STRATEGIES FOR COASTAL MANAGEMENT OF ESTUARINE BEACHES BY MUNICIPALITIES: A CASE STUDY OF CLIFFWOOD BEACH, NJ

By

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ABSTRACT OF THE THESIS

Strategies for coastal management of estuarine beaches by municipalities: A case study of Cliffwood Beach, NJ

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Damaging coastal storms and sea level rise have placed many homes and recreational areas on estuarine shores at risk. The developed shore of Raritan Bay, NJ is particularly vulnerable. The US Army Corps of Engineers implemented coastal risk-management projects throughout many communities on Raritan Bay, but there are many segments of shoreline that are not included in these plans. Local differences in shoreline orientation and sediment supply caused by headlands and human structures have resulted in variations in beach processes and landscape changes overs small spatial scales. Municipalities have some freedom in managing beaches and dunes at these spatial scales using earth-moving equipment, sand fences, and vegetation, but scientific expertise is often missing at the local level. This study seeks to address ways coastal erosion and vulnerability of infrastructure can be addressed in an efficient and cost-constrained way using Cliffwood Beach, in Aberdeen Township, as a study site. Topographic data and sediment grain size characteristics were collected along six cross-shore lines. Erosion at this site reaches rates of up to 7.9 m^3/m/year. Municipal management actions evaluated

include soft solutions (beach nourishment, dune building and sand backpassing) and hard solutions (construction of wood bulkheads and geotubes). Soft solutions are favored to retain recreational and environmental values. Beach and dune volume calculations indicate that an initial nourishment project would require 17,500 m^3 of fill material to reestablish the beach width and dune volume at the critically eroding area. Thereafter, 1,000 m^3 of sand could be backpassed each year from accretionary portions of the beach downdrift to the eroding area to keep pace with erosion and make the protection project sustainable.

ACKNOWLEDGEMENT

I am grateful to all those with whom I have had the pleasure to work during this and other related projects. Each of the members of my Thesis Committee have provided me extensive personal and professional guidance and taught me a great deal about both scientific research and life in general. I would especially like to thank Dr. Karl Nordstrom, my thesis advisor. He has shown me, by his example, what a good scientist and person should be. I would also like to thank Tracy Youngster, Ph.D. candidate in the Department of Ecology and Evolution at Rutgers University, for her contribution in my understanding of the ecological elements of this project.

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Nobody has been more important to me in the pursuit of this project than the members of my family. I would like to thank my parents; whose love and guidance are with me in whatever I pursue. I would also like to thank my wonderful partner Haley, for her love and support throughout this process.

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Introduction

Estuarine beaches often erode at higher rates than ocean beaches but are given less attention by scientists and local managers (Nordstrom, 1992). Differences in shoreline orientation and sediment supply caused by headlands and human structures lead to variations in beach processes and landscape changes over small spatial scales (Jackson and Nordstrom, 1992) complicating management approaches to erosion problems. There has been increasing interest in estuarine beaches (French and Burningham, 2011), especially in New Jersey due to the flooding and erosion problems in coastal communities caused by Hurricane Sandy and other coastal storms coupled with sea level rise. Human impact on these fetch-limited environments has been well documented (Sedrati et al., 2009; Nordstrom et al., 2009; Silveira and Psuty, 2009). Impacts include disruptions in sediment supply due to engineered structures like seawalls, or the emplacement of structures that alter the nearshore wave environment (e.g. groins and breakwaters). New Jersey has the second highest population density in coastal counties in the USA, behind only New York (US Census Bureau, 2008). The Raritan Bay shoreline, for example, is densely developed, leaving infrastructure and recreational sites vulnerable to flooding and erosion. Beaches along Raritan Bay also serve as local natural landscapes and provide recreational opportunities, and the infrastructure built to make use of recreational sites is also vulnerable to coastal hazards.

Municipalities have some freedom in managing beaches and dunes using earth-moving equipment, sand fences, and vegetation, but they often lack funds and expertise to implement large-scale shore protection projects. Damage from high energy storms coupled with sea level rise has placed many homes and recreational areas at risk. The US

Army Corps of Engineers has implemented strategies of coastal storm risk-management throughout many communities on Raritan Bay, but there are many sections of shoreline that are not included in these funded plans. Scientific expertise at the local level is usually missing when decisions are made regarding coastal management issues (Jackson and O'Donnell, 1993; Goss and Gooderham, 1996). This study will serve as an example of ways to address problems of erosion, overwash and flooding that plague many estuarine communities by examining alternatives for a shoreline segment at Cliffwood Beach, NJ, a short estuarine beach segment located in Aberdeen Township, NJ (Figures 1 and 2). The results will have local applications and also apply generically to inform other municipalities of ways to assess and determine appropriate solutions to estuarine beach erosion and flooding.

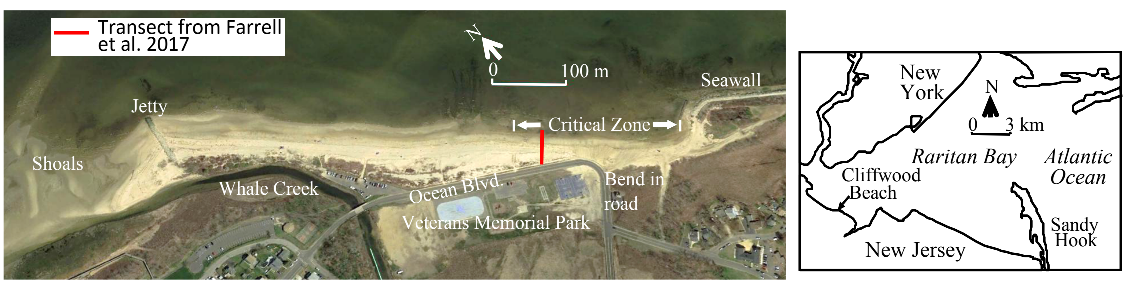

Figure 1: Cliffwood Beach study area. The red line indicates the location of the transect monitored by Farrell et al. 2017, which was monitored to track changes in sediment volume and shoreline position changes from 1986 to 2016. Photo taken from Google Earth, 2016.

Figure 2: Ground view of the Cliffwood Beach study area depicting the low tide terrace, foreshore, sand fence and dune. Photo taken on March 9, 2018.

The goal of this thesis is to identify the main contributing factors to the problems at Cliffwood Beach, discuss appropriate strategies to address the contributing factors, and provide cost estimates for protection strategies so that the municipal managers can make an informed decision on how to best protect the problem area. Potential shoreline protection strategies to be considered include actions that the municipality can take using local resources and more comprehensive projects that require funding from the state or federal government. For the latter, my goal is to provide the municipality with the appropriate information needed to prepare a proposal for funding consideration. Data was collected to assess the geomorphology sediment characteristics, and vegetation.

Background to present-day conditions

Cliffwood Beach has been an eroding shoreline of concern for decades, with a history of artificial beach nourishment, construction of a seawall, and other coastal protection projects (Jackson and Nordstrom, 1994). A fairly comprehensive shore protection project was completed in late-1970s and early 1980s (Jackson and Nordstrom, 1994), and the present landscape reveals the legacy of those actions (Figure 1). That project included the construction of a seawall, completed in 1976. The seawall was a stone structure with a splash pad, concrete void filler and interior fill. The seawall was backed by a graded cliff-face slope planted with stabilizing vegetation and a layer of gabions to prevent loss of fill landward of the structure. A jetty was also constructed at the inlet of Whale Creek (Figure 1). The beach was artificially nourished in front of the seawall with 145,260 cubic meters of sediment as a precaution against damage from wave energy (Jackson and Nordstrom, 1994). Another 170,520 cubic meters of sediment was used to construct artificial beach and dune west of the seawall to provide flood protection. These nourishment projects were conducted by October 1982, and an additional 33,500 cubic meters of sediment were added following Hurricane Gloria in September 1985 (Jackson and Nordstrom, 1994). Fill sediments were moderately sorted medium sand (0.35 mm mean diameter) (Jackson and Nordstrom, 1994). A 15 m-wide bulldozed dune was created on the landward part of the nourished beach to provide flood protection, with sand fences and vegetation plantings emplaced to stabilize the surface and trap new sand blowing in from the widened beach.

From 1987 to 2017, there was a steady trend of shoreline retreat and a reduction of cumulative sediment volume at the site (Figure 3) (Farrell et al., 2017). The increase in sediment volume and shoreline position in the late 1980s was a result of transport of the fill sediment placed bayward of the seawall in the beach nourishment project conducted in the early 1980s. From 1993 to 2002, the shoreline at Cliffwood Beach retreated despite maintaining the same cumulative sediment volume, presumably the result of aeolian transport into the dune. After 2002, there was no sand in front of the seawall to supply the beach downdrift, and the cumulative sediment volume of the beach began to decrease.

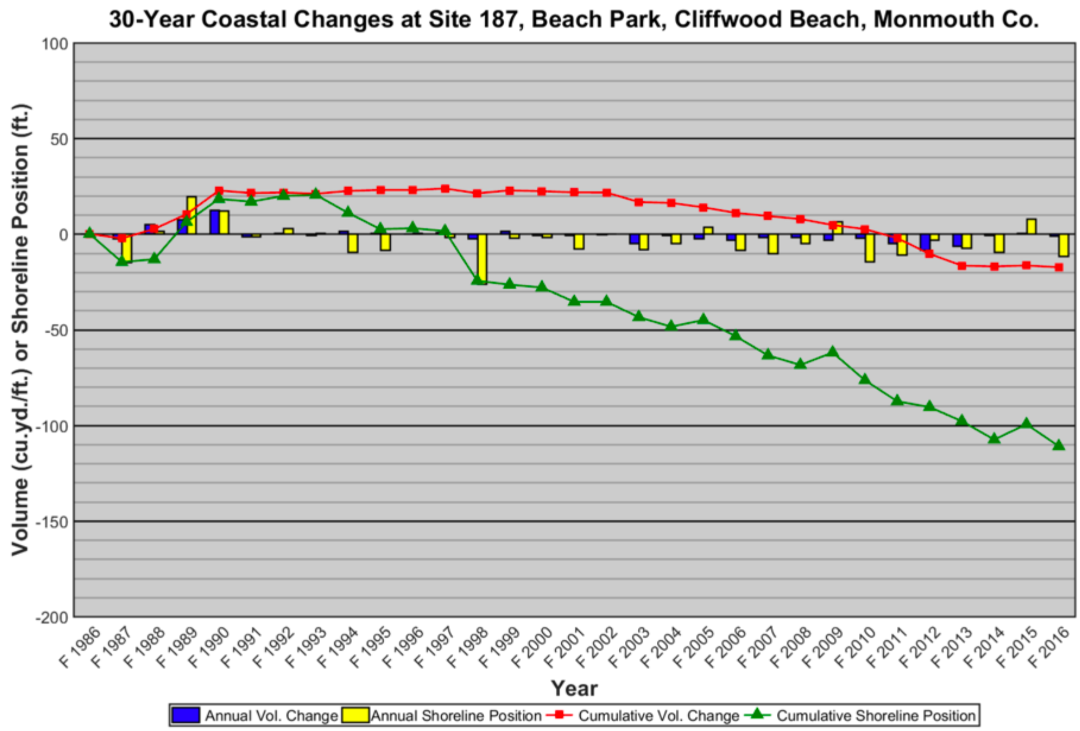

Figure 3: Thirty-year coastal change at Cliffwood Beach. Analysis is from 1986 to 2016 showing annual and cumulative shoreline position and cumulative sediment volume. The increase in sediment volume and shoreline position in the late 1980s was a result of a previous beach nourishment project that was implemented. Over this thirty-year period, the site averaged a loss of about 2.5 m^3/m of sand per year and a 1-meter retreat of the shoreline per year (from Farrell et al., 2017).

Site Description

Cliffwood Beach is located on the southwest side of Raritan Bay, a funnel-shaped coastal plain estuary. Tides are semi-diurnal with a mean range of 1.5 meters and a spring range of 1.7 meters (NOAA, 2018). The location of interest is the approximately 730 meter long unprotected beach segment bounded by Whale Creek to the west and the seawall to the east. The area of greatest concern on the beach, the “critical zone” identified in Figure 1, is about 200 meters downdrift of the seawall, where the beach is sand-starved and narrow and the dune system that still exists on the rest of the beach has been removed by wave action.

The beach is exposed to ocean swell waves that enter the bay to the north of Sandy Hook (Figure 4 (inset), but locally generated wind waves are dominant. Prevailing winds are from the west, but northwest winds and northeast storm winds are common. The northeast winds blow across greater fetch distances and blow water into the bay, which both contribute to higher wave heights for a given wind velocity. Water is blown out of the bay during strong westerly winds.

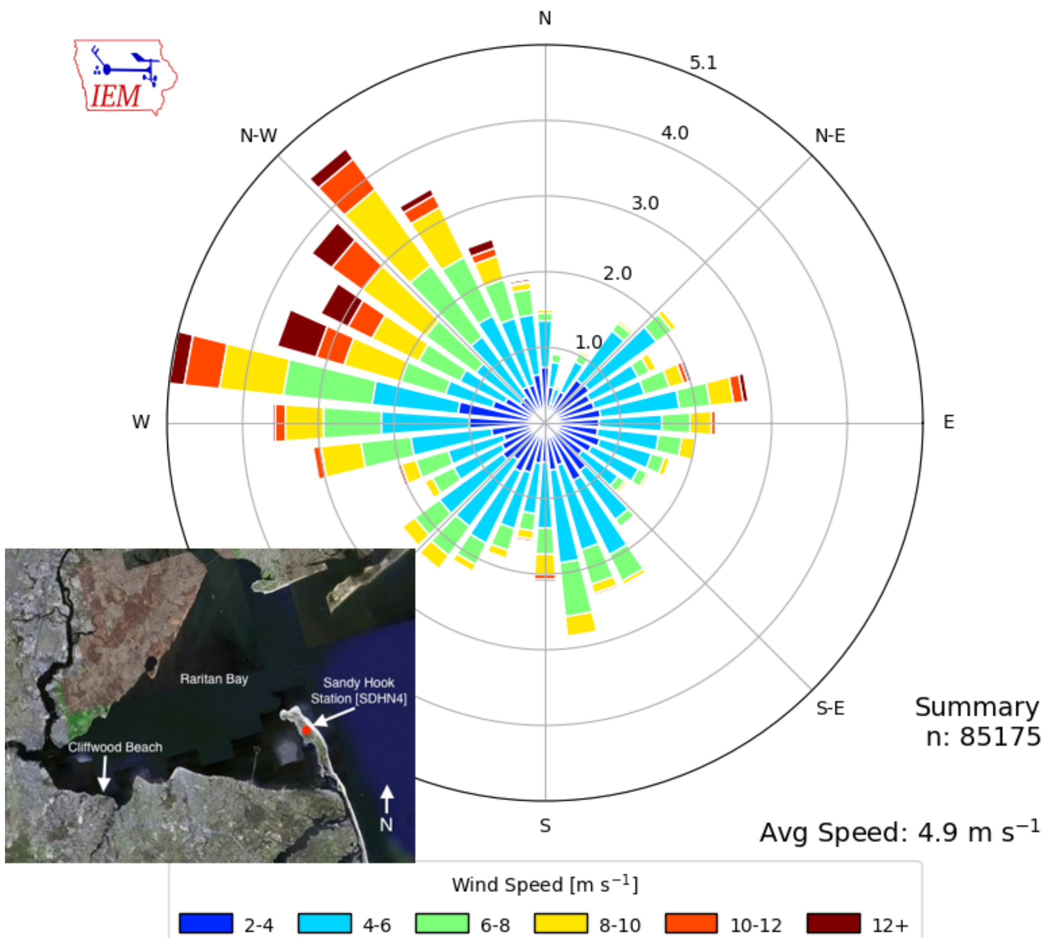

Figure 4: One-year wind rose from Sandy Hook, NJ. Wind rose plot shows record from December 14, 2017 to December 22, 2018 at Sandy Hook, NJ. Dominant winds are from the west, with an average wind speed of 4.9 m·s^{-1}. Generated from Iowa State University's Iowa Environmental Mesonet.

The shoreline azimuth of the beach segment is 127-307 degrees, resulting in the northeasterly winds and waves generating currents to the west. Littoral transport to the east occurs during times of northwesterly wind, but transport rates to the east are much lower because wave energies are diminished due to shorter fetch distances for wave generation and lower water levels that increase bottom friction. The jetty represents the only artificial obstruction to alongshore sediment transport to the west. The jetty slopes bayward, allowing sediment to bypass the structure across much of the beach profile during strong easterly winds.

Objectives and considerations for future

When determining what course of action to take to address erosion problems, it is important to set both strategic and tactical objectives (Marchand, 2010). Strategic objectives are determined by the long-term vision about the desired development of the coast. A strategic objective should be based on ideas such as sustainable development of the natural and socioeconomic systems along the coast or maintaining the safety of coastal infrastructure.

More detailed objectives should be developed to identify what tactics must be carried out to achieve the strategic objectives agreed upon by municipal leadership. Setting tactical objectives requires choosing between many different options for actions:

- Hold the line: maintain or upgrade the level of protection by defenses
- Advance the line: build new defenses seaward of the existing defense line
- Managed realignment: allow retreat of the shoreline, with management actions to control or limit movement

- No active intervention: a decision to not invest in providing or maintaining defenses

A meeting was held with township personnel in December 2017 to discuss the purpose of the project, its value to the township, the ability of the township to manage the beach using local resources, and local arrangements for conducting field work. Local officials consulted included the mayor, town manager, head of the department of public works, and head of the environmental commission. Township personnel indicated preference for a “hold the line” strategy, in which the level of protection that the dunes provide west of the “critical zone” is maintained, and the level of protection at the critical zone is upgraded and enhanced.

Accordingly, strategic objectives for Cliffwood Beach are focused on:

1) Enhancing the safety and longevity of Ocean Boulevard and Veteran’s Memorial Park.

2) Maintaining the recreational capacity of the beach.

Tactical objectives thus should include establishing and/or preserving the dune strength and stability along the entire shoreline, maintaining an adequate beach width for dunes to naturally evolve, and preventing damage to infrastructure while adapting to sea level rise.

Methods

Historical changes that occurred at Cliffwood Beach, are analyzed using a series of historical aerial photographs that reveal the evolution of the landforms, shoreline position, vegetation cover, and past management outcomes. Field data were gathered to determine the management strategies appropriate for Cliffwood Beach in the future. Key data collected to help inform decisions include (1) cross-shore topographic profiles, which allow for quantifying parameters including beach width, dune height, and sediment volume; (2) spot elevation data to determine low elevations along the dune and around the recreation facilities to determine likelihood of flooding; and (3) grain size data on the beach to determine appropriate sediment for fill material if beach nourishment is selected as an alternative. Potential management alternatives were then evaluated considering geomorphic, ecological, social and economic indicators derived from the literature.

Historical aerial photographs

The historical aerial photographs of Cliffwood Beach were obtained from 'historicaerials.com', a website owned and operated by Nationwide Environmental Title Research, LLC. The years selected from the historical aerial photographs that were available were chosen to reflect major changes in the site's geomorphic history. The photographs are qualitatively discussed in terms of changes in landforms, shoreline position, vegetation cover, and management outcomes.

Cross-shore profiles

Seasonal variation of beach erosion/accretion and spatio-temporal evolution of beach profiles taken perpendicular to the shoreline azimuth are useful for understanding coastal processes, projecting long-term erosion/accretion trends, predicting the future evolution of coastal landforms and selecting appropriate management measures (Cooper et al., 2000; Gujar et al., 2011; Andrade and Poulos, 2014). With this in mind, Real Time Kinematic (RTK) GPS topographic surveys were collected at six shore-perpendicular transects. Transects were selected to capture the range of beach width and height along the entire stretch of shoreline between the west end of the seawall and the jetty at Whale Creek. Transects were designated T1 through T6 and are located approximately every 100 meters from the seawall to the Whale Creek jetty (Figure 5). Measurements were taken December 14, 2017, March 9, 2018, June 7, 2018, September 25, 2018, and December 22, 2018. A seventh transect at the "critical zone" (designated CZ) was also surveyed in December 2017 to measure the width of the beach at its most narrow and vulnerable location. All surveys were taken at breaks in slope, from a point landward of the dune crest to several meters bayward of the break in slope between the upper foreshore and low-tide terrace.

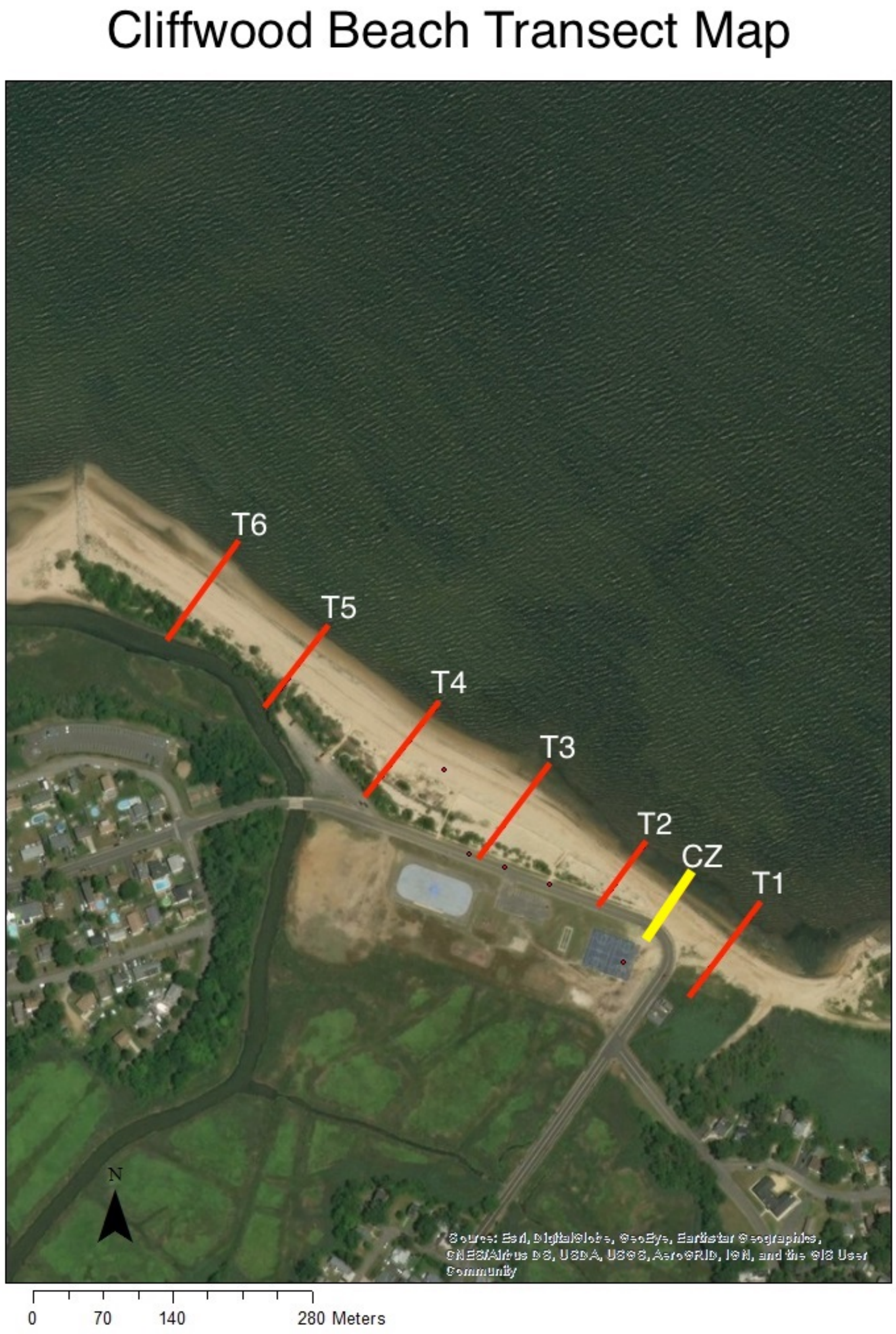

Figure 5: Map showing the location of the six numbered transects monitored every three months December 2017-December 2018 using an RTK GPS unit. Profiles at CZ were taken only in December of 2017.

Topographic data were plotted as cross-shore profiles and used to calculate beach width, dune width, and dune height. Beach width is the horizontal dimension of the beach, from the break in slope at the landward edge of the low-tide terrace to the break in slope between the backshore and base of the foredune. Beach width is an important quantity to assess coastal resilience, because wider beaches are able to provide more sediment as an erosional buffer and dissipate more of the oncoming wave energy.

Dune width represents the distance from the base of the foredune to the back of the dune (at the road verge or Whale Creek) and is an important quantity to assess the ability of the dune to retain enough sediment during wave attack to remain a barrier against landward flooding. Dune height represents the maximum elevation of the dune crest. Dune height has important implications for the dune system’s ability to provide a barrier against storm surge, wave uprush, and overwash of sand onto roadways and other infrastructure. Selected high and low elevations were surveyed along the longshore extent of the entire dune crest to supplement cross-shore elevations at transect lines and provide an indication of overall vulnerability to overwash.

<u>Landward spot elevations</u>

Other elevation data were collected to assess the contribution of flooding from the landward side of the infrastructure via Whale Creek, the landward marsh, and runoff from rainwater to determine whether flooding occurred from these sources rather than by wave uprush and overwash across and through the dune system. Representative high and low elevations were recorded using the RTK instrument, with a particular emphasis on low-points around Ocean Boulevard and Veteran’s Memorial Park.

Elevations along the top of the jetty adjacent to Whale Creek at the western end of the study area were also recorded. This information is used to determine the degree to which the jetty inhibits sediment from leaving the littoral cell. If moving sand from this location back to the critical zone in a sand backpassing operation were to be considered, sand tightening of the jetty (raising its elevation) could allow for a reservoir of sand to accrete updrift at a faster rate, making backpassing more efficient.

Elevations were compared to sea level rise projections for the state of New Jersey up to the year 2100 obtained from the Science and Technical Advisory Panel Report (Kopp et al., 2016). The NJ Floodmapper open access tool was then used to model the current mean higher high water, as well as sea level rise of one and two feet. These data allow for a qualitative assessment of the impacts sea level rise will have on coastal facilities and the landward, low-lying areas.

<u>Sediment volume analysis</u>

The volume of the beach and dune was calculated as total cubic meters of sediment from the low-tide terrace to the back of the dune and reported as cubic meters of sediment per linear meter of shoreline. The volume data were then applied along the entire beach segment to estimate the total beach and dune volume. This estimation was performed by first dividing the study area into alongshore segments centered on each transect. The volume per linear meter calculated for each transect is then multiplied by the alongshore distance between transects.

Erosion rates were calculated from the topographic data as the average rate of loss per linear meter per year. The erosion rates were determined by using the December 14, 2017 and December 22, 2018 topographic records. These erosion rates were then used to supply volume change estimates across the critically eroding portion of the beach (between the seawall and Transect 3) according to the methodology described above.

Nourishment calculations

The area of interest for a potential fill area for a nourishment or backpassing project is between the seawall and Transect 3. For the sediment volume analysis, it is assumed that no sand has entered the system since around 2002 because historical aerial photographs show an absence of sand in front of the seawall beginning at this time. This sand was the primary source of sediment to the system, and the seawall represents a significant obstruction to littoral drift from the east.

Locations east of Transect 3 have progressively lost sand volume since 2002 and the dunes have either partially or fully eroded away. Key to protecting the road and park landward of the beach is the presence of a stable dune system. As a first approximation, Transect 3 is used to represent the westernmost location at which the sediment volume in the system is sufficient to maintain a dune height relatively close to that of the dune system in areas outside of the critical zone. The dune here has survived despite the steady trend of shoreline retreat and volume loss depicted in Figure 3.

Based on these assumptions, the profile at Transect 3 taken on December 14, 2017 is used to represent the minimum sediment volume needed to protect the vulnerable infrastructure landward. The December profile was chosen because winter represents the beginning of the peak coastal storm season. By extending the Transect 3 profile across the alongshore distance from Transect 1 to Transect 3 an idealized beach and dune at this critically eroding area can be generated using data tools in Matlab. The trapezoidal numerical integration Matlab function was then used to estimate the total volume of sand required to generate this idealized beach.

The current volume of this segment was then estimated by calculating the volume of sediment per linear meter at each transect within this critically eroding stretch of shoreline. These volumes were then multiplied by an equidistant alongshore distance centered on each respective transect, thus providing an estimate of the total volume for this stretch of shoreline. The difference between the idealized beach volume and the current volume can then be regarded as an estimate of the volume required for an initial nourishment project.

The difference between the December 2017 and December 2018 profile integrations was then calculated and used to estimate the annual rate of erosion and the yearly backpass volume that would be needed to maintain a constant beach and dune volume within the critical zone.

Sediment grain size analysis

One sediment sample was gathered to a depth of 5 mm at mid foreshore on each of the six transects and in the foredune at Sites 2 and 5 on June 7, 2018 to describe grain size characteristics. Sediments were washed, dried and sieved in a sonic sifter at 1/4 ϕ intervals and analyzed using graphic measures (Folk, 1974) to determine mean grain size (m_z) and sorting (σ_I). The gravel fraction (> 2.0 mm) is included in statistics representing the total sediment population and is also represented as a percent of total weight of the sample. Statistics of the sand fraction alone were also calculated.

Consideration of management strategies

Several indicators were considered when assessing which management strategy will be most appropriate to protect Cliffwood Beach. These indicators are presented in Table 1.

Category	Themes	Variables/aspects	
Geomorphic	Physical Processes	Quantitative	Wind velocity, direction
			Wave height
			Sediment budget (volume change)
		Qualitative	Barriers to sediment exchange
	Landforms	Quantitative	Beach width, volume
			Dune height, width, volume
			Sediment grain size, sorting
		Qualitative	Sand distribution patterns
Vegetation	Composition	Quantitative	Species distribution, coverage
	Function	Qualitative	Value for sand stabilization
			Endangered/threatened species
Social	Relationship to human use	Qualitative	Recreational opportunities
			Historical interest
			Safety
			Aesthetic qualities
			Stakeholder interests
			Consistency with municipal plan
Economic	Cost	Quantitative	Cost of protection projects
		Qualitative	Funding capability
	Lifespan	Quantitative	Durability/replenishment interval

Table 1: Indicators used to evaluate potential management alternatives (Adapted from Nordstrom, 2008 and references therein).

Results

Historical changes

The image of Cliffwood Beach from 1940 (Figure 6) reveals a significantly larger beach bayward of Ocean Avenue. A boardwalk can also be seen running from Whale Creek to the southeast along the entire stretch of beach (including the location of the future seawall). Multiple groins are visible on the eastern portion of the photographs in front of the boardwalk. Multiple structures are visible on the beach, and landward of Ocean Avenue many small closely packed structures are located where the Veteran's Memorial Park now exists. Whale Creek takes a significantly different route to the Bay than currently, cutting through what would become the western end of the present-day beach.

Figure 6: Historical aerial photographs, 1940-1986. Aerial photographs depicting the evolution of Cliffwood Beach, NJ. Photographs were taken in the years 1940, 1947, 1963, 1979, and 1986.

In 1947, the channel of Whale Creek diverges to the west and assumes an orientation similar to that observed today. The linear nature of the channel indicates that the creek was diverted by human action. Patches of vegetation are visible north of the creek on the west end of the beach. The boardwalk remains intact in 1947, but less sand remains in front of the boardwalk where the present-day seawall is located.

A 1957 photo (not in Figure 6) revealed that the boardwalk was no longer present, and the groins that were in place in front of the boardwalk were no longer visible. Structures previously located on the beach seaward of the bend in Ocean Avenue had also been removed. The eastern section of the closely-packed structures where Veteran's Memorial Park now stands had also been removed, and some overwash was present in the space they had previously occupied.

In 1963 (Figure 6), there is even more significant damage and overwash to the closely-packed structures, with only a limited number remaining. In the area of the present-day seawall, where the boardwalk was located, nearly all structures have been removed with the exception of the remnants of a saltwater pool. Vegetation in this area has been lost leaving a larger area of beach sand in its place.

In 1979, many shore protection measures can be seen, including the new jetty at Whale Creek and the large seawall at the eastern portion of the study area. This was a unique time in the site history, as these protection structures are in place but not the large nourishment project. Large areas of marsh peat can be seen on the low tide terrace, and erosion of the beach has occurred toward the southeast. Vegetation previously visible near the jetty has also been eliminated. At present-day Veteran's Memorial Park, the last of the small tightly-packed structures have been removed and replaced with tennis courts, basketball courts, and other recreation features. Any structures that had been visible on the beach prior to 1979 are no longer there.

In 1986, the effect of the nourishment projects can be seen. Significant sand has been emplaced along the beach and in front of the seawall. Dunes were also bulldozed to protect Ocean Avenue, but they lack vegetation at this time. Figure 7 demonstrates the resulting evolution of the Cliffwood Beach study area after the nourishment project.

In 1995 (Figure 7), vegetation had evolved on the dunes and there was visible erosion of the fill deposited in the early 1980s. Much of the sand emplaced in front of the seawall was transported west. A photo from 2002 (Figure 7) revealed no sand in front of the seawall, with visible erosion downdrift of that structure. The dune system was intact and vegetated throughout the entire beach, including the area in front of Ocean Avenue that represents the present-day Critical Zone. The 2017 photo represents the near current conditions of the study area.

Figure 7: Cliffwood Beach photographs from 1995, 2002, and 2017. 2002 Represents the point in time where all fill sand emplaced in front of the seawall has been transported downdrift into the beach system.

<u>Cross-shore Profiles</u>

The topographic cross-shore profiles (Figure 8) allow for quantification of spatio-temporal changes in the beach and dune geomorphology and provide insight into the way the beach and dune systems evolve alongshore. Transects 3 – 6 have a wide and high dune system. Dune widths for these four transects all exceed 25 m, and dune heights exceed 2.8 m. At Transect 2, there has been significant erosion, causing a narrower dune with a width of 15.3 meters and a lower dune (2.56 m). At Transect 1, there is no longer an intact dune. The highest elevation (1.7 m) is an overwash platform.

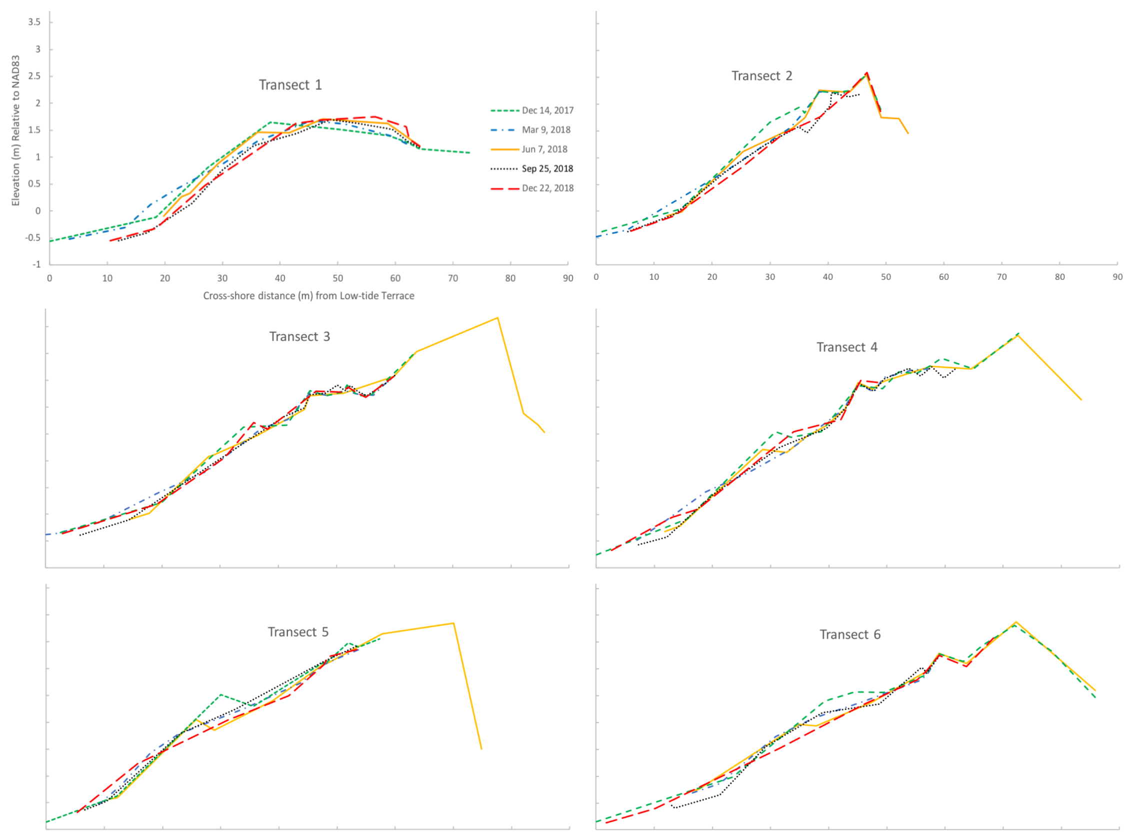

Figure 8: Cross-shore profiles taken quarterly December 2017-2018. Elevation is in meters relative to NJ NAD83 and the cross-shore distance is in meters from the low-tide terrace.

From December 2017 to March 2018 sand was moved from the upper foreshore and base of the dune and was deposited on the lower foreshore and inner low-tide terrace. This is typical of a post-storm beach profile on an estuarine beach (Nordstrom 1992) and was likely due to the high energy event on March 2-3, 2018 that occurred just prior to the day that the profile was taken. This event had high winds from the north, with an average speed of 9.4 m s^{-1} during the two-days (Figure 9).

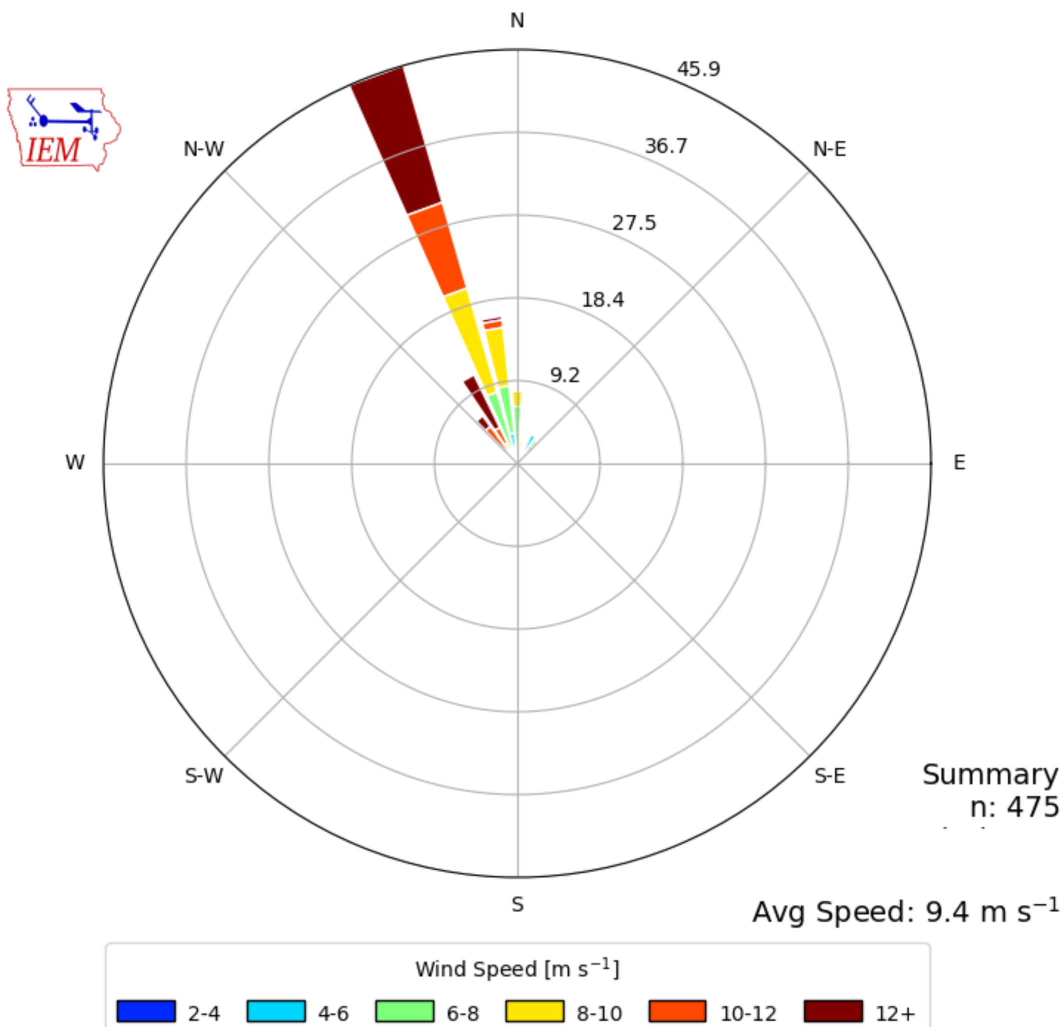

Figure 9: High energy event from March 2-3, 2018 recorded at Sandy Hook, NJ. Winds are from the north with an average wind speed of 9.4 m s^{-1}.

From March 2018 to June 2018, the beach reverted back to a profile similar to the one measured in December 2017, with deposition on the upper foreshore (although at a lower elevation). There was net loss of volume in the beach for all transects, with losses most apparent in the lower foreshore of the beach. This erosion may be the result of alongshore transport downdrift due to a high energy event that occurred April 14-16, 2018. This three-day event had strong winds from the east with an average speed of 8.5 ms^{-1} during that time period (Figure 10).

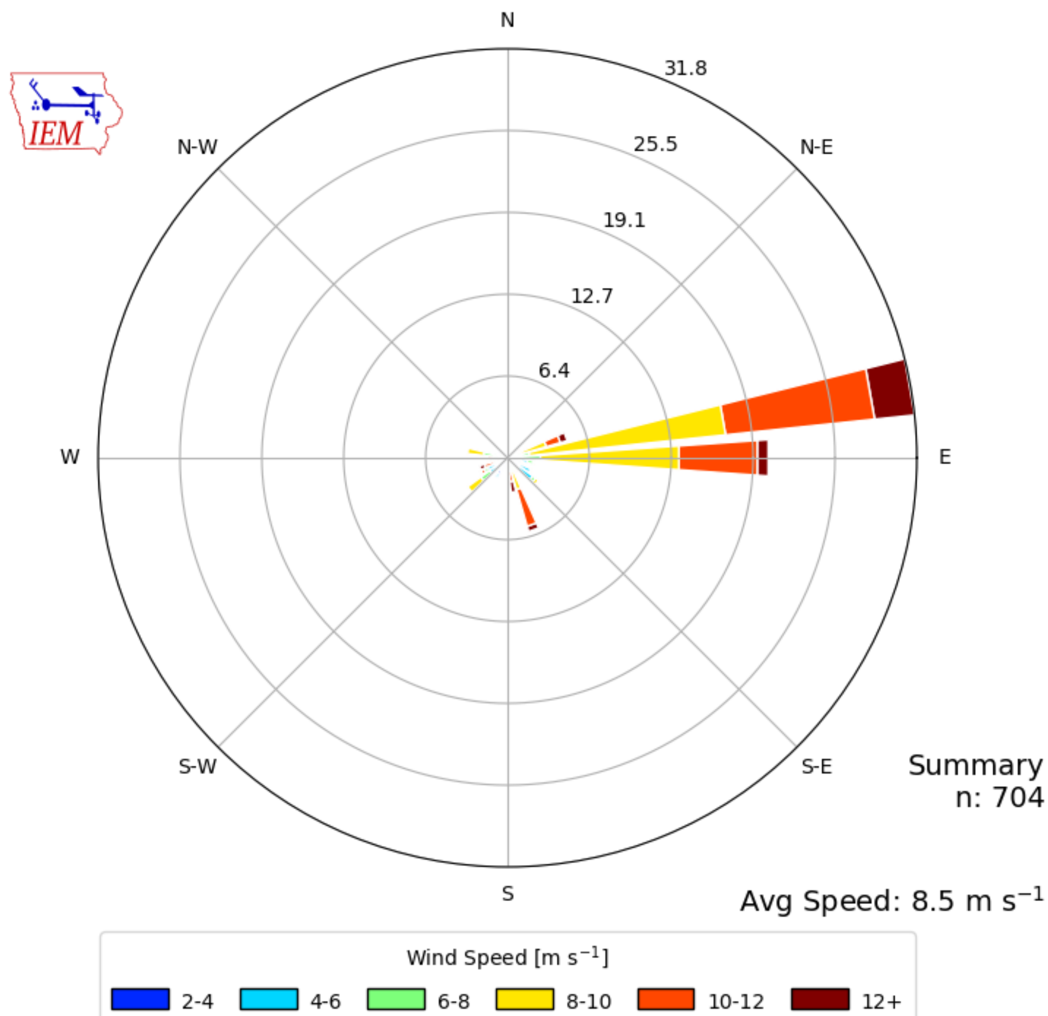

Figure 10: High energy event from April 14-16, 2018 recorded at Sandy Hook, NJ. Winds are from the east with an average wind speed of 8.5 m s^{-1}.

From June 2018 to September 2018 erosion occurred at Transects 1, 2, and 3 and sediment volume was maintained or showed only slight erosion at the downdrift transects 4, 5, 6, as expected, given the westerly net drift. Significant dune erosion and destruction of the sand fence occurred at Transect 2 during this period. This could be a result of easterly winds during Tropical Storm Gordon that occurred September 9-10, 2018, though wind speeds averaged just 7.2 m s^{-1} during this event.

Changes throughout the entire monitoring period reveal progressive erosion of the foreshore and landward translation of the washover deposit on Transect 1, and erosion of the upper foreshore and net loss on the foreshore and bayward portion of the dune at Transect 2. Transects 3-6 reveal cycles of offshore-onshore transport on the foreshore, with little change at the mid-lower foreshore. The parallel foreshore retreat exhibited at Transect 1 is common on beaches where longshore transport is restricted, whereas the cyclic offshore onshore response is more commonly associated with storm erosion and post-storm deposition on beaches where longshore transport is less restricted (Nordstrom 1992).

Grain Size

The results of the grain size data collected at the mid-foreshore at all transects and in the dune at Transects 2 and 5 are depicted in Table 2.

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Dune 2	Dune 5
Total sample								
Mean (mm)	0.30	0.54	0.48	0.78	0.59	0.91	0.34	0.32
Sorting (ϕ)	0.88	1.09	0.62	1.52	1.31	1.57	0.42	0.38
Gravel (%)	5.6	9.8	1.7	22.9	14.5	24.6	0.0	0.0
Sand fraction								
Mean (mm)	0.29	0.45	0.48	0.45	0.42	0.49	0.34	0.32
Sorting (ϕ)	0.40	0.75	0.58	0.76	0.77	0.81	0.42	0.38

Table 2: Grain size characteristics of sediment samples. Samples were gathered at the mid-foreshore at each transect and on the dune at Transect 2 and 5 on June 7, 2018.

The mean size of total samples varies from medium to coarse sand on the foreshore and is medium sand in the dune. Sorting varies from moderately well sorted to poorly sorted on the foreshore and is well sorted in the dune.

The sand fraction on the foreshore is all medium sand. Sorting of the sand fraction varies from well sorted to moderately sorted on the foreshore and is well sorted on the dune. The mean size of dune sand is similar to the 0.35 mm mean diameter sand used to nourish the beach in the 1980s (Jackson and Nordstrom, 1994).

Beach and Dune Width

Beach and dune widths were calculated for all seven transects using the cross-shore profiles (Figure 8). For Transect 1 and the Critical Zone, beach width was measured from the berm crest to the low-tide terrace due to the absence of dune systems at these transects. The results are depicted in Table 3 and Figure 11 below.

Transect ID	T1	T2	T3	T4	T5	T6	CZ
Average Beach Width (m)	30.5	23.6	31.6	33.9	36.6	35.5	16.9
Average Dune Width (m)	N/A	15.3	25.3	41.6	33.1	27.1	N/A

Table 3: Average beach and dune width calculated from cross-shore profiles. The table includes a measure of the beach width for Transects 1 through 6, as well as at the Critical Zone. Where applicable, dune width was also measured and is recorded in the last column of the table.

Nourishment Calculations

As indicated in the Methods, Transect 3 was used to model the idealized beach that would provide the minimum standard of protection required at the eroding area from Transect 3 to the seawall. The volume of this idealized beach from the low tide terrace to the back of the dune at the road verge was calculated to be approximately 34,500 cubic meters. The current volume of this stretch of beach was then estimated. The results of these calculations are shown below (Table 4).

Diagnostic Transect	**Avg. volume (m^3 m^{-1})**	**Alongshore distance (m)**	**Estimated volume for section (m^3)**
T1	65	82	5300
CZ	29	48.5	1400
T2	50	77	3850
T3	140	47.5	6650

Table 4: Estimation of current beach and dune volume. Estimation is for the stretch of beach from Transect 3 to the seawall. The average current volume per linear meter for Transects 1, 2, 3 and the estimated current volume for each section of beach, which was then summed to obtain a total estimated current volume of 17,000 cubic meters.

Based on an idealized beach volume of 34,500 cubic meters and an estimated current volume of 17,000 cubic meters, a nourishment project initiated to ensure the survival of the dune system along the entirety of the beach would require approximately 17,500 m^3 of sand.

Erosion rates calculated from December 14, 2017 to December 22, 2018 for Transects 1, 2, and 3 (Figure 11) reveal that Transect 2 has the greatest erosion rate (7.9 m^3 m^{-1} yr^{-1}). Transect 1 is eroding at a rate of 2.1 m^3 m^{-1} yr^{-1}. Transect 3 is also eroding but at the slowest rate (1.5 m^3 m^{-1} yr^{-1}). Figure 11 serves as a schematic depicting the current state of the beach, erosion rates, and the potential fill area for a nourishment project that could restore beach width and dune volume at the critical zone.

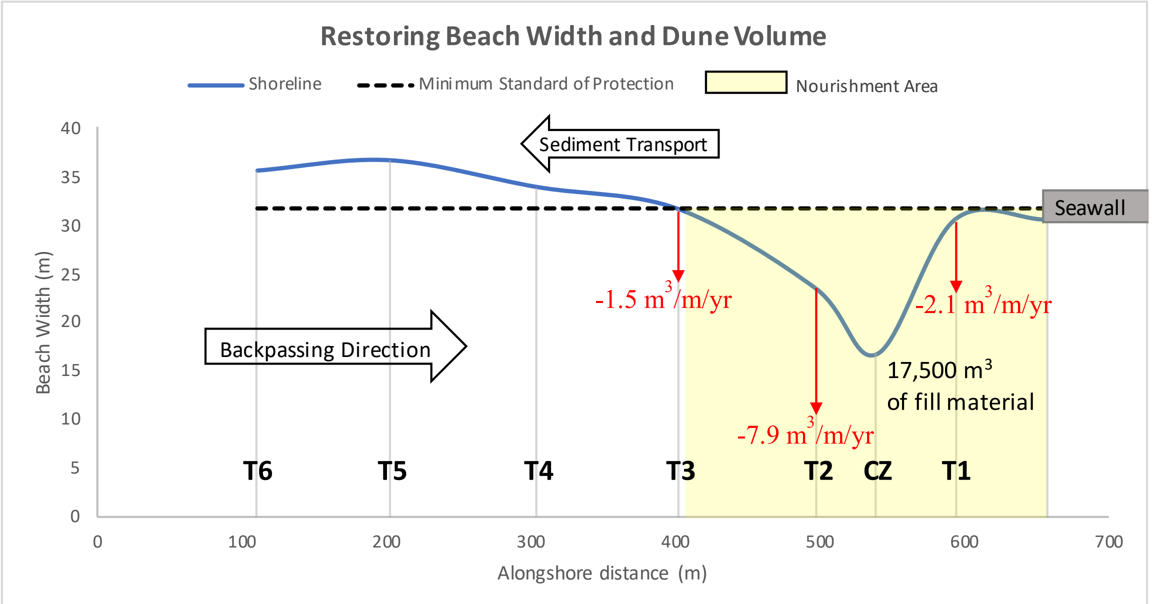

Figure 11: Diagram graphically depicting the beach and dune width for Cliffwood Beach from the seawall to Transect 6. Beach width and alongshore distance are measured in meters. The dashed line indicates the minimum standard of protection needed based on our assessment. The shaded section would require a nourishment of 17,500 cubic meters to attain this level of protection.

Dune height

The highest point of the dune is 3.83 meters above NAVD83 and is located near Transect 4, which also has the greatest dune width (Table 3). The lowest point is 1.89 meters and is located at the beach access walkway between Transect 2 and 3. The lowest point along the dune crest is still approximately 0.5 m higher than areas where the dune system has been eliminated (Figure 12).

Landward elevations

The playground surface of the park (Figure 12) is at an elevation of 1.87 m; the highest point of the parking lot is 1.74 meters. The baseball field at the west end of the park is at an elevation of 2.13 m. Lows of the boundary between the grass and the wetland backing the park range from 1.13 m to 1.73 m, with the lowest point located near the basketball court at the east end of the park. The lowest point of the parking lot is at 1.30 m.

Figure 12: Spot elevations of high and low points in the dune system and surrounding areas. All elevations are in meters, relative to NJ NAD83.

The top of the Whale Creek jetty is at 3.22 m at its most landward point, and slopes downward toward the bay, reaching its lowest elevation of 0.88 m at the bayward end of the structure.

Sea level rise projections

Table 5 (Kopp et al. 2016) shows the probability of sea level rise in the first year of each decade of the 21st century. Projections are based on the Atlantic City tide gauge, which represents a conservative approach to sea level projections in New Jersey. This is a conservative approach because the Atlantic City sea level rise projections differ minimally from those based on the Sandy Hook and Cape May tide gauges (Kopp et al. 2016), and are higher than those at The Battery, New York City, by about 3 inches per century due to land subsidence associated with natural sediment compaction and groundwater withdrawal (Miller et al. 2013). Projections differ depending on the greenhouse gas emissions that are released over the next one hundred years and accordingly the projections for a high emissions scenario and low emissions scenario are presented in the table. Figure 13 shows the current mean higher high water at Cliffwood Beach and projections for sea level rise of 1 and 2 feet (0.3 and 0.6 m, respectively).

High emissions (RCP 8.5)

	1 ft.	2 ft.	3 ft.	4 ft.	5 ft.	6 ft.	7 ft.	8 ft.	9 ft.	10 ft.
2020	0.1%									
2030	14%									
2040	60%	0.1%								
2050	86%	6%	0.1%							
2060	95%	33%	1%	0.1%						
2070	98%	62%	10%	0.7%	0.1%					
2080	99%	79%	29%	4%	0.5%	0.2%	0.1%			
2090	99%	88%	50%	15%	3%	0.6%	0.2%	0.1%	0.1%	
2100	99%	92%	66%	30%	8%	2%	0.7%	0.3%	0.2%	0.1%

Low emissions (RCP 2.6)

	1 ft.	2 ft.	3 ft.	4 ft.	5 ft.	6 ft.	7 ft.	8 ft.	9 ft.	10 ft.
2020	0.1%									
2030	12%									
2040	52%	0.1%								
2050	78%	3%	0.1%							
2060	89%	14%	0.4%	0.1%						
2070	94%	31%	2%	0.2%	0.1%					
2080	96%	46%	5%	0.7%	0.2%	0.1%				
2090	97%	59%	12%	2%	0.5%	0.2%	0.1%	0.1%		
2100	97%	69%	20%	4%	1%	0.5%	0.2%	0.1%	0.1%	0.1%

Estimates are based on (Kopp et al., 2014). All heights are with respect to a 1991-2009 baseline. Values refer to a 19-year average centered at the specified year. Gray shaded areas have less than a 0.1% probability of occurrence.

Table 5: Sea level rise projections for New Jersey. Probabilities represent the likelihood that sea level rise at Atlantic City will meet or exceed the stated values in selected years, calculated for both representative concentration pathway (RCP) 8.5 (a high greenhouse gas emissions scenario) and RCP 2.6 (low greenhouse gas emissions) as defined by the IPCC (from Kopp et al. 2016).

Under a high emissions scenario there is an 86% chance that New Jersey will experience sea level rise of one foot (0.3 m) by 2050 (Table 5). By the year 2100, there is a 92% chance that sea level rise will reach two feet (0.6 m). Figure 13 shows the current mean higher high water (MHHW) level at Cliffwood Beach and the level projected for one and two feet of sea level rise, respectively. This table shows that management decisions should plan for a sea level rise between 0.3 and 0.6 m within the next 30 to 80 years.

Figure 13 also shows the effects of a one- and two-foot sea level rise would have on the low-lying areas landward of the beach. In addition to the dune system be more prone to overwash and flooding from coastal storms, the sea level rise maps suggest that frequent inundation could occur around Whale Creek and other low-lying wetland areas, possibly extending into portions of Veteran's Memorial Park.

Figure 13: Sea level rise mapping. Projection for current MHHW and MHHW after 1 and 2 feet of sea level rise at Cliffwood Beach and Whale Creek. Image created by NJ Flood Mapper open access tool. For a detailed explanation of the method see NOAA CSC, (2012).

Overview of Potential Protection Strategies

Several shore protection strategies should be considered by municipal managers. Each protection strategy has different characteristics that need to be considered, including the life-span of the protection measure, impact it has on the environment, cost, and effectiveness in addressing the problems of erosion and flooding. The management strategy should be related to the dimension of change, and that the scale of the response should be within the context of the entire sediment cell of the local system (Brunsden and Lee 2005; Cooper and Pethick 2001; Marchand et al. 2011).

Retreat from coast

The combined effects of rising sea levels and rising costs of coastal protection (Fankhauser, 1995; Turner and Adger, 1995) can make the traditional 'hold the line' policy an unrealistic long-term objective for coastal managers (Ledoux et al., 2005). In its place, the concept of managed retreat or realignment of coastal defenses landward has been suggested as a sustainable, environmentally friendly long-term coastal defense strategy (Brooke, 1992; French, 2006). This strategy is not compatible with the current vision of managers of Cliffwood Beach, but the rationale is presented here for consideration for future application.

The primary purpose of managed retreat is to increase the efficiency and long-term sustainability of flood and coastal defenses by recreating coastal habitats and allowing these habitats to serve as a buffer to coastal storms and flooding (Ledoux et al., 2005). Managed retreat allows for landforms and habitats to evolve naturally, but there is limited implementation of adaptation responses that move infrastructure and development landward to create the space for these habitats (French, 2006; Morris, 2012; Cooper and Pile, 2014). Many view a policy of managed retreat as imminent, although widespread adoption of this policy will likely take decades to implement (Parsons and Powell, 2001), in part because retreat is often a reactive measure rather than proactive (Ledoux et al., 2005). Other factors that complicate implementing managed retreat include lack of institutional arrangements, patterns of funding, and case studies documenting effectiveness (Titus, 1998; Ledoux et al., 2005).

Managed retreat at Cliffwood Beach would be appropriate because of the presence of a relatively large wetland and sparsity of infrastructure and residential housing landward of the critically eroding shoreline. Ocean Boulevard and Veteran's Memorial Park represent the only significant obstacles to a managed retreat, and these facilities would have to be removed or relocated. Managed retreat would allow the coastline to migrate landward, eventually achieving a state of dynamic equilibrium with a natural barrier/dune system fronting the marsh and serving as a buffer to coastal storms and flooding.

The economic cost of a managed retreat is difficult to estimate, as most of the costs are expected to be land and capital loss (Parsons and Powell, 2001). While it would certainly be costly to relocate Ocean Boulevard and Veteran's Memorial Park, the municipality would be facilitating the revival of an ecologically and recreationally valuable estuarine coastal landscape.

Traditional beach nourishment

Traditional beach nourishment involves replacing sediment lost through alongshore drift or erosion with sand from other sources (often offshore or inland quarries) (Hanson et al. 2002; Nordstrom, 2008). Nourishment is currently the primary shore protection strategy in many countries (Hamm et al., 2002). The goal of beach nourishment is to create a wider beach to provide increased protection from storm damage by dissipating the energy of incoming waves. Nourishment not only provides shoreline protection in estuaries but can also provide beach habitat when implemented properly (Nordstrom, 1992; Nordstrom, 2005; Andrade et al. 2006). Nourishment is typically a repetitive process that does not directly address the physical forces that cause erosion, but simply mitigates the erosion problem temporarily (Dette et al. 1994; Smith et al. 2009). The total loss of beach fill fronting the seawall and in the critical zone at Cliffwood Beach since the 1980s underscores the temporary nature of beach fill.

Nourishment projects are considered costly. Parkinson and Ogurcak, (2018) found that nourishment construction costs in Florida have risen from $5 m^{-3} during the late twentieth century to over $10 m^{-3} in the past decade. Parkinson and Ogurcak (2018) also found that these costs are rising at a rate of about $5 m^{-3} every 15 years since the mid 1970s. Analysis of nourishment projects from 2000-2015 in New Jersey indicate that the average cost per cubic meter to be $16.62 (obtained from National Beach Nourishment Database) (see Campbell and Benedet, 2006). Municipalities must be prepared to pay for labor, capital, and the raw material cost of importing and placing sand on the beach. The cost of building dunes using sand fences or earth-moving equipment must be added to the cost of beach fill.

Because of high and recurring expenses, traditional nourishment projects usually require a municipality to apply for a funded project from government sources (e.g. US Army Corps of Engineers). Non-federal nourishment projects in New Jersey are funded through a state/local cost-share, with the state contributing 75 percent and the local governments contributing 25% (NJDEP DoCE, 2012). To competitively apply for nourishment projects, it is important to know volumes of sand initially needed, rates of loss, grain size characteristics of the native beach material, dimensions of existing and required beaches and dunes, and ecological constraints and opportunities.

Facilitating the evolution of natural vegetation on nourished beach and dune systems is also an important factor to consider. Natural vegetation traps and anchors sediment and can stabilize the sediment in a way that allows for consistent protection following intermittent disturbances (Johnson, 2016). Vegetation presence, species morphology, species richness and diversity, cover, and vegetation zonation are all factors that have been demonstrated to influence foredune morphology and development (Bitton and Hesp, 2013). Salt-spray (Sykes and Wilson, 1991) and sand burial (Moreno-Casasola, 1986) have been identified as the most critical factors affecting vegetation zonation on coastal dunes. The cross-shore location of species planted in the dune should consider tolerance of these factors. Wave energy and salinity are lower on an estuarine shoreline than on ocean beaches, so many species could be located closer to the shoreline than on ocean shorelines where most planting guidelines have been developed.

Backpassing

Backpassing represents a less traditional form of nourishing beaches using sediment from within the same littoral cell. Backpassing operations take advantage of the natural "conveyor belt" or alongshore drift. Sediment that accretes in a depositional area downdrift can be mechanically moved to critically eroding areas updrift. There is precedent for this type of operation in New Jersey, as Avalon obtained a state permit allowing the municipality to mechanically backpass sediment from depositional areas to erosional areas at an average rate of 38,000 m^3 yr^{-1} using its own equipment (Mauriello, 1991; Nordstrom et al., 2002). The Gunnison Beach area of Sandy Hook, NJ has also been monitored to determine the potential for sediment backpassing as a strategy to balance its local sediment budget (Psuty and Pace, 2009).

The speed at which mechanical manipulations of the beach can be made allows a municipality to control the local sediment budget and keep pace with the rate of erosion in a critical area. Nordstrom et al. (2002) note that backpassing operations have the ability to reduce the maximum distance of the landward displacement of the shoreline in erosional areas during storm events. Mechanical backpassing can induce more rapid accretion than would occur under natural conditions and make the depositional phase of erosion/deposition cycles more frequent (Nordstrom et al., 2002). Though mechanical manipulation of the landscape is more frequent in backpassing operations than traditional nourishment projects, the magnitude of these manipulations is much smaller. By using sand from accretionary areas within the same littoral cell, municipalities avoid the need for mining offshore sand sources and the associated costs. This type of small-scale coastal management helps to avoid the need to apply for large external funding packages and allows for a more localized approach to small critical areas of beach that are chronically eroding.

Hard-structures

Hard-structure solutions include shore parallel structures (seawalls, revetments, bulkheads) that protect against landward retreat and shore perpendicular structures (groins and jetties) that trap sand moving alongshore.

The most commonly utilized hard structures to address coastal flooding are shore-parallel structures like seawalls, revetments, and bulkheads that are designed for areas where there is high wave energy (NRC, 2014). These structures are built to protect against coastal risks where the natural beach and dune system has been restricted or reduced and other risk reduction options are not available due to lack of space or sediment (NRC, 2014).

A seawall is a shore-parallel structure constructed to protect against retreat of the shoreline and inundation or loss of the upland by flooding and wave action (Kraus and McDougal, 1996). Seawalls have been shown to serve as effective flood protection and are and especially appropriate option where chronic erosion or inundation are imminent and where further shoreline recession cannot be accommodated (Kraus and McDougal, 1996). Examples of such cases can be found in the Netherlands (Pilarczyk, 1992) and at Norderney, an island off the North Sea coast of Germany (Kunz, 1993).

Seawalls can interrupt alongshore sediment transport and change the way beach profiles respond to changes in wave climate (Morton, 1988; Kraus and McDougal, 1996). The difference in profile response at Transect 1 compared to the other profiles, mentioned earlier, is an example. Seawalls may prevent long-term recovery or rebuilding of the beach, as they can restrict berm formation from wave uprush and dune formation via aeolian deposition (Carter, 1988; Morton, 1988). Kraus and McDougal (1996) make the astute distinction that seawalls are “shore-protection structures and not beach-protection structures”. For this reason, the use of a seawall at Cliffwood Beach would not be an appropriate option to ‘hold the line’ as it would not curtail the chronic erosion seaward of the structure and would likely initiate accelerated erosion downdrift of its placement.

The design and installation of a seawall can also be expensive, and the cost differs depending on the design height, anticipated wave loadings, and the construction materials used, among other factors (NRC, 2014). Linham et al. (2010) found that the cost of a vertical seawall ranges from \$0.4 million km^{-1} to \$27 million km^{-1}. Other cost estimates were reported by the UK Environment Agency (2007), which estimated an average seawall cost of \$2.7 million km^{-1} (in 2013 dollars).

The primary difference between bulkheads and seawalls is that seawalls are designed primarily to intercept wave energy, while bulkheads are primarily used to retain or prevent sliding of landward soil and sediment with the protection from wave action as a secondary function. Bulkheads can be used as primary protection in estuaries because of the low wave energies (Nordstrom, 1992), so a bulkhead may be preferable to a more massive seawall. Bulkheads can be made up of vertical sheet pilings of different materials such as steel, timber and aluminum, depending on the expected wave loadings, cost considerations, and the subsurface conditions. Steel sheet piling can be used in locations with hard soil and some soft rock, whereas aluminum and timber sheet piling can only be used in areas with softer soil (ACoE, 2014). Bulkheads can be cantilevered or anchored structures (Figure 14). A cantilever bulkhead derives its support solely from ground penetration. Because of this, the sheet piles must be driven deep enough to resist overturning. Cantilever bulkheads are susceptible to failure due to scouring as this jeopardizes embedment of the piling (ACoE, 2014), although there is little potential for scour bayward of structures built on the low tide terrace (Nordstrom, 1992). Anchored bulkheads have the advantage of additional support from embedded anchors (or deadmen) buried landward of the bulkhead and tied into the shore-parallel wales that hold the sheet piles in place (ACoE, 2014).

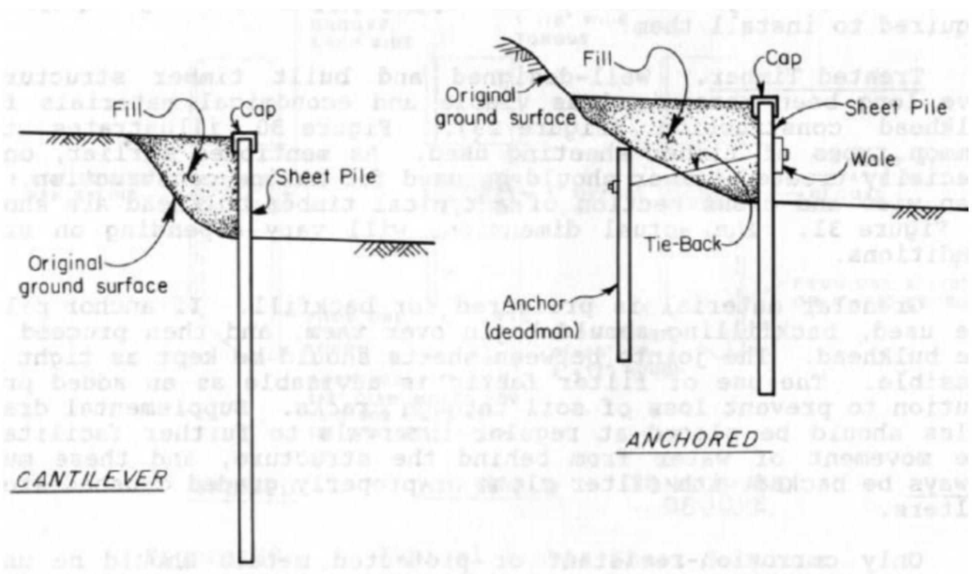

Figure 14: Anchored and cantilever bulkheads. Diagram depicting differences between cantilever and anchored bulkheads. (Image Source: ACoE, 2014)

As at seawalls, the beach in front of a bulkhead will decrease in volume and width (Kraus and Pilkey, 1988; Kraus and McDougal, 1996). Bulkheads on eroding shorelines can (1) result in permanent removal of sand from the littoral transport cell, thus limiting sand supply to downdrift locations; (2) reflect wave energy such that the shoreface at the toe of the structure can become significantly steepened; and (3) eliminate the intertidal shore causing loss of habitat and recreational access (NRC, 2007). Because of these unwanted effects, the use of a bulkhead at Cliffwood Beach is not recommended except as an emergency measure to protect Ocean Boulevard. The use of a bulkhead in this capacity would protect the road but could lead to accelerated erosion farther downdrift and would not curtail the chronic erosion observed in the Critical Zone.

Geotextiles represent a more innovative protection measure that could be utilized to build a wall at Cliffwood Beach. Geotextiles form a water permeable barrier that hold back sediment and provide added protection from wave uprush (NRC, 2007). The geotextile may be used to create a tube filled with sediment (here called a geotube) and has the advantage of being flexible, allowing for optimal configuration to suit site-specific needs (Eurosion, 2004). Geotextile sand-filled containers (GSCs) have been used as a coastal protection strategy for more than fifty years in places like the United States, Netherlands and Germany (Saathoff et al. 2007).

Often GSCs in the form of geotubes, cylindrical geotextile sand-filled structures, are used in combination with artificial dune construction. Allan and Komar (2002) demonstrated how a dune constructed with sand-filled geotextile bags and covered with vegetated sand was able to survive fairly extreme conditions that included overtopping. Heerten et al. (2008) documented a successful instance of geotubes covered with sand and sand fencing in erosion mitigation. Though the geotubes were exposed after a larger storm event, they prevented the event from substantial erosion. This is a typical response to GSC-based structures, and municipalities can expect to periodically rebury GSCs after high energy events (Figures 15 and 16) (Nordstrom, 2019).

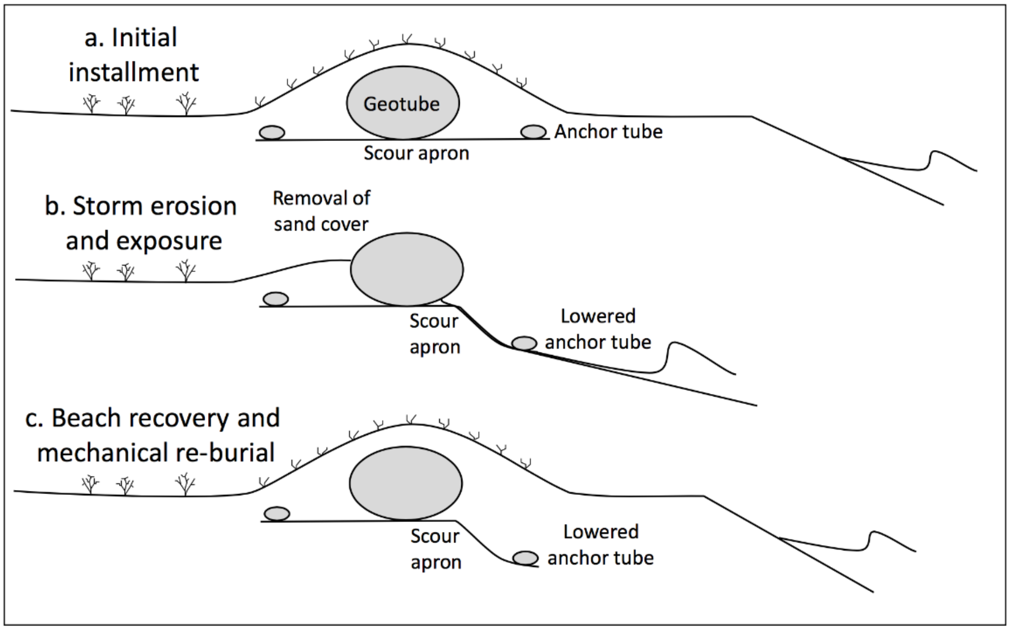

Figure 15: Geotube installment and maintenance. Diagram depicting the installment, post-storm erosion and exposure, and the recovery and re-burial of a geotube used for shoreline protection (Nordstrom, 2019).

Figure 16: Geotubes in practice. Geotube being emplaced on shoreline prior to being buried with sand (Nordstrom, 2019).

Coastal residents often view physical barriers as a more desirable defense strategy than soft solutions like nourishment (French, 2001), however hard structures like seawalls often accentuate erosion and thus can be detrimental to erosion mitigation objectives. GSCs have been considered to be a “pseudo-soft” solution because although they impede the natural morpho-dynamics of the coastal zone, they can be removed relatively easily if necessary (Corbella and Stretch, 2012). The use of GSCs has been argued to provide a middle ground between hard structures that are appealing to politicians and residents, while still being environmentally friendly (Corbella and Stretch, 2012). Furthering the appeal of GSCs, and more specifically geotubes, is their low cost in comparison to other traditional hard structures. For example, a project in Half Moon Bay, California using geotubes between 3 m and 4 m in diameter estimated the construction cost to be $75 per linear foot, whereas a revetment in the same location was estimated to be $200 per linear foot (Moffat and Nichol Engineers, 2001). Costs for geotube installations can vary depending on the source of the sediment used to fill the geotextile. Use of local beach material would lower costs, but the sediment used as fill would be eliminated from the active beach profile.

A geotube may be a sufficient temporary solution to the intermittent inundation and overwash that occurs at Ocean Boulevard. A geotube could be used to build dune systems where they have been eliminated, providing protection from wave uprush and flooding at the Critical Zone. The flexibility of geotubes could allow for an arrangement that curves congruent with the bend at the vulnerable portion of Ocean Boulevard. Although a geotube could help provide protection from wave uprush and flooding from the bay, it will not address the sediment deficit downdrift of the seawall. For this reason, a geotube could be used as a temporary measure to protect the road. Without a beach nourishment project to supplement the use of a geotube, the Critical Zone will continue to erode and the geotube would be frequently overtopped or uncovered and require frequent maintenance.

Discussion

The cross-shore topographic profiles (Figure 8) provide evidence that the erosional issue is primarily constrained to the regions immediately downdrift of the seawall. Despite a relatively consistent beach width of 30 to 35 meters along the entire beach, the dune system has become narrower or eroded away in the vicinity of Transects 1 and 2. This is likely due to the shore parallel structures updrift of the study area which limited sediment entering the system. This conclusion is supported by the historical aerial photographs that reveal the effect of the earlier bulkhead and subsequent seawall (Figure 6).

A nourishment project would be required to restore the beach and dune system in this area. A beach replenishment of 17,500 cubic meters would be costly for a municipality and may require support through state or federal funding. Sediment from external sources would be required for any significant nourishment project. The fill material should be similar in size and shape to the native sediment. Sediment that is finer grained will likely not be compatible with the local coastal processes, and thus is likely to be eroded faster (Stauble et al., 1984). Coarser material would inhibit aeolian transport of sediment into the dune (Speybroeck et al. 2006). If this coarse material contains a high proportion of shell or shell fragments, issues like cementation and stress to invertebrates can also occur (Speybroeck et al. 2006).

At Cliffwood Beach, the existing size of foreshore sediment is approximately 0.45 mm sand. The exception to this occurs at Transect 1, where grain sizes are much finer. The cause of this could be that much of the sediment at Transect 1 was provided by aeolian transport off the previously nourished beach, which is supported by the strong northwesterly winds (Figure 4) and field observations that reveal dune accumulations at the west end of the seawall. Additionally, the finer grained material could be deposited as a result of local sheltering among the many deteriorated cultural elements (concrete blocks and basalt cobbles and boulders) in the near shore and foreshore at this location. The suggested fill size for beach fill would be about 0.45 mm along the entire beach to be compatible with the local wave regime and existing sediment.

The use of sand-trapping fences to facilitate dune building should continue to be employed at Cliffwood Beach. Sand fences have the ability to build dunes where no dune exists, fill gaps in the crestline of existing dunes, and create a higher or wider dune, allowing it to function more efficiently as a barrier to wave run-up (Nordstrom, 2008). The use of sand fences in municipal management of beaches is important as they represent one of the few structures permitted seaward of the dune crest, are inexpensive, and can be easily installed (Nordstrom, 2000).

There are varied opinions regarding the most effective sand fence configuration (Miller, et al. 2001). Currently a straight fence alignment parallel to the shoreline is being employed at Cliffwood Beach. Though this alignment seems to provide the most economical method to building dunes (Miller et al. 2001), this configuration may create slopes too steep to establish planted stabilizing vegetation (Nordstrom, 2008). As a strategy to build dunes in a closer approximation to natural dunes, the municipality should consider placing paired shore-parallel (Schwendiman, 1977) or paired zig-zag fences (Snyder and Pinet, 1981). These configurations have been demonstrated to create wider and more gently sloping dunes, likely increasing the survival of planted vegetation (Nordstrom, 2008).

While a nourishment project would be sufficient to recreate a beach and dune system along the critically eroding beach segment, the erosion problem at Cliffwood Beach would not be solved. Chronic erosion is likely to continue, as the seawall continues to act as a barrier to sediment entering the system. To manage this erosion problem a municipally managed backpassing operation should be considered. A backpassing operation would require 1,000 m^3 of sand to be backpassed from accretionary portions of the beach downdrift at a rate of 83 cubic meters (about 8-12 truckloads) per month. Sand tightening of the Whale Creek jetty (by building up the elevation of the seaward portion) should be considered if a backpassing operation is performed, as it would reduce losses over and around the structure, allow for more accretion east of it and increase the potential to use the accreting area as a sediment source.

Backpassing would make the nourishment project sustainable because it would maintain the sediment budget within the beach compartment. This aspect of sustainability would provide a more "permanent" solution to the erosion issue and could increase the likelihood of state or federal investment in a "once-and-done" large-scale replenishment project. The suggested rate of backpassing may be too much for the municipality to manage given existing equipment and human resources. Any amount of backpassed sediment would be valuable, but full backpassing capacity would be preferable.

From June 2018 to September 2018, high energy events much of the dune system was damaged. Scarping at the toe of the dune occurred and a significant portion of the remaining dune at Transect 2 washed away (Figure 8). Sand fences were knocked down and portions of the more stable dune to the west eroded. This suggests that the erosion is beginning to affect areas farther downdrift as time passes and supports the need for management actions sooner rather than later.

If funding and resources cannot be obtained for a large nourishment project in the near future, a geotube may be required to provide temporary protection at the critical zone. The geotube would provide protection at the bend in Ocean Blvd. where frequent flooding and overwash is occurring. The geotube represents a short-term solution and would require frequent maintenance following large storm events.

The implementation of a geotube and/or reestablishment of a dune system at this site would only serve to defend against the flooding and overwash that is occurring as a result of wave uprush and erosion of the shoreline. Elevation data of the areas landward of the dune system suggest that other sources of flooding are also threatening. Inundation is likely to affect a large portion of the area landward of Cliffwood Beach by the year 2050. This inundation would be a result of higher sea levels, coupled with low elevations near Whale Creek and in the wetlands backing Veteran's Memorial Park. Sea level rise projections should be continually monitored by the municipality and taken into account when considering further development in the area. Inundation from the landward side could be addressed by installing a ring levee enclave around the park or by elevating the roadway, though a definitive statement on this issue is beyond the topic of this thesis.

The meetings held with township officials in preparation for this study also revealed the difficulties many municipalities face when addressing coastal erosion and the associated threats to infrastructure. Though coastal scientists may expect the municipal management of the coastal zone to be a process heavily informed by scientific data, evidence and recommendations, this is not always the case. Instead, the choices made at the municipal level are often a collection of disjointed decisions based on other factors that end up becoming the de facto approach to coastal management. While the municipality has acknowledged for some time that the state of Cliffwood Beach has been chronically deteriorating, little thought has gone into generating actionable measures that can be taken to address the issue. From our conversations with municipal officials, it was clear that this was largely a function of lack of expertise, institutional capacity, and funding. This highlights the importance of facilitating collaboration between coastal scientists and local managers. A more open flow of knowledge and expertise between these two groups will allow municipalities to be well-informed about the state of the coastal zone within their jurisdiction, as well as the mitigation and adaptation measures that are available to them.

Conclusions

The results of our study of Cliffwood Beach have led to the following conclusions regarding the conditions of the beach and dune system and recommended management actions the municipality should take:

1. The erosion occurring at the Cliffwood Beach study area is a result of lack of sediment supply due primarily to the presence of the seawall to the east, which is limiting alongshore transport of new sediment into the littoral cell.

2. The recommended management strategy for Cliffwood Beach is to implement a nourishment project that widens the beach and reestablishes the dune system in the critical zone where the dune is being eroded away. This nourishment project would require approximately 17,500 m^3 of fill material.

3. Applications for funding to renourish the beach may be submitted to the New Jersey Department of Environmental Protection, Coastal Engineering Division. This application can be supplemented with the findings of our study.

4. In the interest of making a nourishment project more sustainable and thus more appealing for state investment, a sand backpassing operation should be considered. This would entail moving approximately 80 m^3 of sediment from the downdrift portion of the beach to the critically eroding stretch of beach each month. This backpassing operation would require sand tightening of the Whale Creek jetty.

5. Until funding for a nourishment project can be obtained, a geotube should be considered as a low-cost option to temporarily protect Ocean Boulevard and Veteran's Memorial Park. The geotube could be covered with local sediment, though it may require frequent maintenance (reburial) after high energy events.

6. Managed retreat should be considered as a long-term, sustainable management plan for Cliffwood Beach given the rate of erosion and relatively small amount of infrastructure and residential facilities landward of the beach.

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