1) the shoreline position; and (2) the position of the dune crest line.

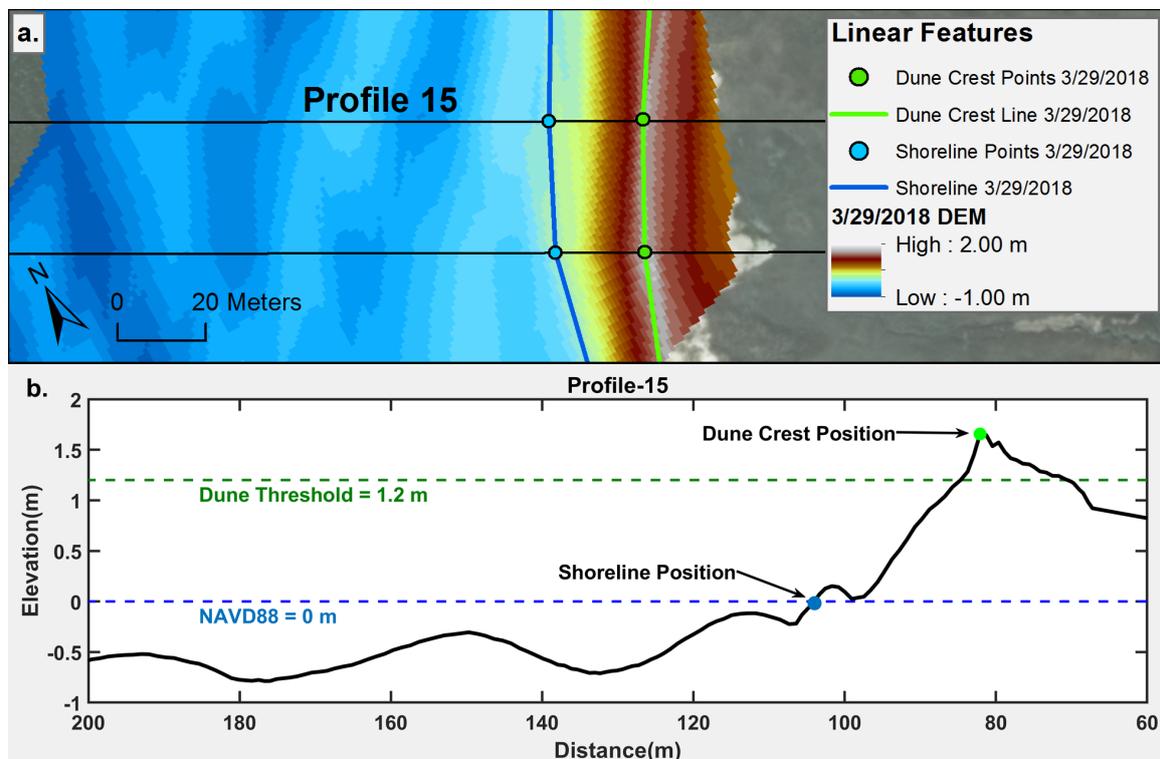
*Shoreline:* The intercept of the NAVD88 0.0 elevation on each transect and along the DEM was used to represent a shoreline position (Figure 9). The use of the constant elevation reduced the uncertainty and permitted a more definite comparison of feature through the five year record. The metric of displacement was determined by the application of the DSAS program created and maintained by the USGS [43] that compares position along established transects to generate vectors of change. The resulting displacement was portrayed temporally and spatially by the Shoreline Mapping Program [44].

*Dune crest:* The dune was a linear feature inland of the active beach. It was usually vegetated but may incorporate aspects of overwash to flatten and extend the feature inland. Profiles were created from the 30 m spaced survey transects and the highest elevation immediately inland of the free sand beach established the position of the dune crest. The dune crest line was the linear connection of the high elevations in the alongshore direction. Dune crests may be interrupted in areas of overwash. Dune crest position and changes were portrayed with the application of DSAS [43] and the Shoreline Change Mapper Program [44].

**Edge of peat outcrop:** in addition to the collection of cross-shore transects, the spatial position of the leading edge of a peat outcrop was tracked in the field at 1 m intervals where it was encountered in each of the 2017 and 2018 surveys. There was no displacement metric generated for the peat outcrop because the peat edge eroded on the basis of undercutting, or protection by overlying sand, or by factors exploiting fractures in the peat mass.

**Cross-section of Geomorphological features:** The spatial boundaries of the tidal flat, beach, dune, washover, and marsh features were determined by their elevations and relative position. Profiles incorporate the locations of the boundaries of the features and their cross-sectional areas encompassed within the DEM. Creating the boundaries and applying them to the DEM were steps in the calculation

of volumes, volume changes, and the resulting sediment budget. In addition, the topographic profiles included the locations of peat outcrop edges when they were present.



**Figure 9.** Determination of linear features: Shoreline position and dune crest. (a) transects across DEM and establishing intercept of shoreline and dune crest, with connections of points from adjacent profiles to establish linear track of feature. 2015 orthoimagery [42]. (b) profile along transect with intercept of NAVD88 datum and determined dune crest position.

### 2.2. Elevation, Volume, and Volumetric Change Uncertainty

DEMs need an uncertainty value to establish some measure of validity to the products, a combination of instrument and interpolation uncertainty. The GPS unit using Real-Time Kinematic (RTK) survey style had a horizontal uncertainty of  $\pm 0.02$  m and vertical uncertainty of  $\pm 0.04$  m determined from comparison with control points and precision reported during quality assurance and quality control checks. Uncertainty introduced by interpolation was quantified by building DEMs with incomplete data sets, missing one transect,  $i$ , and then comparing the interpolated values,  $Z_{Interpolated}$ , with the actual values,  $Z_{Survey}$  at the same location,  $j$ . A measure of elevation uncertainty was calculated by iterating this process for all  $(n - 2)$  transects, omitting only the transects at the boundaries of the survey, and for each point within the survey, a total of  $m$  points. Combining the uncertainty from the instrument,  $U_{Instrument}$  and the error from interpolation in the DEM creation yields an estimate of vertical uncertainty per square meter in the DEM,  $U_{Elevation}$  (Equation (1)). This was used to determine the volume uncertainty,  $U_{Volume}$ , of volumes derived from one survey DEM, using the number of surveyed points,  $p$ , and the area of the DEM (Equation (2)) [36]. Volumetric change uncertainty,  $U_{VolumetricChange}$ , between two DEMs, was calculated using RMSE of the volume uncertainty of the two DEMs (Equation (3)).

$$U_{Elevation} = \frac{\sum_{i=1}^{n-2} \sum_{j=1}^{m_i} |Z_{Interpolated_j} - Z_{Survey_j}|}{Area} + U_{Instrument} \tag{1}$$

$$U_{Volume} = \frac{U_{Elevation}}{\sqrt{p}} \times Area \tag{2}$$

$$U_{VolumetricChange} = \sqrt{U_{VolumeSurvey1}^2 + U_{VolumeSurvey2}^2} \tag{3}$$

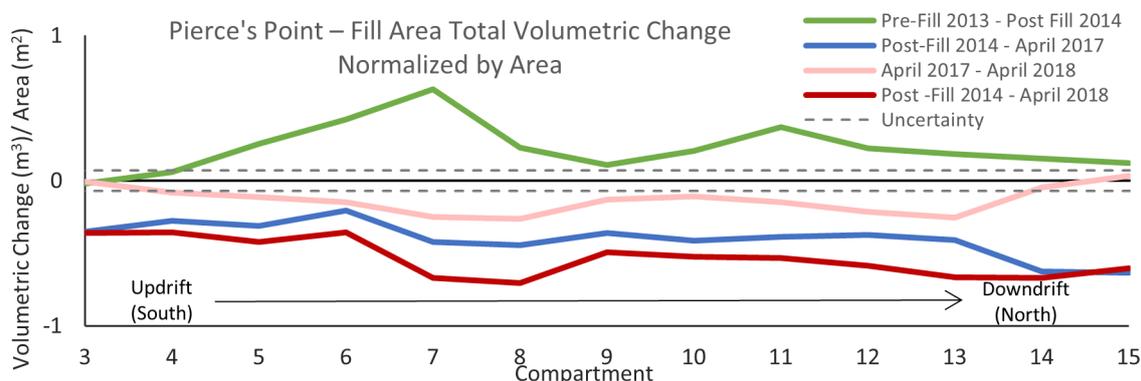
Uncertainty values were calculated for each of the compartment volume determinations and for comparisons between surveys. However, because of the variable spacing of transects between the 2013–2014 and 2017–2018 surveys, there were some compartments used in this analysis that lacked the earlier data points and uncertainty values could not be determined.

### 3. Results

The topographical survey data were processed and analyzed initially to create a measure of the retention of the beach nourishment within the fill area. Subsequent analyses established a matrix of geomorphological features and their spatial and temporal variation, both within the fill area as well updrift and downdrift. The presentation of the datasets plotted the 1D tracking of the peat edge, as well as the determination and displacement of the 1D linear traces of shoreline position and dune crest. Additionally, the cross-shore transects were used to generate representative 2D profiles describing the topographical evolution of the site. The DEMs also contributed information on the distribution and displacement of the tidal flat, beach, and dune features in a temporal sequence. In addition, the DEMs were used to derive metrics on the sediment budget for the site as well as for the geomorphological features in a spatial and temporal context.

#### 3.1. Pierce's Point

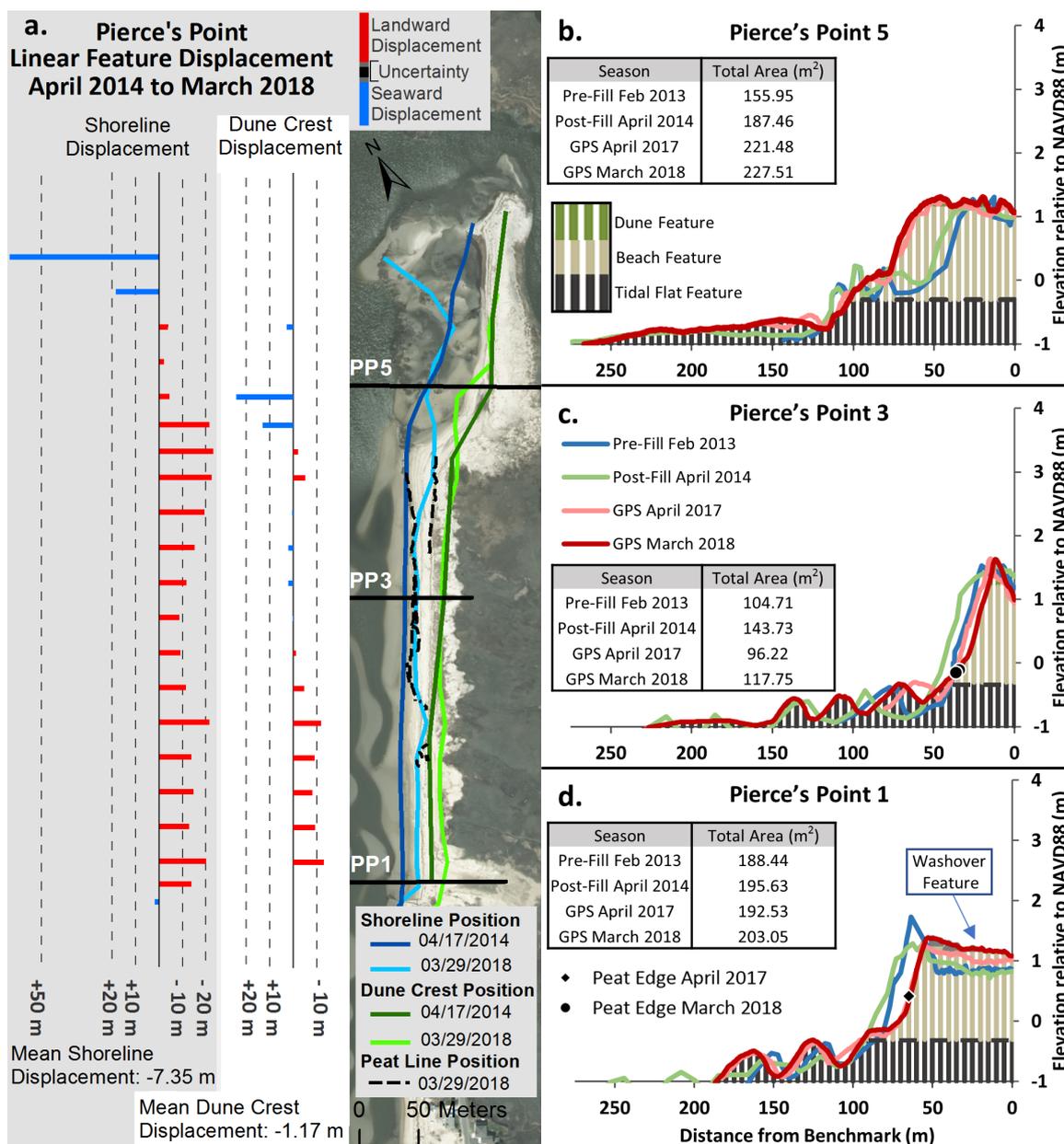
The entire length of the study area at this site consisted of 23 compartments. However, sediment placement via beach nourishment in the fill area was restricted to Compartments 3–15 (Figure 10). The amount of sediment placed in each compartment during the 2013–2014 period and the areas of the compartments varied, especially at the margins. To compensate for this variation, the units of initial accumulation and subsequent change are expressed in m<sup>3</sup> per m<sup>2</sup> of the referenced Compartment. Initially, the fill had a major node at Compartment 7, and a secondary node at Compartment 11. The comparison of the volumes calculated in Spring 2014 to the results from the next survey in April 2017 showed a loss in each of the Compartments except for the most downdrift unit of the fill area, Compartment 15. The next annual period, April 2017–April 2018, recorded a continuation of the removal of the emplaced sediment, with increasing losses downdrift. Over the period from the post-fill survey to Spring 2018, the entirety of the initial accumulation of 3033 m<sup>3</sup> ± 121 m<sup>3</sup> had been eroded, with major losses at the site of the primary node of beach nourishment, a net loss of −6843 m<sup>3</sup> ± 88 m<sup>3</sup>.



**Figure 10.** Volumetric change normalized by compartment area within the fill area at Pierce’s Point. Values between the two grey dashed lines fall within the uncertainty calculation.

The dataset from the entire study area was used to plot the shoreline position (0.0 elevation NAVD88) and the dune crest position (determined from profiles) and to calculate their displacement from the post-fill April 2014 to the March 2018 surveys . The depiction of the comparison (Figure 11a)

was derived from the survey transects spaced 30 m apart for the length of the study area. There was general inland shift of the shoreline position for the length of the sediment placement, resulting in a mean inland displacement of  $-13.04$  m for that portion of the site. The two northernmost transects had the largest seaward displacements, with sediment accumulating on the marsh surface. The updrift portion of the site was affected by the remains of the deteriorating bulkhead that created gaps in the shoreline position at the southern margin of the study area. The shoreline position in the downdrift zone was either stable or shifted seaward, a mean net change of  $4.56$  m. The dune crestline was more stable than the shoreline. It shifted inland in the southern half of the site for a mean net change of  $-1.17$  m, where it existed.



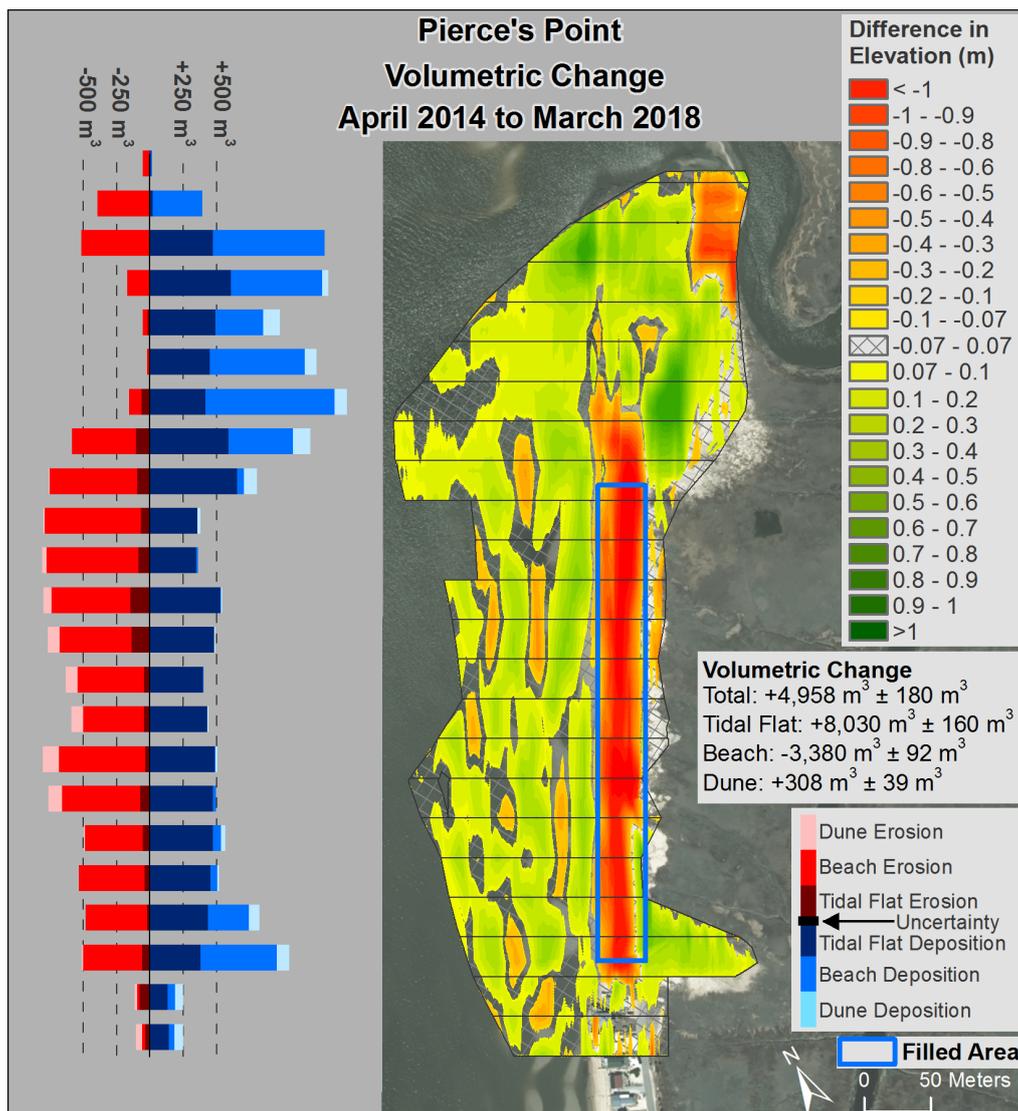
**Figure 11.** (a) Linear displacement of shoreline position and dune crestline, April 2014–March 2018. Shoreline and dune crest position extracted from survey datasets and the location of selected profiles. 2015 orthoimagery [42]. (b–d) Selected profiles February 2013–March 2018.

Geomorphologically, the area immediately north of the housing was the site of a major washover feature that penetrated inland about 80 m during this period. This feature was the site of the deteriorating bulkhead that collapsed during the interval of comparison. The profile at Pierce's Point 1 records the loss of the beach and the accumulation inland of the dune as a large overwash fan (Figure 11d). Although Profile PP1 had a positive cross-sectional growth following the placement of sand on the beach, the subsequent accumulation was entirely in the washover feature. In the vicinity of Profile PP3, the beach fill was entirely removed, and the shoreline and the dune crest shifted inland (Figure 11c). The cross-section area on this profile increased about 40 m<sup>2</sup> because of the beach nourishment but decreased about 26 m<sup>2</sup> from post-nourishment to the March 2018 survey. Profile PP5 records the accumulation of sediment over the exposed marsh and peat outcrop (Figure 11b). This beach form was offset inland about 50 m from the trend of the shoreline to the south. Nearly all of the accumulation was in the beach feature with modest growth in the tidal flat or dune zone. Whereas the post-fill addition to the profile was 32 m<sup>2</sup> compared to the pre-fill transect, the March 2018 survey had an additional increase of 40 m<sup>2</sup>, indicating considerable alongshore transport and accumulation in the post-fill period.

The volume changes at Pierce's Point were determined from a comparison of the post-fill DEM and the March 2018 DEM (Figure 12, Table 1). The general outcome of the comparison of elevations depicts a broad band of volume loss in the vicinity of the beach fill and a gain in tidal flat bars and troughs, a gain downdrift of the fill, and a gain in a large washover fan immediately north of the housing. The volume changes are further portrayed in 30 m wide alongshore compartments and the positive and negative totals for the compartments are assigned to tidal flat, beach, and dune features grouped by elevation boundaries. The dominant trend was a loss of beach volume with most of the loss in the zone of beach nourishment. Only seven of the compartments showed a gain the dune zone, essentially in the overwash area extending inland across the marsh. The tidal flat was the major area of accumulation over the period; all but one Compartment had a positive budget in the tidal flat. In the four years following a recorded net gain from beach nourishment of 3033 m<sup>3</sup> ± 87 m<sup>3</sup>, the beach feature had a net loss of 3380 m<sup>3</sup> ± 92 m<sup>3</sup>, the dune feature had a net gain of 308 m<sup>3</sup> ± 39 m<sup>3</sup>, and the tidal flat had a net gain of 8030 m<sup>3</sup> ± 160 m<sup>3</sup>. In the site, there was a net gain of 4958 m<sup>3</sup> ± 180 m<sup>3</sup>. Volumes within the geomorphological features by survey and by Compartment are compiled in Supplementary Data (Tables S1–S3).

**Table 1.** Volumes by Zone, Feature, and survey period at Pierce's Point. The zones are: Updrift (Compartments 1–2), Fill (3–15), Downdrift (16–23). The asterisk (\*) indicates that uncertainty was not calculated because points were lacking within that zone.

Zone	Feature	Volume (m <sup>3</sup> )			
		Pre-Fill (2013)	Post-Fill (2014)	April 2017	March 2018
Updrift (1–2)	Tidal	3952 ± 12	3954 ± 12	4097 ± 12	4119 ± 12
	Beach	4503 ± 8	4507 ± 8	4605 ± 8	4560 ± 8
	Dune	530 ± 9	528 ± 9	589 ± 8	590 ± 8
Fill (3–15)	Tidal	21,171 ± 206	23,650 ± 206	26,639 ± 38	28,656 ± 38
	Beach	20,436 ± 50	22,419 ± 50	17,398 ± 23	16,290 ± 23
	Dune	1042 ± 58	1058 ± 58	739 ± 12	823 ± 12
Downdrift (16–23)	Tidal	15,962 ± 118	17,591 ± 118	19,287 ± 34	20,450 ± 34
	Beach	14,099 ± 87	13,784 ± 87	16,539 ± 33	16,480 ± 33
	Dune	81*	3*	155 ± 14	483 ± 14
Total		81,774 ± 274	87,493 ± 274	90,048 ± 68	92,451 ± 68

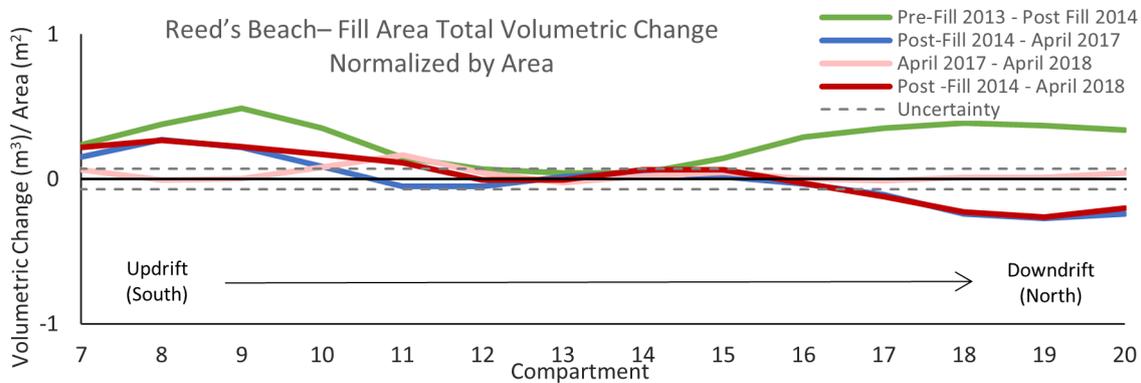


**Figure 12.** Elevation and volumetric change at Pierce’s Point by geomorphological feature, by Compartment, and by study site total, in the comparison of the post-fill (April 2014) survey to March 2018 survey. Compartments are outlined in black, area where fill was placed is outlined in blue. 2015 orthoimagery [42].

### 3.2. Reed’s Beach

The entire length of the study area at this site consisted of 22 compartments. However, sediment placement via beach nourishment in the fill area was restricted to Compartments 7–20 (Figure 13). The amount of sediment placed in each compartment during the 2013–2014 period and the areas of the compartments varied, especially at the margins. To compensate for this variation, the units of initial accumulation and subsequent change are expressed in m<sup>3</sup> per m<sup>2</sup> of the referenced Compartment. Initially, the fill was probably deposited in similar concentrations throughout much of the fill area. However, the interval between the pre-fill and post-fill surveys was likely a period of major change. That comparison showed a major node at Compartment 9 and a broad fill at Compartments 16–20. It is likely that the broad fill in 16–20 was the downdrift transport of the fill, but the node to the south was accumulation received from updrift and not part of the original fill. The comparison of the volumes calculated in April 2014 to the results from the next survey in April 2017 showed a loss in each of the Compartments in the fill area, especially at the downdrift margin. The next annual period, April 2017–April 2018, recorded a modest recovery in Compartments 10–12, and little change in the

downdrift portion of the fill area. Over the period from the post-fill survey to June 2018, there was a reduction of 11% of the April 2014 accumulation of  $2247 \text{ m}^3 \pm 55 \text{ m}^3$  in the fill area, with the primary loss at the northern extent of beach nourishment, a net change of  $-263 \text{ m}^3 \pm 43 \text{ m}^3$ . However, that net volume change is skewed by the transfer of sediment from the updrift beach nourishment sites.



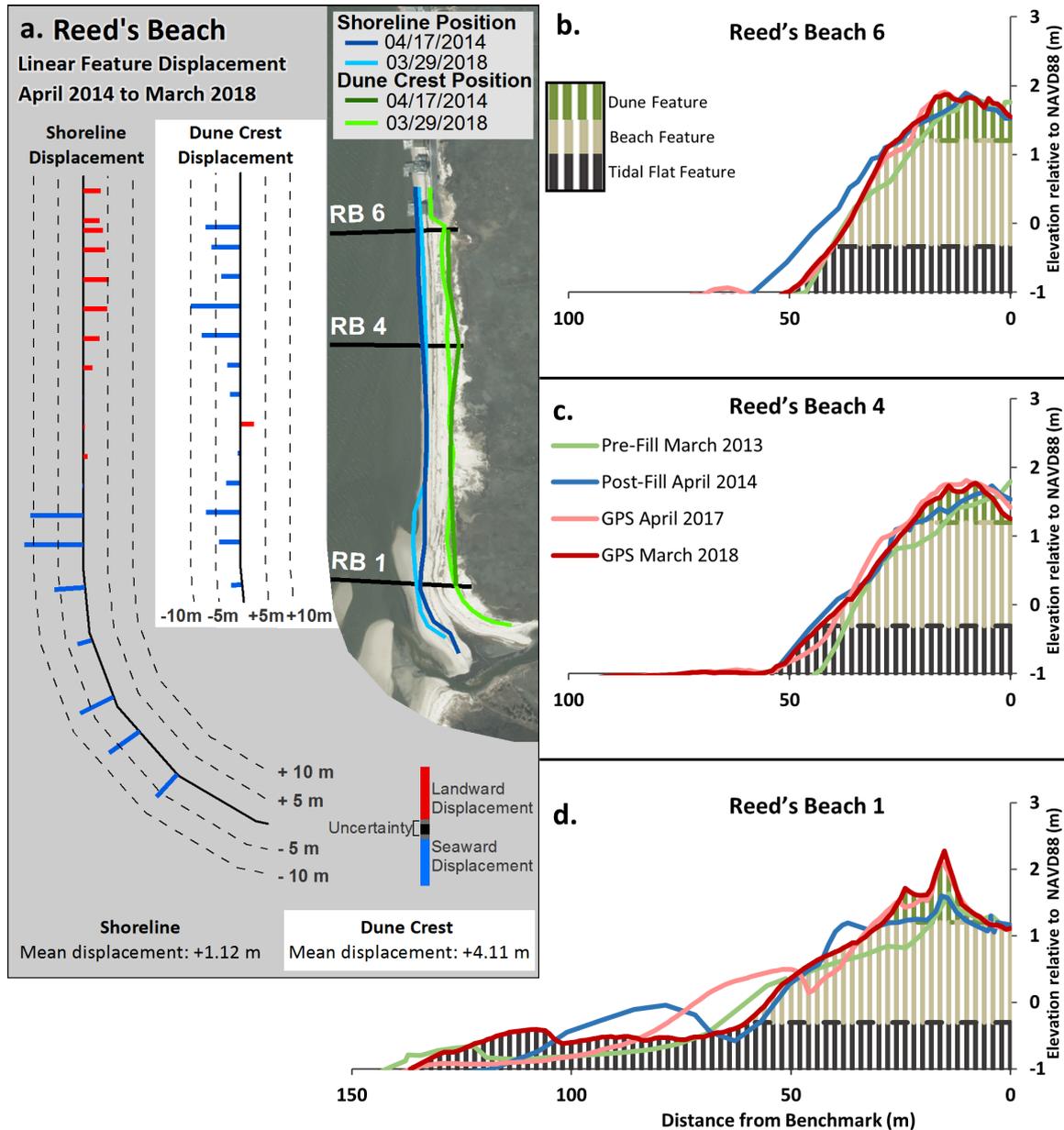
**Figure 13.** Volumetric change normalized by compartment area within the fill area at Reed's Beach. Values between the two grey dashed lines fall within the uncertainty calculation.

The dataset from the entire study area was used to plot the shoreline position (0.0 elevation NAVD88) and the dune crest position (determined from profiles) and to calculate their displacement from the post-fill April 2014 to the March 2018 surveys (Figure 14a). The depiction of the comparison was derived from transects spaced 30 m apart for the length of the study area. There was general inland shift of the shoreline position (0.0 elevation NAVD88) for the northern 180 m of the sediment placement, relative stability in the middle section, and seaward displacement in the southern 120 m of the fill. The shoreline extended seaward at the entrance to the creek. The shoreline had a mean seaward displacement of 1.12 m for the entire site. The mean displacement for the fill area was 0.83 m. The dune crestline was largely displaced seaward, a mean of 4.11 m, with a greater shift in the northern half, attaining a maximum seaward displacement of 11.10 m.

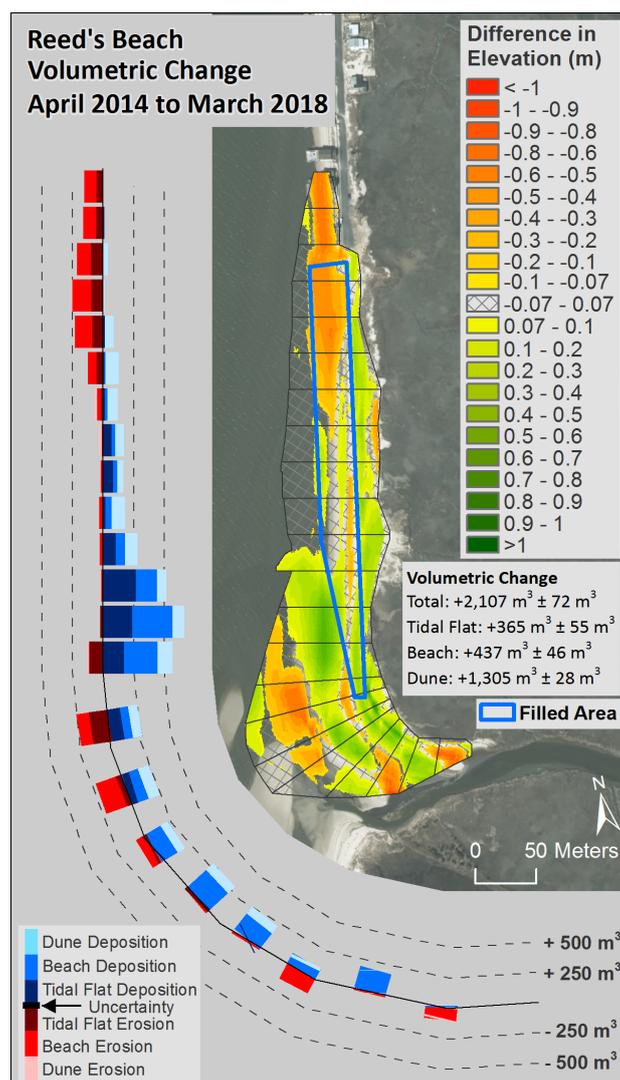
Geomorphologically, the fill area immediately south of the housing was the site of loss of cross-section area in the beach and tidal flat but gain in the dune zone, for a mean net change of  $-6.12 \text{ m}^2$  (Figure 14b). At Reed's Beach 4, the initial gain produced by the beach fill in the beach and nearshore tidal flat was minimally re-distributed to higher elevations on the subaerial beach portion of the profile and widened the seaward portion of the dune zone (Figure 14c). The total cross-section area in March 2018 was similar to the cross-section following the 2014 fill. The topography at the creek mouth, Reed's Beach 1 at the southern margin of the site, had considerable accumulation in the tidal flat, beach, and dune in the comparison from end of fill to the April 2017 survey, but lost most of the gain by the March 2018 survey (Figure 14d). Overall, the three profiles recorded a re-working of the fill to migrate up the subaerial beach to accumulate in the upper beach and on the seaward margin and crest of the foredune.

The comparison of the DEM from post-fill, March 2014, to the DEM from March 2018 (Figure 15, Table 2) depicts the modification of the sediment emplaced on the beach and gives a metric of sediment budget for the entire site and for the geomorphological features present in the alongshore compartments as well as for the entire site. In the northern 150 m of the site, the fill had been totally removed with some gains in the dune feature. The middle 120 m of the site had modest change with accumulation in the beach, dune, and tidal flat, with much of the area having elevation changes less than the value of uncertainty ( $\pm 0.07 \text{ m}$ ). The greatest change was in the southern 120 m of the fill zone, where the tidal flat and the beach had gains of more than  $200 \text{ m}^3$  in each of three compartments. South of the fill location, there was loss in the tidal flat and beach as well as gain in the beach and dune. This was an area associated with the creek and the shoals at the mouth of the creek and it was also an area that was adjacent to the nourished beaches located to the south. There was a net gain of sediment in the study

site over the post-fill period,  $2107 \text{ m}^3 \pm 72 \text{ m}^3$ , in the combined tidal flat, beach, and dune, with the dune feature gaining more than half of the total. The total net gain was nearly 6% greater than the amount of sediment recorded in the post-fill survey. Volumes within the geomorphological features by survey and by Compartment are compiled in Supplementary Data (Tables S4–S6).



**Figure 14.** (a) Linear displacement of shoreline position and dune crestline, April 2014–March 2018. Shoreline and dune crest position extracted from survey datasets and the location of selected profiles. 2015 orthoimagery [42]. (b–d) Selected profiles March 2013–March 2018.



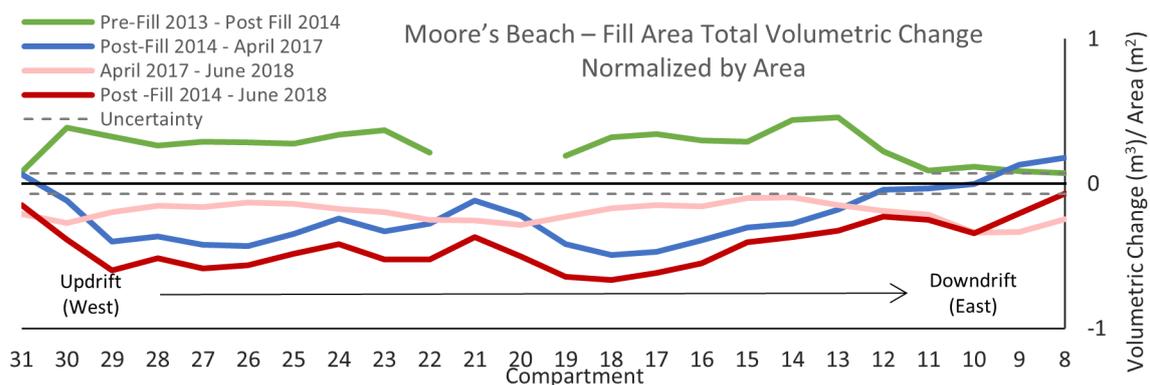
**Figure 15.** Elevation and volumetric change at Reed’s Beach by geomorphological feature, by Compartment, and by study site total, in the comparison of the post-fill (April 2014) survey to March 2018 survey. Compartments are outlined in black, area where fill was placed is outlined in blue. 2015 orthoimagery [42].

**Table 2.** Volumes by Zone, Feature, and survey period at Reed’s Beach. The zones are: Updrift (Compartments 1–6), Fill (7–20), Downdrift (21–22).

Zone	Feature	Volume (m <sup>3</sup> )			
		Pre-Fill (2013)	Post-Fill (2014)	April 2017	March 2018
Updrift (1–6)	Tidal	4360 ± 11	4347 ± 11	4353 ± 5	4325 ± 5
	Beach	4531 ± 16	4528 ± 16	5269 ± 14	4942 ± 14
	Dune	204 ± 5	162 ± 5	309 ± 5	403 ± 5
Fill (7–20)	Tidal	13,059 ± 50	13,882 ± 50	13,969 ± 21	14,364 ± 21
	Beach	13,840 ± 40	15,782 ± 40	16,071 ± 19	16,018 ± 19
	Dune	392 ± 29	867 ± 29	1953 ± 12	1929 ± 12
Downdrift (21–22)	Tidal	725 ± 8	725 ± 8	432 ± 12	630 ± 12
	Beach	688 ± 8	688 ± 8	149 ± 9	483 ± 9
	Dune	--	--	--	--
Total		37,799 ± 62	40,982 ± 62	42,504 ± 37	43,089 ± 37

### 3.3. Moore's Beach

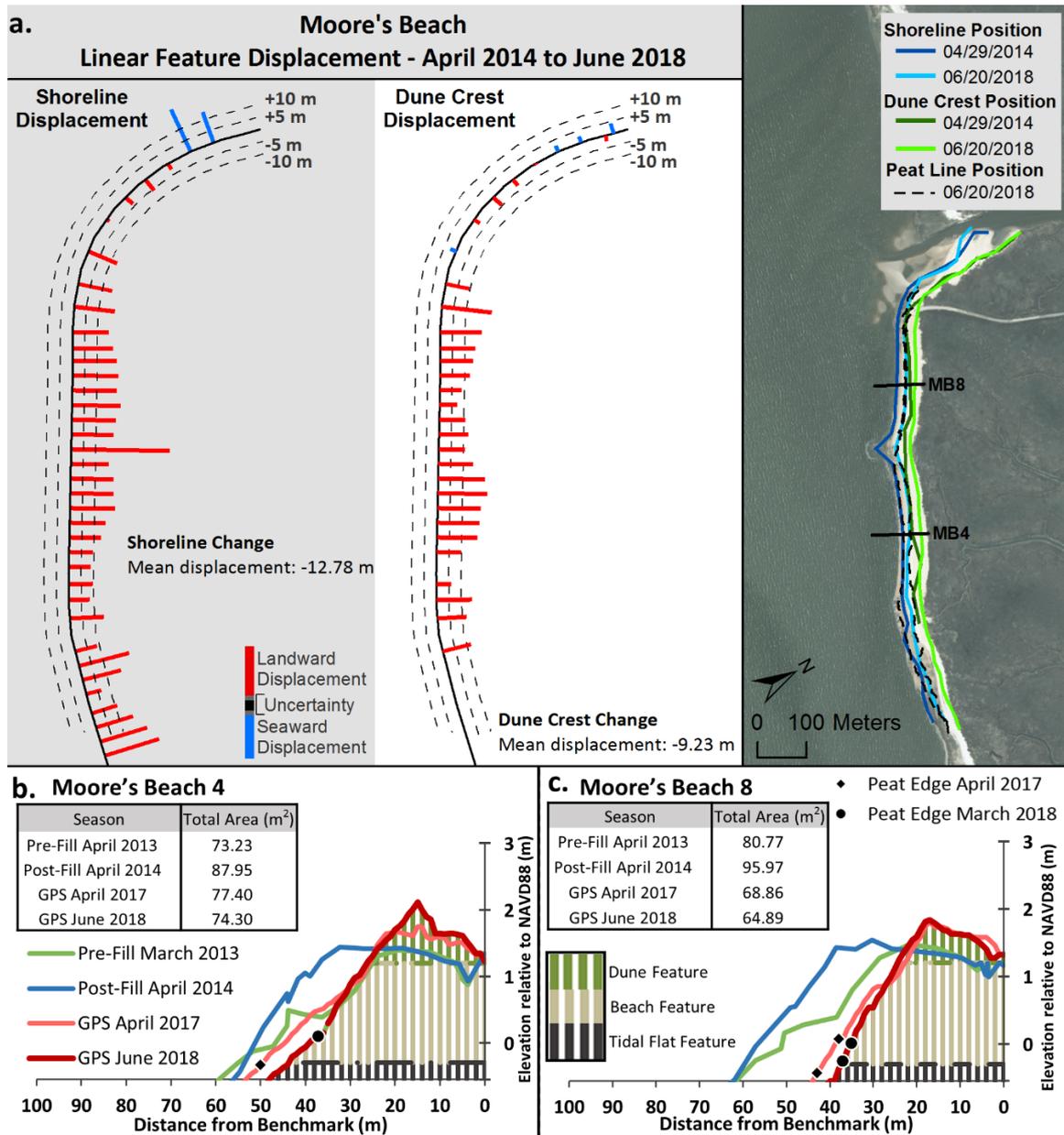
The entire length of the study area at this site consisted of 39 compartments. However, sediment placement via beach nourishment in the fill area was restricted to Compartments 8–31 (Figure 16). The amount of sediment placed in each compartment during the 2013–2014 period and the areas of the compartments varied, especially at the margins. To compensate for this variation, the units of initial accumulation and subsequent change are expressed in  $\text{m}^3$  per  $\text{m}^2$  of the referenced Compartment. Furthermore, the metrics of fill refer to the volumes present in the fill area in April 2014 compared to the pre-fill survey in February 2013. Initially, the fill was placed in Compartments 20–31. Later, fill was placed in Compartments 8–19, with a gap between the two deposits. The western portion of the fill had similar amounts across the compartments, whereas the eastern portion had a major node in Compartments 13–14 grading to small amounts in the downdrift margin of the fill area. The comparison of the volumes calculated in Spring 2014 to the results from the next survey in April 2017 showed a loss in each of the Compartments except for the most downdrift unit of the fill area, Compartments 8–9. The next annual period, April 2017–June 2018, recorded a continuation of the removal of the emplaced sediment, with losses of a similar magnitude across the entire fill area. Over the period from the post-fill survey to June 2018, the entirety of the April 2014 accumulation of  $6980 \text{ m}^3 \pm 78 \text{ m}^3$  in the fill area had been eroded, with losses decreasing toward the downdrift margin of the fill area, a net loss of  $12,426 \text{ m}^3 \pm 67 \text{ m}^3$ .



**Figure 16.** Volumetric change normalized by compartment area within the fill area at Reed's Beach. Values between the two grey dashed lines fall within the uncertainty calculation.

Shoreline position displacement and dune crestline displacement in the area of fill, with the exception of the tidal creek at the western margin of the site, had a landward displacement (Figure 17a). The maximum inland shoreline displacement was  $-40 \text{ m}$  in the vicinity of several exposed building foundations in the center of the site. Inland shoreline displacement was also large downdrift of foundation ruins in the eastern portion of the site. The mean displacement was  $-12.78 \text{ m}$  from April 2014 to June 2018 throughout the study area. Several edges of peat layers were exposed in the beach face in 2018 along all of the study area except at the western tidal creek.

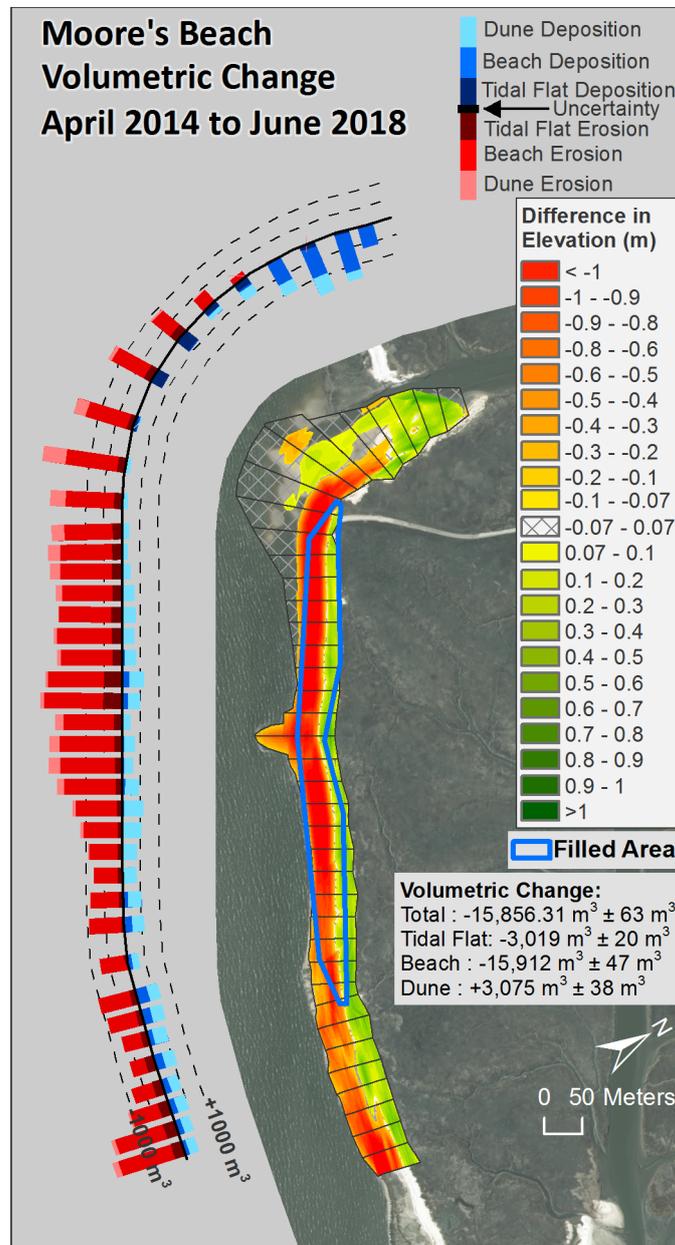
The two representative estuary-facing profiles (Figure 17b,c) recorded the placement of the trucked fill on the beach face, March 2013 to April 2014, and the subsequent total removal of the sediment from the beach and its transfer inland to the dune zone through overwash and eolian processes. Some accumulation in vegetation high on the profiles produced a dune crest peak at the estuarine margin of the dune feature. The tidal flat deepened quickly and no ridge and swale topography was identified.



**Figure 17.** (a) Linear displacement of shoreline position and dune crestline, April 2014–June 2018. Shoreline and dune crest position extracted from survey datasets and the location of selected profiles. 2015 orthoimagery [42]. (b–c) Selected profiles April 2013–June 2018.

The comparison of DEMs from the end of fill (April 2014) to the June survey of 2018 at Moore’s Beach produced a spatial array that had net accumulation of the beach and dune features in the western five compartments (Figure 18, Table 3). This is an area that is flanking a tidal creek and with less direct exposure to the estuarine waves. In those compartments that were more orthogonal to the estuary and its ambient processes, the net changes were a loss in each of the compartments, with a consistent loss of the beach feature and gain in the dune feature. The latter feature incorporated sediment that accumulated as washover fans transgressing into the wetland inland of the beach/dune system. Initially, a recorded  $6980 \text{ m}^3 \pm 78 \text{ m}^3$  of sediment was accumulated on the beach. That material was completely eroded. The volumetric change for the site was a net loss of  $15,856 \text{ m}^3 \pm 63 \text{ m}^3$ , primarily in the beach, with accumulation in the dune feature balancing the loss in the tidal flat. Even the downdrift 200 m of the survey site continued to show a net loss in the beach and tidal flat. Volumes

within the geomorphological features by survey and by Compartment are compiled in Supplementary Data (Tables S7–S9).



**Figure 18.** Elevation and volumetric change at Moore’s Beach by geomorphological feature, by Compartment, and by study site total, in the comparison of the post-fill (April 2014) survey to June 2018 survey. Compartments are outlined in black, area where fill was placed is outlined in blue. 2015 orthoimagery [42].

**Table 3.** Volumes by Zone, Feature, and survey period at Moore’s Beach. The zones are: Updrift (Compartments 32–39), Fill (8–31), Downdrift (1–7).

Zone	Feature	Volume (m <sup>3</sup> )			
		Pre-Fill (2013)	Post-Fill (2014)	April 2017	June 2018
Updrift (32–39)	Tidal	2541 ± 58	3068 ± 58	2819 ± 18	3513 ± 18
	Beach	8091 ± 35	8530 ± 35	9409 ± 24	9041 ± 24
	Dune	426 ± 15	412 ± 15	1263 ± 9	1075 ± 9
Fill (8–31)	Tidal	9519 ± 26	9632 ± 26	8048 ± 13	7038 ± 13
	Beach	36,070 ± 45	43,105 ± 45	33,354 ± 25	29,063 ± 25
	Dune	1758 ± 44	3296 ± 44	4795 ± 24	4780 ± 24
Downdrift (1–7)	Tidal	3225 ± 5	3225 ± 5	2576 ± 4	2355 ± 4
	Beach	12,534 ± 22	12,534 ± 22	11,051 ± 11	10,152 ± 11
	Dune	542 ± 11	542 ± 11	1195 ± 13	1470 ± 13
Total		74,710 ± 62	84,344 ± 62	74,511 ± 49	68,487 ± 49

#### 4. Discussion

The sediment budget metrics derived from the geotemporal comparisons of the DEMs provide for an analysis of the post-fill modifications of the beach nourishment, but also permit an evaluation of the drivers and the responses in the three sites. Although all sites are within the fetch-limited estuarine environment, the dimensions of change are somewhat different, and their geomorphological responses offer insights to their continuing vectors of evolution.

The Moore’s Beach site had the greatest dimension of volume change and displacement of geomorphological features following placement of the fill, a loss of 15,856 m<sup>3</sup> ± 63 m<sup>3</sup>. All of the emplaced fill had been eroded, and there was no gain of volume in the tidal flat within the study area. A combination of the absence of offshore bars and troughs and the greater offshore water depths at this site probably caused greater incident wave energy to reach the shore and generated greater opportunity for sediment mobilization and transport. The two remnants of building foundations in the beach acted as groins and slowed some of the alongshore transport, but also caused an increased inland shoreline position displacement downdrift. The geomorphological evolution of the site was recorded in the volume changes and the spatial shifts of the tidal flat, beach, and dune features (Figure 18). The DEM comparison showed a loss of sediment from the tidal flat and the beach for the entire site, except at the creek mouth at the updrift end of the study area. Nearly all of the volume gains were in the dune elevation category, augmented by some beach volume gains downdrift of the fill area. Thus, in a classic rollover mode, the beach-dune system was shifting inland through transfers of sediment across the dune zone and into the adjacent marshes. In addition, the beach face was occupied by exposed peat for the length of the study area, except for the creek mouth. The negative sediment budget for the site, the increased exposure of peat low on the profile, and the absence of nearshore sand bars pointed to a decreasing sediment mass to support the continuing presence of the dune-beach component of this barrier island as it shifted inland, accompanied by washover fans topping an ever-expanding peat exposure at the estuarine margin.

The Pierce’s Point site had a mix of losses and gains, primarily in the tidal flat and beach, with a net gain of nearly 5000 m<sup>3</sup>. The tidal flat gained more than twice as much as was lost from the beach, thereby indicating that there was input from outside the study area. The tidal flat updrift of the site was replete with multiple bars and troughs extending seaward of the tidal zone and updrift as well. This was a large source of sediment in the offshore topography for potential beach accretion. However, the surveys indicated a general increase in offshore bar width along with an offshore displacement, while retaining a similar elevation of the bars. A further evaluation of the bar and trough topography was that oyster racks in the offshore have a prescribed elevation of the cages above the bottom and they did not require adjustment during the period of these surveys. The major subaerial accumulation was in the beach elevation category downdrift of the fill area and in the embayment adjacent to the

tidal creek. The growth of this feature suggests downdrift accumulation associated with alongshore transport at beach face elevations. This accumulation was also atop a marsh surface that existed between the downdrift end of the fill area and the creek. There was some dune feature growth at the updrift margin of the study area and at the inland margin of the accumulation downdrift of the fill. However, these positive components of the dune feature were areas of washover that achieved the elevations assigned to the dune category. They were limited in spatial extent, and unvegetated where sediment could easily be remobilized. The barrier island rollover mode was present in the northern half of the site and in several of the compartments in the updrift portion of the site. There was a peat exposure at these locations and an inland displacement of the beach and dune features in these locations. In many of the downdrift compartments with peat exposure, the sand accumulations were tens of meters inland and over the pre-existing marsh. Over the four-year period of monitoring, the original fill area had lost all of the sediment placed on the beach, with little transport into the adjacent dune zone except at the location of the large overwash fan at the updrift margin. With exposure of the peat low on the beach and little transfer of sediment into the upper beach and adjacent dune, most of the site had a negative sediment budget and the geomorphological features were diminishing. There was growth of the subaerial beach and dune feature at the downdrift portion of the study area, but that volume was perched atop a marsh feature that will not contribute sediment to the dune-beach form as it erodes. The unknown contributor at this site was the source of the great amount of sediment on the tidal flat and offshore. There was no sign of beach accretion in the vicinity of the study area that might be indicative of onshore transport. Rather, the signs pointed to alongshore transport, displacement associated with interruptions or interference with alongshore transport, and modifications of the offshore bars and troughs where tidal creek processes interacted with the incident wave and current processes. That is, the tidal creeks were sites of shoals that took on the form of deltas rather than shore-aligned bars and troughs. The net result was a transgressive barrier island morphology that was responding to the negative sediment budget in the beach-dune system.

The Reed's Beach site was a mix of volume gains and losses, with net gain in each of the tidal flat, beach, and dune features, amounting to  $2107 \text{ m}^3 \pm 72 \text{ m}^3$ . However, the gain was because of the large placement of fill on the two beaches immediately updrift, at Cook's Beach and Kimble's Beach, rather than the fill on-site. Northerly alongshore transport had removed most of the sediment placed at these updrift beaches. Field observation at these locations in 2018 had revealed that they were now shorelines of exposed peat and active marsh. Much of the positive sediment budget at Reed's Beach was in the tidal flat at the mouth of the creek at the updrift end of the study site. Some of the location of accumulation was related to the shifting of the creek channel and the modification of the associated deltaic shoals. Some of it was associated with accumulation along the creek margin in the elevations of beach and dune topography. Downdrift of the creek, the beach zone had either no change or had a negative sediment budget, representing a loss of about half of the emplaced beach fill in the northern portion of the site. The node of volumetric gain to the south was most likely fed by material placed updrift. Once beyond downdrift of Compartment 15, the only volume gains were in the dune zone. In this area, the gains widened the dune zone by shifting the dune crest seaward and augmenting the accumulation on the inland margin of the dune, probably through eolian transport. In the updrift portion of the site, the dune showed gains through overwash processes and expansion over the adjacent marsh. There were no peat exposures in the beach at this site, although the beach to the south of the creek was composed entirely of peat and marsh at the shoreline. Relative to the barrier island rollover model, the northern (downdrift) portion of Reed's Beach exhibited inland migration of the tidal flat and beach topographies, while retaining volume in the dune zone and seaward displacement of the dune crest. Toward the updrift margin of the study area, there was an increasing volume in the three landform categories, expansion of the dune zone into the adjacent marsh, and a net seaward displacement of the features. These positive metrics were the product of the sediment source from updrift and that source seems to have been exhausted. There is considerable sediment available for downdrift transport that is presently in the tidal creek delta. That may buffer

some of the succeeding geomorphological evolution. In addition, this site is at the southern margin of sediment trapped by the lengthy jetty at Bidwell Creek, 1.3 km to the north. This location updrift of the jetty may assist in retaining shoreline position and the associated beach-dune topography in a relatively stable condition and support maintenance of the barrier island system.

In each of the three sites, the beach fill was largely mobilized and transported out of the fill zone. At each site, the sediment budget metrics have portrayed the relative gains and losses in the geomorphological features in the alongshore context, emphasizing the importance of alongshore transport in areas of limited fetch. The analyses of the DEMs have identified vectors of change of the beach features that are part of the desired beach habitat. However, the locations of these beach features were primarily at the margins of the tidal creeks or locations where the beach was migrating over marsh or dunal vegetation. Whereas the creek margins are favorable habitats because they are bare sand on the upper beach, they are not loci of natural sediment accumulation and therefore have limited longevity. Furthermore, the presence of peat exposures in the beaches is indicative of the limited sediment available to maintain the sandy beach feature and the potential limited extent of the beach habitat, both in the zones of fill as well as in the downdrift locations. The large alongshore displacements at Moore's Beach will continue and diminish the volume of sediment composing the beach and dune topography, leading to increased exposure of the peat. Pierce's Point will also continue to lose sediment in the area immediately north of the housing and have an increasing exposure of the peat in the beach face, partially offset by the sediment accumulation in the beach elevation zone near the creek mouth. Reed's Beach benefited by the contribution of the fill at updrift locations and the retention of sediment caused by the jetty at Dias Creek. The beach and dune system at this site will be retained much longer than at the other two sites.

## 5. Conclusions

As aptly described by Sherman [21] and Rosati [22], the application of sediment budget to monitor coastal change provides a focus on the net volume change on a limited area over seasonal to decadal time spans. It is especially appropriate to identify the modifications to sediment placed on an area via beach nourishment because of the opportunity to track the more immediate adjustments to the fill and to continue to monitor the subsequent redistribution over a longer period [23]. The comparisons are germane to a management objective [24] as well as to outcomes beyond the intended area of concern [20]. The use of DEMs coupled with landform features, this study, provides a basis for comparing units of varying dimensions and components of the geomorphological system in a variety of situations, applicable in fetch-limited estuarine or ocean environments. In addition, the derivation and incorporation of uncertainty values add credence to derived metrics. Furthermore, the data and analyses generated in this study support the proposition that barrier island systems and their characteristics do exist in rollover and non-rollover mode in areas of restricted fetch [3,35,45]. The generation of annual comparisons under specified conditions rather than opportunistic available data sets establishes a far better metric of net change because of the elimination of extreme events that could bias the survey outcomes. Our data and their analyses indicate that fill at the sites has been largely eroded, there is inland displacement in a barrier island rollover mode at different rates, and the sites will undergo continuing modification related to the updrift input. Under the purview of this project, the monitoring of these sites will continue for five years, through 2022.

**Supplementary Materials:** The following are available online at <http://www.mdpi.com/2076-3263/9/1/16/s1>, Table S1: Volume of the Tidal Flat at Pierce's Point within each Compartment (Comp.). The asterisk indicates that uncertainty was not calculated because there were no points within that Compartment. Table S2: Volume of the Beach at Pierce's Point within each Compartment (Comp.). The asterisk indicates that uncertainty was not calculated because there were no points within that Compartment. Table S3: Volume of the Dunes at Pierce's Point within each Compartment (Comp.). The asterisk indicates that uncertainty was not calculated because there were no points within that Compartment. Table S4: Volume of the Tidal Flat at Reeds Beach within each Compartment (Comp.). The asterisk indicates that uncertainty was not calculated because there were no points within that Compartment. Table S5: Volume of the Beach at Reeds Beach within each Compartment (Comp.). The asterisk indicates that uncertainty was not calculated because there were no points within that Compartment.

Table S6: Volume of the Dunes at Reeds Beach within each Compartment (Comp.). The asterisk indicates that uncertainty was not calculated because there were no points within that Compartment. Table S7: Volume of the Tidal Flat at Moore's Beach within each Compartment (Comp.). The asterisk indicates that uncertainty was not calculated because there were no points within that Compartment. Table S8: Volume of the Beach at Moore's Beach within each Compartment (Comp.). The asterisk indicates that uncertainty was not calculated because there were no points within that Compartment. Table S9: Volume of the Dunes at Moore's Beach within each Compartment (Comp.). The asterisk indicates that uncertainty was not calculated because there were no points within that Compartment.

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## Abbreviations

The following abbreviations are used in this manuscript:

NJDEP	New Jersey Departments of Environmental Protection
NOAA	National Ocean and Atmospheric Administration
RMSE	Root Mean Square Error
DEM	Digital Elevation Model
USGS	United States Geological Survey
DSAS	Digital Shoreline Analysis System
GPS	Global Positioning System
RTK	Real Time Kinematic
LiDAR	Light Detection and Ranging
NAVD88	North American Vertical Datum 1988

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