Nantasket Beach Seawall Repair and Reservation Master Plan Services

Final Report, Tasks 3 and 4

Coastal Engineering and Shore Protection Alternatives Assessment

Prepared for

Massachusetts Department of Conservation and Recreation

Prepared by

Woods Hole Group, Inc. *and* The Louis Berger Group, Inc.

February 2010

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COASTAL ENGINEERING AND SHORE PROTECTION ALTERNATIVES ASSESSMENT

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ABSTRACT

Nantasket Beach is located in the Town of Hull, Massachusetts. The southern portion of the beach is part of the Nantasket Beach Reservation, operated by the Department of Conservation and Recreation (DCR). The DCR portion of Nantasket Beach has experienced ongoing erosion. Although the erosion rates have been relatively minor (less than -1.0 feet/year), this erosion, coupled with a lack of a significant sediment supply, has been significant enough that there is little to no high tide beach along a majority of the DCR portion of Nantasket Beach. The alongshore sediment transport rates are also relatively small (between 10,000 - 50,000 cubic yards per year). Evaluation of the coastal processes indicated that the average annual net movement of sand is from south to north, although sand does move in both directions depending on the wave climate. However, the cobble portion of the sediment distribution generally moves only during stronger northern and north-eastern approaching storms, resulting in a net transport from north to south. In the recent past, repairs to the seawall and fortification of the wall were needed in the northern and southern sections of the wall following large storms. Currently, the remaining unprotected mid-section of the wall is also at risk for damage and possible failure.

An alternatives investigation was undertaken to provide shore protection for the DCR property and adjacent Town and private property, and to provide economic and recreational benefits to the surrounding communities. Aside from No-action, alternatives included the following:

- Seawall toe protection (similar to the southern portion of the seawall)
- Revetment (similar to the northern portion of the seawall)
- Beach nourishment (without rocks, with toe protection, or with revetment)
- Construction of new seawall 30 feet back, with revetment, and sand dune
- Removal of seawall, providing protection with beach nourishment alone.

The preferred alternative is <u>Seawall Toe Protection with Beach Nourishment</u> for the following reasons:

- **Seawall is Necessary and Beneficial:** Leaving the seawall in place is the most cost-effective solution for satisfying the need for protection of the Nantasket Beach Reservation and upland resources owned by DCR, the Town of Hull, and private owners.
- **Strengthening of Seawall with Toe Protection:** Toe protection in front of the mid-section of the seawall would strengthen the seawall and provide reliable protection for the seawall during large storms. Rocks should be covered by sand during nourishment. The combined seawall and toe protection also provides a second line of defense after the nourished beach is put in place.
- **Beach Nourishment:** The beach is a valuable resource for the citizens of Hull and other surrounding communities, and is actively used by residents, particularly in the summer. Although toe protection and the seawall alone can provide adequate protection, beach nourishment is required to meet the recreational, economic, and overall storm damage protection goals of the project. Therefore, beach nourishment should be a component of the solution.
- **Sediment Source for Nourishment:** Sand can be supplied from readily available land sources in eastern Massachusetts. However, an offshore sand source would be significantly more cost-effective than a land source. While offshore sources have so far not been permitted in Massachusetts, efforts should be made at the State-level to establish an offshore source for Nantasket, as well as other coastal communities in Massachusetts.

In summary, the recommended alternative provides the most shore protection and recreational benefits and is the most cost-effective. Shore protection efforts are planned to be combined with upland improvements of the Reservation to enhance the recreational and economic value of this asset in the Commonwealth.

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List of Key Abbreviations

Berger	The Louis Berger Group, Inc.
CAC	Citizens Advisory Committee
cm	centimeters
cy, cyds	cubic yards
cy/yr	cubic yards per year
DCR	Massachusetts Department of Conservation and Recreation
DEP	Massachusetts Department of Environmental Protection
ft	feet
ft/yr	feet per year
km	kilometers
LIDAR	LIght Detection And Ranging
l/s-m	liter per second for each meter of beach front
MA	Massachusetts
m	meter
mm	millimeter
MHW	Mean High Water
MLW	Mean Low Water
MTL	Mean Tide Level
NGVD	National Geodetic Vertical Datum of 1929
NOAA	National Oceanographic and Atmospheric Administration
PEP	Prefabricated Erosion Prevention
USACE	United States Army Corps of Engineers
WHG	Woods Hole Group, Inc.

Note

This report represents a joint report for Tasks 3 (Expanded Alternatives Assessment Study) and Task 4 (Beach Nourishment Optional Services) of the Project entitled *"Nantasket Beach Seawall Repair and Master Plan Services"*, contracted to the Louis Berger Group, Inc. (Contract DSP 080 P99-1979-D2A). The Department of Conservation and Recreation issued the Notice-to-Proceed for this contract on February 28, 2006. The Woods Hole Group is a subcontractor to the Louis Berger Group under this contract.

Generally, the Louis Berger Group was responsible for engineering, socioeconomic, permitting, and environmental aspects of this report. The Woods Hole Group was responsible for all aspects related to coastal processes as they relate to shoreline protection. Specific contributions to this report were provided primarily as follows:

Chapter 1: Introduction	Woods Hole Group/Louis Berger Group
Chapter 2: Background Geology and History	Woods Hole Group
Chapter 3: Historical Shoreline Change	Woods Hole Group
Chapter 4: Wave Climatology and Transformation	Woods Hole Group
Chapter 5: Sediment Transport	Woods Hole Group
Chapter 6: Development of Alternatives	
Sections 6.1 to 6.2	Woods Hole Group
Section 6.3	Louis Berger Group
Chapter 7: Coastal Protection Alternative Analysis	
Sections 7.1 to 7.2	Woods Hole Group
Sections 7.3 to 7.5	Louis Berger Group
Chapter 8: Sand Source Investigation	Woods Hole Group
Chapter 9: Summary and Conclusions	Woods Hole Group/Louis Berger Group

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EXECUTIVE SUMMARY

Nantasket Beach is located in the Town of Hull, Massachusetts. The southern portion of the beach is part of the Nantasket Beach Reservation, operated by the Department of Conservation and Recreation (DCR). The beach is a valuable resource for the citizens of Hull and other surrounding communities, and is actively used by residents, particularly in the summer.

Over the years, the DCR portion of Nantasket Beach has been eroding. Beach erosion is relatively slow. However, repairs to the seawall and fortification of the wall were needed in the northern and southern sections of the wall following large storms. Currently, the remaining unprotected mid-section of the wall is also at risk for damage.

As part of the study commissioned by the DCR entitled "Nantasket Beach Seawall Repair and Master Plan Services", this report examines the coastal processes relevant for Nantasket Beach. This information, along with other site specific data and information, was used to develop and analyze eight alternatives for shoreline protection of the Nantasket Beach Reservation.

COASTAL PROCESSES

Wave refraction and diffraction result in an uneven distribution of wave energy along the coast that affects sediment transport in the region. Wave propagation data across the continental shelf and to the shoreline revealed areas of increased erosion or areas of increased energy. The refraction and diffraction mechanisms also result in changes in the offshore wave direction that appear to significantly influence the rate and direction of sand movement along Nantasket Beach for specific wave conditions. On an annual basis, increased wave energy exists along the DCR portion of Nantasket Beach, with an area of increased wave energy located at the northern portion of their section of coastline (the location of the previous seawall failure).

Areas of accretion and erosion develop along entire Nantasket Beach due to the irregular offshore bathymetry and thus, the uneven distribution of wave energy. There are regions along Nantasket Beach where the net sediment transport is to the south, and others where the net sediment transport is to the north. In either case, the rates are relatively small.

Net sediment transport in the DCR portion of Nantasket Beach is from south to north with the average rate of transport of approximately 4,000 to 5,000 cy/yr, and maximums varying between approximately 13,000 and 50,000 cy/yr. However, during certain wave conditions, sand will also move from north to south.

Cobbles in the DCR portion of Nantasket Beach are only transported during the stronger northern and north-eastern approach waves, which have enough energy to mobilize the cobble component of the Nantasket shoreline. The more commonly occurring, but lower energy, eastern and southern waves cannot mobilize the cobble. Therefore, the net transport of cobble is from north to south, while the net transport of sand (which is mobilized for all wave approach directions) is from south to north.

There is a lack of sediment supply for the DCR portion of Nantasket Beach due to the combination of the net northward sediment movement and the limited sediment supplied by regions to the south (due to the Atlantic Hill headland). Therefore, on an average annual basis, the DCR portion of the beach is erosional.

ALTERNATIVES FOR SHORELINE PROTECTION

Alternatives for shoreline protection were assessed with participation and review by the Citizens Advisory Committee (CAC), members of the Town of Hull, and resource agencies. Eight alternatives were developed:

- **Alternative 1: *No Action.*** This alternative would consist of taking no action at Nantasket Beach and making no changes to the existing seawall or fronting beach.

- **Alternative 2: *Seawall Toe Protection.*** This alternative would add stone toe protection in front of the existing seawall in areas where no current toe protection exists (i.e., mid-section of the seawall). Toe protection is similar to a small revetment that would be placed seaward of the existing seawall. This alternative has been implemented along the southern section of the Nantasket Beach seawall.

- **Alternative 3: *Seawall with Revetment.*** This alternative would place a revetment in front of the existing seawall, providing added protection not only for the existing seawall and upland infrastructure, but also providing an improved wave dissipation structure when compared to a vertical concrete seawall.

- **Alternative 4: *Beach Nourishment.*** This alternative would consist of adding a beach nourishment directly seaward of the existing seawall with no modifications or changes to the seawall itself.

- **Alternative 5: *Seawall Toe Protection and Beach Nourishment.*** This alternative is a combination of Alternatives 2 and 4, where toe protection would be placed in front of the mid-section of the seawall and then the beach nourishment would be placed on top of the toe protection, extending seaward by approximately 180 to 200 feet.

- **Alternative 6: *Seawall with Revetment and Beach Nourishment.*** This alternative is a combination of Alternatives 3 and 4, where a revetment would be placed in front of the mid-section of the seawall and then the beach nourishment would be placed in front of the revetment, extending seaward by approximately 180 to 200 feet.

- **Alternative 7: *Retreat and Construct New Seawall, Revetment, and Dune*.** This alternative would remove and demolish the existing seawall, retreat approximately 30 feet landward, construct a new seawall, fronting revetment, and place a dune-like feature in front of the new seawall. Existing parking areas and infrastructure (e.g., MJM bathhouse) would need to be demolished or moved as part of this alternative.

- **Alternative 8: *Remove Seawall and Beach Nourishment.*** This alternative would remove and demolish the existing seawall and replace the seawall with a natural dune and fronting beach nourishment. The dune would also utilize ACT ProTecTubes™ as a core of the dune. A significant amount of landward area would be required to create a stable dune system, and this would require removal of nearly all of the current parking areas, roadways, a significant number of public reservation buildings, as well as some business properties and buildings.

RECOMMENDED ALTERNATIVE

The recommended alternative was selected based on five key points:

1. The Nantasket Beach Seawall is Necessary and Beneficial

Although seawalls are not always the most ideal coastal protection method, in heavily developed areas, seawalls are very effective. For example, the value of a sound seawall was demonstrated in Galveston, Texas, during the passage of Hurricane Ike on September 14, 2008. The portions of Galveston located landward of the seawall experienced minimal damage, while areas without seawall protection or other coastal protection measures were significantly damaged and/or destroyed. The Nantasket Beach seawall has been in place since approximately 1915, and has been an effective protection measure throughout the years. The protective values alone provided by the seawall justify its presence in a highly developed and urban setting like Nantasket.

Additionally, leaving the seawall in place is the most cost-effective solution for satisfying the need for protection of the Nantasket Beach Reservation and upland resources owned by DCR, the Town of Hull, and private owners. The existing seawall is structurally sound, but has been compromised by the continued erosion of the beach, which has rendered the initially designed support inadequate. Specifically, the seawall no longer extends far enough into the subsurface to remain stable. Therefore, the existing seawall needs additional support through beach nourishment, toe stabilization, or both (see Point 4 below). Utilizing the current location of the seawall, coupled with a nourishment project, maintains upland area for community Master Plan improvements and layouts. Therefore, it is recommended that the existing seawall be a component of the solution at its current location.

2. Beach Nourishment is a Key Component

Nantasket Beach is a valuable, convenient recreational resource in the area and is one of the few large urban beaches in the Boston area. Nantasket Beach is very accessible, in part due to its available parking facilities. The popularity of the beach may increase with potential accessibility options such as better public bus connections, potential ferry connection, etc. Due to its open-ocean setting with an absence of rivers and major stormwater outfalls entering the beach, the beach has consistently good water quality even immediately after large storm events. However, currently because of the limited beach berm, beach visitors need to leave the beach during high tide. Therefore, beach nourishment is an important component for shoreline protection. Beach nourishment will significantly improve its recreational value, increase the storm damage protection, and provide increased economic return. Ultimately, Nantasket Beach should remain a viable recreational beach, which means that a useable, sandy beach environment needs to be provided to service a variety of beachgoers (e.g., surfers, sunbathers, families, swimmers, etc.) It is recommended that the preferred alternative should include a beach nourishment component.

3. *Sediment Source for Nourishment*

All feasible and preferred alternatives include beach nourishment. Therefore, important consideration needs to be given to potential sediment sources. Basically, sediment can be obtained from either an offshore borrow source, dredging of a navigational channel, and/or an upland source. A subaqueous borrow source is typically the most cost-effective option and provides a good source of beach compatible material once a suitable site is identified. However, recent experience has shown that obtaining permits to mine offshore material is a lengthy, costly process and may ultimately be unsuccessful. For example, DCR has recently tried to obtain permits to mine an offshore borrow site for nourishing Winthrop Beach, MA. The permitting process has taken over 10 years and has currently been unsuccessful. Considering that the offshore sand source was recently denied for the nourishment of Winthrop Beach, an upland-based source may be a feasible option for Nantasket Beach, at least for the foreseeable future. An offshore borrow site for Nantasket could be a difficult pursuit, at minimum resulting in a significant time commitment and delaying possible nourishment of Nantasket beach for at least 5 years.

Although significantly more expensive, based on the results of the technical assessment and modeling performed, an upland-based sediment source does appear technically feasible for nourishing Nantasket Beach. However, there are some limitations using a multi-year nourishment approach as well. If multi-year upland nourishment is selected, Nantasket Beach and the current seawall would be vulnerable to potential damage from a single storm event for a number of years. Until enough sediment (approximately 30%) is supplied to the beach, Nantasket and the seawall would remain vulnerable over these initial seasons (approximately 5 to 6 years for a reasonable upland sourced construction rate).

Therefore, it appears any sand source will leave the seawall and Nantasket exposed for the next few years. The offshore source will likely take years to permit and get approval, while upland sources will take numerous years to construct, while being exposed to storm events. Without some sort of seawall fortification, the seawall will remain at risk for the next 5 to 6 years if sand nourishment alone is the solution. Therefore, it is recommended that beach nourishment be coupled with some seawall fortification measure, with the intent that the fortification method provides insurance against storm events and does not take the place of beach nourishment. This is discussed further in Point 4 below.

4. *Strengthen Seawall with Toe Protection and Start Nourishment from Upland Source(s)*

At present the seawall is at risk of failure in the mid-section during a large storm. The USACE (2006) determined that the elevations in front of the seawall shall not be less than the following in order to provide adequate support:

- No-storm condition: 7 feet
- 100-year storm conditions: 9 feet

At times, elevations in front of the unprotected mid-section of the wall have decreased to an elevation below 7 feet, such as during the October 18, 2006 survey. In addition, undercutting by waves during the December 1992 storm resulted in the collapse of a section of the seawall. This stretch of the beach was closed off for many years until the wall was recently repaired.

Nourishing the beach with sand from an ocean-source can be done rapidly over one season, thus limiting the exposure of the seawall to the risk of collapse during a severe storm. However, as discussed, the potential availability of an ocean-based sand source may take numerous years to permit, leaving the seawall and the Nantasket Beach Reservation vulnerable during this time. Additionally, nourishing the beach from upland sources, although feasible, would also leave the seawall and Nantasket vulnerable for a number of years. For example, based on an assessment of feasible scenarios, nourishing the beach with 700,000 cy of sand will require approximately nine to ten years (at 75,000 cy/year) and the added sand will not provide adequate protection for the seawall for the first 5 years, until sufficient sand has been added to the beach.

It is recommended that seawall fortification (specifically toe protection) be included in the preferred solution. Once adequate volumes of sand are placed on the beach, rocks would be covered by sand. Thus, the beach would be similar in appearance as nourishment without added toe protection in the mid-section of the seawall. Additionally, the toe protection would provide a second line of defense during major storms.

The added protection of is also recommended given the changes in global climate over the last decades. Specifically, while official NOAA rates for annual sea level increases have been incorporated in our analyses, other predictions indicate that even greater increases may be possible over the next century.

5. Pursue an Offshore Sediment Source for Long-term Nourishment

A commitment by DCR to nourish the beach implies that the beach will require renourishment in the future, as the sand will erode over time. Using upland sources for sand is significantly more expensive than using ocean sources. Therefore, we consider it important, and fiscally wise, to pursue an appropriate sand borrow site for beach nourishment. An approved offshore borrow site would also allow for cost-effective and rapid future nourishments for Nantasket Beach.

Affected communities and organizations such as the CAC can assist in furthering the goal of having an appropriate offshore site authorized. It is likely that using offshore sand sources will have lower overall environmental impacts and a lower carbon-footprint than using land sources, considering issues such as air quality, noise, traffic, etc.

Further, identifying and permitting an appropriate offshore borrow site will not just be important for Nantasket Beach but also for other beaches and its surrounding communities in the Commonwealth.

Conclusion

The technical team recommends Alternative 5 for the preferred Alternative at Nantasket Beach. Alternative 5 (toe protection and nourishment) should be coupled with short-term nourishment from an upland source and long-term offshore nourishment. This solution provides immediate protection for the seawall and upland infrastructure, as well as a second line of defense when needed. An offshore sand source should be pursued vigorously as it will also be needed by other coastal communities in the Commonwealth in the future.

Shore protection with beach nourishment, coupled with planned improvements of the upland portion of the Nantasket Beach Reservation, will considerably enhance the value of this important recreational asset in the Commonwealth. Despite its urban setting, the beach has excellent water quality, and should continue to be enjoyed by the greater community, as it has been over its long and storied past.

1.0 INTRODUCTION

Nantasket Beach is located in the Town of Hull, Plymouth County, Massachusetts (Figure 1-1). It lies approximately 4 miles southeast of the main entrance to Boston Harbor and approximately 12 miles east-southeast of Boston on the southeast shoreline of Massachusetts. Nantasket Beach is a crescent beach approximately 3-1/2-miles long which extends from two natural headlands, Allerton Hill to the northwest and Atlantic Hill to the southeast. The beach is oriented in a northwest-to-southeast direction and is exposed to the open waters of Massachusetts Bay and the Atlantic Ocean. The northerly portion of Nantasket Beach is primarily residential with private home and cottages paralleling the shoreline. Coastal dunes and other shoreline protection measures (stone revetments and jersey barriers) are intermittent along the northern portion of Nantasket Beach. The southern portion of the beach (Figure 1-2) comprises the Massachusetts Department of Conservation and Recreation (DCR) Nantasket Beach Reservation, which spans 1.3 miles of coastline and encompasses 26 acres and is a heavily used public beach. Along this portion of the beach where there is public access, a roadway runs parallel to the beach, and there are parking lots, a bath house, and other recreational facilities to support beachgoers in the area. A reinforced concrete seawall (approximately 4,500 feet in length) backs the beach in this area, which helps to retain and protect the upland facilities and infrastructure.

Nantasket Beach is a valuable resource from both a commercial and recreational standpoint. The beach and the associated waterfront amenities serve as the defining feature for the Town of Hull and represent a significant draw for visitors and summer residents. Through time, Nantasket Beach has become one of the region's most valued recreational and natural resources, and is currently one of the busiest beaches in Greater Boston. The beach, the walking areas directly behind the seawall and adjacent commercial establishments offer numerous recreational activities and direct access to beach services (restaurants, hotels, bath houses, etc.). However, the beach, specifically the southern portion, has been eroding for over 150 years (Chapter 3). Although the rate of erosion has been relatively slow, the beach width has been significantly reduced compared to historical widths, to the point where there is no useable beach during high tides in the mid- and southern parts of the Reservation (Figure 1-3). In addition, the loss of sediment fronting the seawall that spans the DCR portion of Nantasket Beach has resulted in a destabilization of the structure. The seawall, originally constructed in the early 1900's, was designed to be supported by material on the seaward side of the structure. Now that a significant portion of this material has eroded, the structural stability of the seawall has been compromised. Recent storms have resulted in continued loss of the beach, and in certain cases (e.g., December 1992 storm), failure of seawall sections. Currently, the beach continues to narrow and the seawall remains at risk. Consequently, the Massachusetts Department of Conservation and Recreation (DCR) is concerned about the viability of the beach for recreational use and the ability of the seawall to continue to provide upland protection. As such, DCR sought to identify the most cost-effective, long-term course of action to remedy this urgent situation.

Figure 1-1. Nantasket Beach in Hull, Massachusetts. The DCR Reservation is located between the arrows.

Figure 1-2. Aerial view of the southern, DCR portion of Nantasket Beach at low tide.

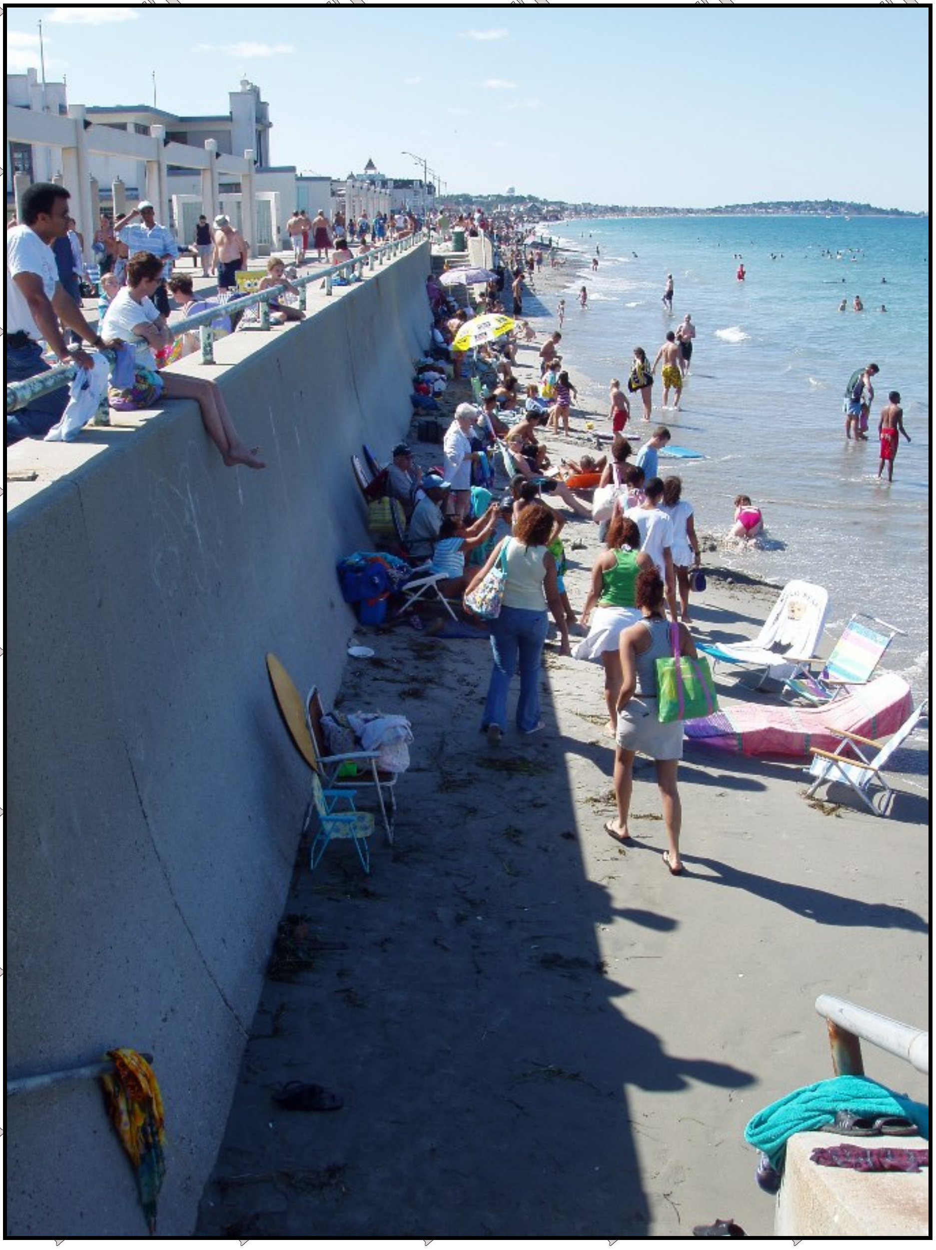

Figure 1-3. The condition of Nantasket Beach during a typical high tide.

The present study was undertaken at the request of the DCR. This coastal processes and engineering feasibility evaluation was conducted by Woods Hole Group, located in Falmouth, Massachusetts. Woods Hole Group was a subconsultant to the Louis Berger Group, Inc. based from their Needham, Massachusetts office. The overall study was focused on assessing the coastal processes that act on Nantasket Beach, identifying and evaluating the feasibility of alternative solutions, determining the potential impacts on Nantasket Beach and the surrounding environment, and making recommendations as to the preferred solution.

The proposed project consists of three primary elements, although other tasks were completed as part of the overall evaluation. These primary elements include:

1. A coastal processes and engineering feasibility study, including evaluation of existing conditions and identification and evaluation of potential alternatives for Nantasket Beach.

2. A Reservation Master Plan that evaluates the regional area and develops a master plan for the Nantasket Beach infrastructure that meets the community and regional goals.

3. A draft and final Environmental Impact Report (EIR) for the expanded alternatives assessment of both the coastal alternatives and the master plan redevelopment alternatives. The EIR will identify potential adverse impacts and any necessary mitigation, and ultimately support the selection of a recommended course of action.

The purpose of the coastal processes and engineering feasibility evaluation presented herein was to evaluate the existing coastal processes that currently act on Nantasket Beach, as well as assess potential alternatives that may be viable solutions to stabilize the seawall and improve recreational ability at Nantasket Beach. The study focuses on evaluating the physical processes (concentrating on the wave and current environment) occurring within the vicinity of Nantasket Beach in order to assess potential alternatives that may be used to create a long-term solution along the shoreline. The feasibility evaluation consisted of some limited field data collection, numerical modeling of coastal processes, an alternative evaluation, and a preliminary sand source investigation. The study ultimately evaluates the performance of each of the alternatives and the ability to provide a sustainable beach. Numerical modeling results are used to complete a detailed alternatives analysis. All elements of the project are geared towards arriving at a technically feasible, cost-effective, and long-term solution at Nantasket Beach.

The report follows a logical step-by-step process that presents the components of the coastal processes study, as well as the alternatives considered and evaluated in the feasibility evaluation. The report is organized and divided into the following main chapters.

- Chapter 2 briefly describes the history of Nantasket Beach, including the geology of the region and the previous coastal engineering that has been conducted along the coastline. In essence, Chapter 2 sets the backdrop for the study.

- Chapter 3 presents the historical shoreline change analyses that have previously been completed of the Nantasket Beach littoral system. The shoreline change analysis was used to estimate magnitude and direction of sediment transport, monitor the historic impact of engineering modifications to the region, examine geomorphic variations in the coastal zone, and verify the numerical nearshore and sediment transport models.

- Chapter 4 presents the results of the wave transformation modeling effort. Wave modeling is detailed and utilized to propagate the waves towards Nantasket Beach. Chapter 4 presents the development, verification, and results of the transformation scale modeling effort.

- Chapter 5 presents the results of the sediment transport modeling, including sediment movement during both average annual conditions and larger storm events.

- Chapter 6 details the development of the alternatives to be evaluated, summarizes the alternatives considered in the alternatives analysis, and presents the methodology for assessment of the various alternatives. Chapter 6 also eliminates alternatives that are not technically feasible or have a significant environmental impact.

- Chapter 7 presents the final results of the alternative analysis. The ultimate goal of the overall project is to create a beach system that provides storm damage protection and recreational use. Therefore, an assessment of the performance of each of the final alternatives is presented. This section addresses also socio-economic benefits, permitting, and costs.

- Chapter 8 presents a preliminary investigation of potential sand sources for nourishing Nantasket Beach. The chapter includes identification of the source sites, with specific emphasis on the feasibility and performance of potential land based sources.

- Finally, Chapter 9 presents the conclusions of the study and a final summary.

2.0 BACKGROUND GEOLOGY AND HISTORY

The present configuration of Nantasket Beach can be attributed to a series of shoreline processes and several former drumlin (elongate-shaped glacial hill) islands. In geological terms, Nantasket Beach is known as a complex tombolo, which is a coastal feature that forms when several islands and the mainland are interconnected by a complex series of land bridges. In this case, Nantasket Beach unites several former drumlin islands and the mainland (Johnson and Reed, 1910). The existing spit of land consists of several drumlins, including Hampton Hill, Sagamore Hill, White Head, Strawberry Hill, Allerton Hill, and Telegraph Hill as shown in Figure 2-1. In addition to glaciation and coastal processes, human interaction and development has had a significant influence on the existing formation and topography of the area.

Figure 2-1. USGS topographic map of Nantasket Beach (Mass GIS).

2.1 GEOLOGY OF NANTASKET BEACH

Significant information relating to the geology and history of Nantasket Beach is available within many previous reports and studies of the project area. In particular, the USACE Coastal Engineering and Processes Study (USACE, 2003) summarizes much of the work and historical knowledge to date, and was used as the primarily resource for understanding the history of the region.

The New England region is largely composed of moderate to thick surficial deposits of glacial origin overlying bedrock. New England has been glaciated several times and the coast experienced as many as four major periods of glaciation, ranging from Nebraskan to Wisconsinan in age (FitzGerald et al., 1994). The best geological record exists for the deposits left behind by the most recent glaciation, called the Wisconsinan Stage, which ended about 8,000 years ago. Retreat of the glaciers in southeastern New England began around 18,000 to 14,000 years ago.

Most of the surficial sediments in the Nantasket area are composed of glacial deposits of ice-contact till and stratified drift (sand and gravel outwash, with minor silt, clay, and till), swamp deposits, and beach deposits. As previously discussed, Allerton Hill, Strawberry Hill, Sagamore Hill, and Hampton Hill are all examples of drumlins, which are composed of variable materials, sometimes mantled over bedrock, or composed wholly of either rock or glacial drift deposits. Glacial till is the poorly-sorted, non-homogeneous material deposited at the base of the glacier (lodgment till), or alternatively, deposited as material within the ice sheet which melted out as it was let down on the existing landscape (ablation till). The term "stratified drift" encompasses the generally well-sorted sand and gravel deposited by glacial melt water either on an outwash plain in front of an ice sheet, or in glacio-fluvial environments under, within, on top of, or adjacent to an ice sheet.

The work of Johnson and Reed conducted in 1910 preserved much of the historical geologic record of Nantasket Beach as they were able to map abandoned marine cliffs and beach ridges prior to further development of the area. Based on an examination of the ancient beach ridges at Nantasket Beach, the size and alignment of the marine cliffs cut into the drumlins, and offshore profiles, Johnson and Reed (1910) concluded that five drumlins were once located east of Nantasket Beach (north of Atlantic Hill). Through erosional forces exerted by tidal fluctuations and wave action together with a slowly varying sea level these drumlins eroded and the sediments were transported and deposited among the other drumlin islands to form the complex tombolo system that makes up Nantasket Beach today. As such, the Nantasket barrier form evolved around a series of drumlins that served as anchor points. Johnson and Reed (1910) also suggested that historically, Nantasket Beach has been largely an accretionary feature.

To further the discussion on the derivation of Nantasket Beach, FitzGerald et al. (1994) presented their observation that the amount of sand that would have been available from the drumlins is insufficient to account for the volume of the spit of land which makes up Nantasket Beach. They also noted that the sediment of the drumlins is also quite different from the fine, well-sorted sand that comprises much of the material at Nantasket Beach. In addition, Nantasket Beach is adjacent to a major offshore sand deposit (FitzGerald et al., 1990). This led to their suggestion that the sediments of Nantasket Beach were derived from several intercepted drumlins and other glacial deposits located offshore that were then reworked onshore late during the Holocene transgression. The existence of Nantasket Beach can then be attributed to the erosion and redistribution of sediment from the existing drumlins as well as the drumlin remnants offshore.

2.2 HISTORY OF NANTASKET BEACH

Nantasket Beach has also been significantly influenced by anthropogenic activities throughout the years. Anthropogenic impacts and infrastructure development have been significant contributors to the current configuration of Nantasket Beach. The first public house was constructed in 1826 and subsequently, numerous recreational structures were constructed during the 1800s. These structures were typically wood buildings constructed on wood pilings combined with wood bulkheads to restrict tidal flow under the structures (USACE, 1949). In 1880, a railroad was constructed which ran along the barrier spit and prior to 1900, riprap (3-4 cubic foot stone) was added along the seaward edge of the railroad to provide protection from coastal storms. This riprap is still in place north of and within the DCR Reservation, most of which has been buried by the fill placed behind the existing seawall (USACE, 1949).

During the 1900s, concrete seawalls were constructed to protect portions of the Nantasket Beach shoreline within the DCR Reservation. One of the first concrete seawalls on record was constructed in 1916 in front of the bath-house facility (approximate 1,425-foot long section between profiles 9 and 10 in Figure 2-2). Ten to twelve years later another portion of the seawall was constructed in front of the Rockland Café and Nantasket Pavilion, which existed at the time between profiles 8 and 9 in Figure 2-2. Additionally, a concrete bulkhead was constructed in 1920 (between profiles 7 and 8 in Figure 2-2) to protect the Nantasket Hotel. Another portion of seawall was constructed in 1915 to protect the Tivoli Pavilion (between profiles 6 and 7 in Figure 2-2). Additional concrete seawalls were built to protect the northerly and southerly parking areas. The seawall fronting the southern parking area (between profiles 4 and 6 in Figure 2-2) began construction in 1915, with a portion being completed in 1927. The seawall fronting the northern parking area (north of profile 10 in Figure 2-2) was constructed in sections from 1926 to 1938 to a total length of approximately 2,500 feet. The seawalls built during this time were unreinforced concrete gravity-type walls with an effective top elevation ranging from 18.2 to 19.6 feet relative to mean low water (USACE, 1949). Access stairs to the beach were intermittent along the seawall. According to the USACE Beach Erosion Control Report (1949), the seawalls protecting the buildings withstood storm attacks but overtopping did occur on occasion, causing damage to the buildings. The 1949 report also stated that the wall in front of the southern parking area was in good condition with the occurrence of minor spalling, while the wall fronting the northern area suffered damage north of profile 13 (Figure 2-2). The damage along this northerly portion of the seawall required two sections to be demolished and rebuilt (with reinforced concrete), one in 1941 and another in 1944 (USACE, 1949). The seawalls built during this time period existed in essentially the same locations as they do today.

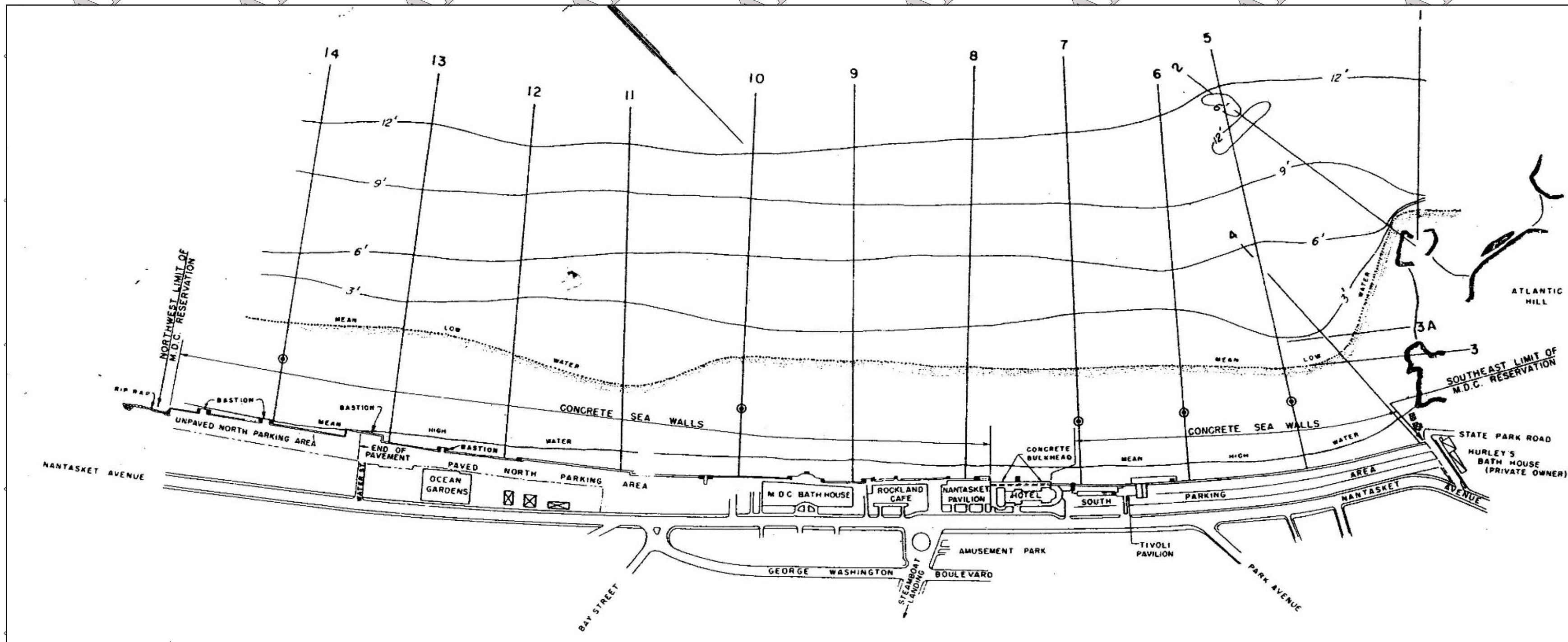

Figure 2-2. DCR 1949 plan of existing structures at Nantasket Beach (USACE, 1949).

Further development and construction of shoreline protection occurred in the latter half of the 1900s. A first aid and comfort station was constructed in 1959 just south of Phipps Street at the northern end of the DCR Reservation (area 1 shown in Figure 2-3). Additionally, a riprap revetment was constructed in 1949 to an elevation of 18.2 feet relative to mean low water (area 2 shown in Figure 2-3). In 1965, a concrete cap was constructed on the northernmost 125 feet of seawall within area 3 shown in Figure 2-3. Portions of the seawall (within areas 5 and 7 shown in Figure 2-3) were reconstructed in the late 1950s and early 1960s (USACE, 1968). The 1968 Beach Erosion Control Report (USACE, 1968) stated that overall the shoreline protection structures were in good condition except for a portion of the seawall within area 3 (Figure 2-3).

During the 1970s to 1990s, the shore protection measures including the seawalls, riprap revetments, access ramps, stairs, and walkways all experienced a gradual deterioration due to storm events and associated natural forces (USACE, 1993). In addition, the beach elevation in front of the seawall lowered due to increased erosion, the natural depletion of sand sources, and the removal of sediments/cobble due to beach manicuring/maintenance procedures (USACE, 1968; Hayes et al, 1973; and USACE, 1993). This reduction in beach elevation reduced its effectiveness in offering protection and increased the potential for the seawall to be undermined. During the nor'easter "Halloween Storm" of October 30-31, 1991 and a subsequent nor'easter which occurred on December 11-12, 1992, the seawall within the DCR Reservation suffered significant damage resulting in the failure and weakening of a 650-foot section of the wall (USACE, 2002). This produced increased wave overtopping and flooding of backshore areas.

Numerous reports and studies of Nantasket Beach have been conducted over the past 50-60 years. Cooperative beach erosion control studies were conducted by the DCR and the USACE (USACE, 1949; USACE, 1968). A study of erosion processes at the DCR beaches was conducted by Hayes, which presents the causes for erosion and proposes recommendations for remediation (Hayes et al, 1973). In addition, a report was prepared in 1980 for the Disaster Recovery Team, Commonwealth of Massachusetts by the Camp Dresser and McKee, Inc. entitled "Evaluation of Coastal Protection Measures at Nantasket in Hull, MA, Volumes 1 and 2". This report details the damage which occurred during the February 1978 storm.

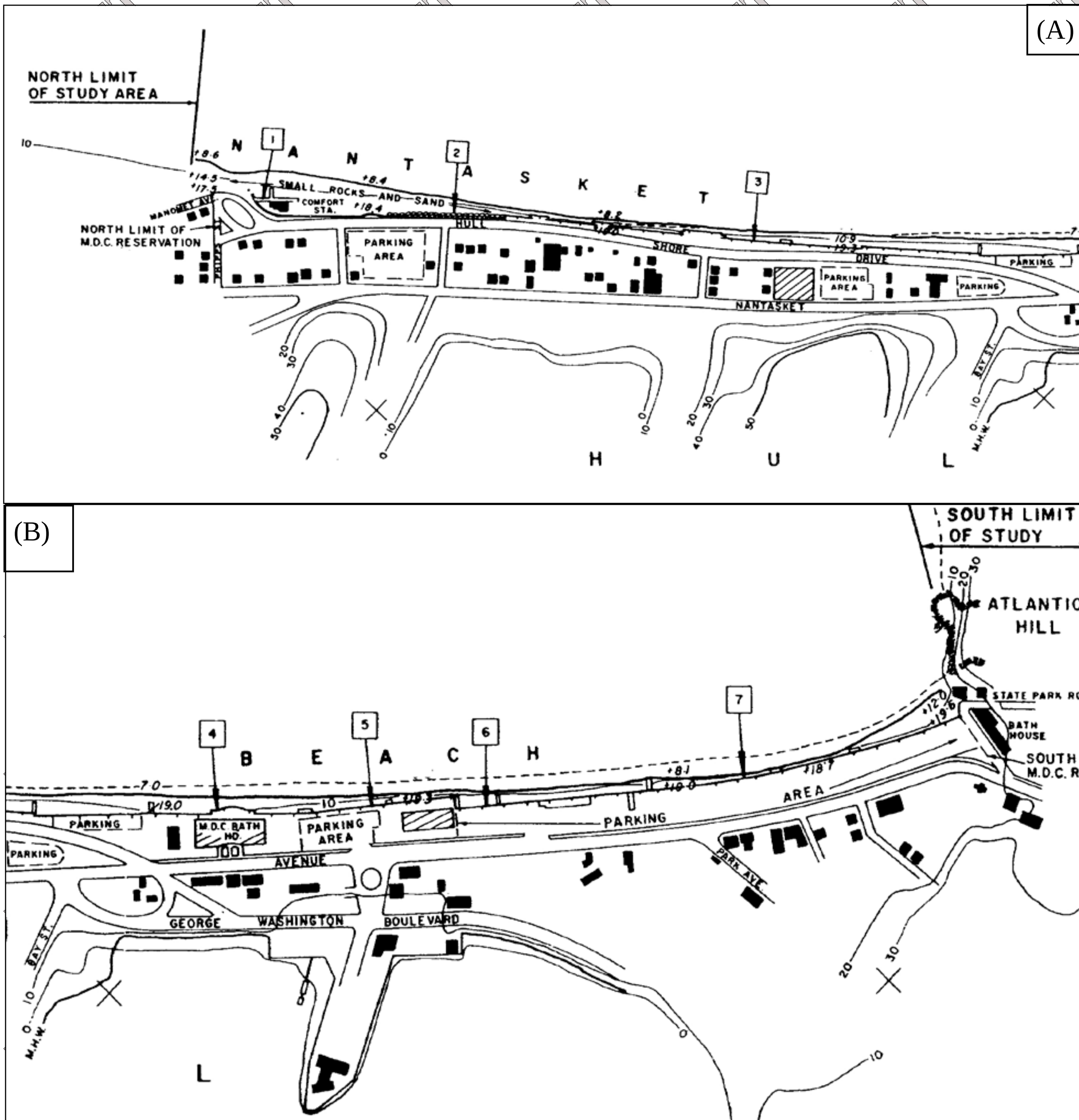

Figure 2-3. MDC 1968 plan of existing structures at Nantasket Beach (USACE, 1968). Panel (A) is the northern portion of the DCR Reservation and Panel (B) is the southern portion of the Reservation.

The nor'easter storms and subsequent failure of the wall in the early 1990s prompted the DCR to re-engage the USACE for an evaluation of the existing shore protection measures at Nantasket Beach. The Section 103 Shore Protection and Erosion Control Reconnaissance Report (USACE, 1993) details the damage that occurred to the seawall, screens potential alternative solutions, and proposes a protection plan consisting of beach fill for further study. The USACE conducted a survey of the DCR seawall in 2000 to provide details on the structural condition of the seawall, stairs, ramps and sidewalk, as well as provide potential cost estimates for repairs (USACE, 2000). Subsequent to the condition survey, the USACE submitted a 50% Progress Submission Report to the DCR in February of 2001 for replacing and repairing designated portions of the 5,500 linear foot concrete seawall (USACE, 2001). A draft feasibility and environmental assessment was then issued by the USACE in August of 2002 as part of the Section 103 Coastal Storm Damage Reduction Project for Nantasket Beach, MDC Reservation (USACE, 2002). This feasibility study recommended a 50-foot sand fill nourishment project with periodic renourishment coupled with a complete reconstruction of the portion of seawall damaged in the December 1992 storm. This feasibility study (USACE, 2002) also examined other alternative solutions including: 1) an offshore breakwater, 2) a revetment, and 3) elevating the structures. In 2003, the USACE completed an Alternatives/Analysis Study (USACE, 2003), which examined a wide range of alternatives and analyzed the shore protection system for Nantasket Beach as a whole. This 2003 study updated the recommendations made in the 2002 Feasibility Study (USACE, 2002) and the Seawall Repair Study (USACE, 2000).

In December of 2003, subsequent to the USACE 2003 Alternatives/Analysis Study, two coastal storms (December 6^{th} and 7^{th}) inflicted damage and undermined sections of the concrete seawall. A USACE analysis recommended emergency repairs as a 2000 linear foot section of the structure was deemed unstable (Winkelman and Jones, 2005; USACE, 2004a). In August of 2004, a stone revetment was constructed along this portion of the seawall (approximately 2,000 feet in a southerly direction from the Mary Jeanette-Murray Bathhouse) as a temporary, emergency mitigation measure.

In recent years, work has continued by DCR and the USACE in support of the Section 103 Coastal Damage Reduction Project for Nantasket Beach. Two additional studies, a Sand Fill Transportation Study (USACE, 2004b) and a Nantasket Beach (Sediment) Characterization Study (USACE, 2006) were completed most recently. In addition, a first phase of bolstering the coastal protection was implemented, where approximately 930 feet of the northernmost portion of the seawall was replaced and protected with a stone revetment. This included the portion of the seawall that collapsed during the 1992 storms. Most recently, other major repairs have also been made to the access stairs and ramps where needed.

3.0 HISTORICAL SHORELINE CHANGE

In a physical system like that of Nantasket Beach, the geological and historical perspective is an important piece of understanding the past history of the region, determining the effects of the physical processes that have acted on the coastline throughout the years, and providing insight into the future. Regional geomorphic change is the evolution of depositional environments and topographic features over extended periods of time. Aerial photographs, topographic surveys, and hydrographic surveys of coastal and nearshore morphology provide data for quantifying regional geomorphology and change. Coastal shoreline change and digital bathymetric data for the same region, but different time periods, produce a method for determining the physical changes of a region and providing valuable information on potential sediment movement within a region. Existing shoreline change information for Nantasket Beach was used to provide a historical perspective and examine geomorphic variations in the coastal zone. In addition, this shoreline change information was used in ground-truthing the numerical sediment transport model.

Shoreline change analysis, which is a computer-based shoreline mapping methodology used to compile and analyze changes in historical shoreline position, can be determined by accurately quantifying the distance between historical shoreline positions from different time periods after they are placed on the same scale and geographic reference. A new shoreline change analysis was not completed as part of this study. Rather, previous shoreline changing mapping efforts were used and are briefly summarized in this chapter.

3.1 MCZM HISTORICAL SHORELINE CHANGE

Figure 3-1 presents the rates of historic shoreline change between 1847 and 1994 throughout the Nantasket Beach region as determined by Thieler et al. (2001) completed for Massachusetts Coastal Zone Management. The black line shows the rate of shoreline change for the entire time frame (1847 to 1994) where a negative rate of shoreline change represents erosion in terms of ft/yr, while a positive rate of shoreline change represents accretion in terms of ft/yr. Although a significant portion of the Nantasket shoreline has been relatively stable with small rates of erosion or accretion within the relative error of the analysis methodology itself, there are some distinctive areas of erosion and accretion along the shoreline. The area along the DCR portion of Nantasket Beach is clearly erosional as historical rates of erosion range between approximately 0.5 feet to 1.0 feet per year (ft/yr). The area directly north of the DCR portion of the Beach, between Sagamore Hill and Malta Street, is relatively stable with minor changes. The most significant area of accretion occurs between Malta Street and Prospect Avenue, with an accretion rate of up to approximately 0.5 ft/yr). Farther north, from Prospect Avenue to P Street, the beach is again stable, or possibly slightly erosional. Finally, the northern portion of Nantasket Beach, just south of Allerton Hill is primarily accretional. Most of the long-term historic rates are relatively small (less than 1.0 ft/yr), and in general indicate that the shoreline has been relatively stable, and in some cases (for rates less than $\pm$ 0.5 ft/yr) are likely within the error bounds of the analysis.

Figure 3-1. Rates of historic shoreline change between 1847 and 1994 as determined by Massachusetts Coastal Zone Management (2001).

3.2 SOUTH SHORE HAZARDS ATLAS

In addition to the long-term historical shoreline change, a more recent study of shoreline change for Nantasket Beach was conducted in 2005 as part of the Massachusetts Office of Coastal Zone Management South Shore Coastal Hazard Atlas. This study examined rates of shoreline change over a more contemporary time frame between the years of 1938 and 2001. Figure 3-2 presents the rates of shoreline change as determined in this study (Ramsey et al., 2005). The results are presented as small bars along the shoreline, with cooler colors (blues and greens) indicating shoreline accretion (+ ft/yr) and hotter colors (yellows and reds) indicating shoreline erosion (-ft/yr). Black bars represent areas that fall within ±0.5 ft/yr and therefore do not indicate either strong erosion or accretion. The majority of Nantasket Beach is relatively stable, as depicted by these black bars (small rate of change of ± 0.5 ft/year, within the statistical uncertainty of the analysis). There are distinct areas of erosion and accretion, however, as indicated by the yellow and green bars in Figure 3-2 that correspond to the areas of erosion and accretion shown in the longer term shoreline change analysis (Figure 3-1). The southern portion of Nantasket Beach, which comprises the DCR reservation, is erosional, with rates on the order of -1 ft/yr. A small area of accretion exists in the Malta to Prospect Street region, and a larger area exists in the northern portion of Nantasket Beach from H Street to U Street where the rate of change is accreting approximately +1 to +2 ft/yr. These accretionary areas also correspond reasonably well with the longer-term historical shoreline change trends presented in Figure 3-1.

Previous reports and the geologic history have all indicated the shoreline at Nantasket Beach has been relatively stable over the past 300 years (USACE, 1949; Hayes et al, 1973; and Brenninkmeyer, 1976). It has been suggested that this may be partially attributed to the presence of the remnant drumlins offshore. Therefore, a majority of the Nantasket shoreline indicates a general stability over time; however, the previous studies also indicate that the DCR portion of the shoreline has been erosional, both pre and post seawall construction, while the northern section of the Nantasket shoreline has shown the most consistent accretion. This long-term, relatively low, erosion rate has led to a loss of material in the DCR portion of Nantasket Beach. The shoreline has retreated to the point where there is no longer a beach during high tide at the DCR reservation and the seawall that protects the upland infrastructure is also at an increased level of risk for failure.

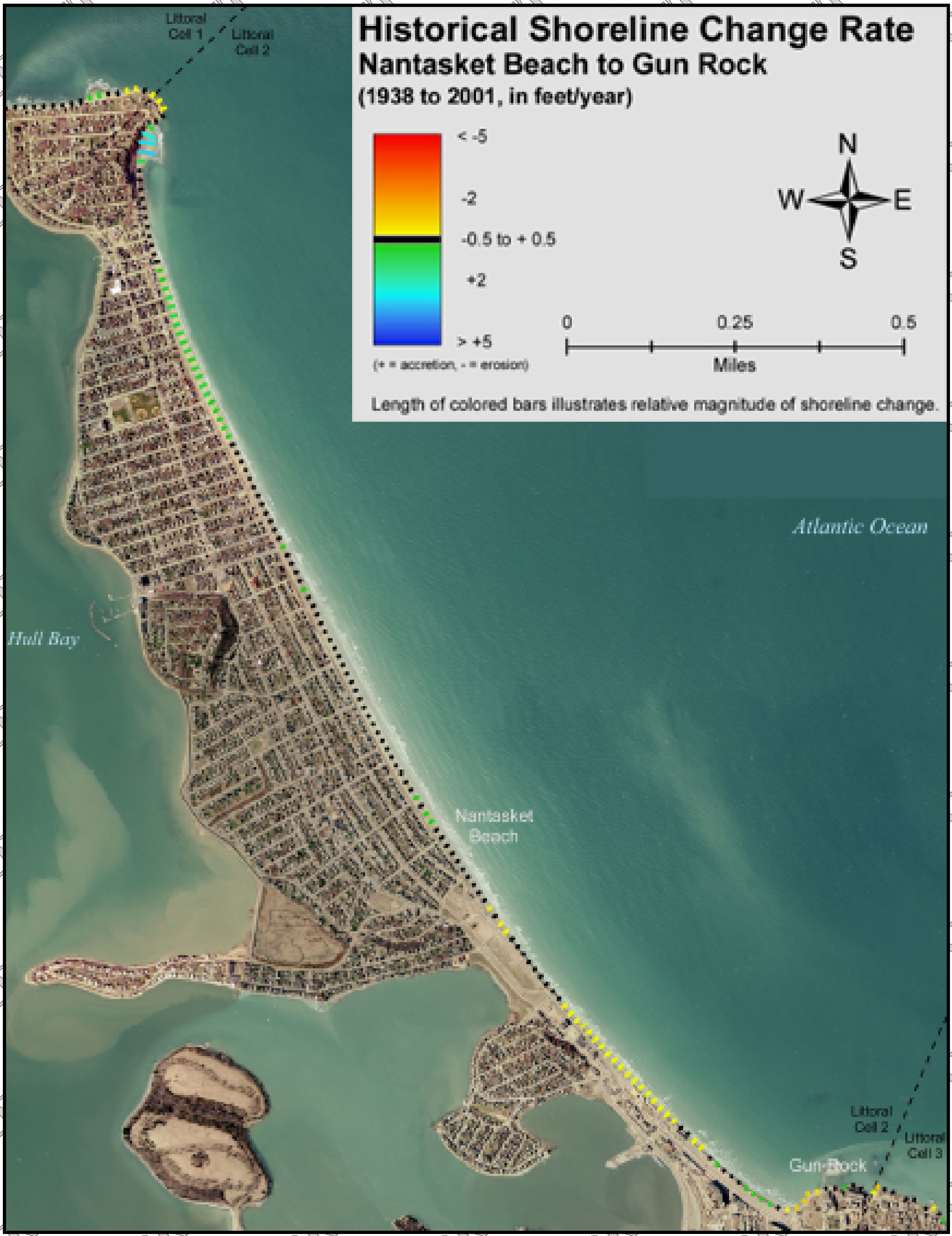

Figure 3-2. Rates of historic shoreline change between 1938 and 2001 as determined by Ramsey et al. (2005).

4.0 WAVE CLIMATOLOGY AND TRANSFORMATION

4.1 ANALYSIS APPROACH

The impact of waves in the nearshore environment, specifically on shorelines that are highly populated or serve significant recreational and/or economic benefits (such as Nantasket Beach), is one of the key reasons to understand wave propagation, transformations, and predictions for site-specific areas. The impact of waves on nearshore processes and shoreline change is highly dependent on the offshore wave climate and the transformation of waves propagating to the shoreline. Subsequently, as the waves interact with the coastline, the wave-induced currents are a major component of sediment transport and shoreline change. Therefore, a key component of understanding the areas of erosion and accretion along Nantasket Beach is determining the nature of the wave field both offshore and in the nearshore region.

Ocean wave energy is comprised of a large variety of waves moving in different directions and with different frequencies, phases, and heights. These waves undergo significant modifications as they advance into the coastal region, interact with the sea floor, and eventually reach land. The ocean climate also changes temporally with seasonal modulations. The variability in offshore wave climate, the transformations occurring as waves propagate landward, and the temporal modulations, all result in significant fluctuations in the quantity and direction of sediment transport in the coastal zone. Therefore, in almost all cases, using a single representative wave height, frequency, and/or direction is not the most accurate technique for assessing the wave climate and, subsequently the sediment transport at the coastline. In many cases, even using a representative averages or ranges of wave conditions may not accurately capture the actual processes that impact the coastline.

This chapter evaluates the wave climate offshore Nantasket Beach and the transformations waves experience as they propagate towards the coastline. To quantify the wave impact along the shoreline, site-specific wave conditions were determined using bathymetric and topographic data, wind data, wave data, and a numerical wave transformation model. Wave transformation models provide predictive tools for evaluating various forces governing wave climate and sediment transport processes. For example, wave refraction and diffraction may have a significant effect on the impacts waves have on a shoreline. Wave refraction and diffraction generally result in an uneven distribution of wave energy along the coast that affects sediment transport in the region. Wave modeling results provide information on wave propagation across the continental shelf and to the shoreline, revealing areas of increased erosion ("hot spots") or areas of increased energy. The refraction and diffraction mechanisms also result in changes in the offshore wave direction that may significantly influence the rate and direction of sand movement. Therefore, the quantitative information provided from the numerical model can be used to explain the physical processes that dominate a region and to furnish appropriate recommendations/solutions for each stretch of coast.

A detailed description of the procedures used to compute the wave conditions along the Nantasket Beach shoreline is presented within this chapter, with a focus on the application and results of wave transformation numerical modeling. A spectral wave model, STWAVE, was used to propagate random waves from an offshore location to the nearshore region and to investigate potential changes to the wave field caused by the bathymetry.

4.2 Wave Model Description

The spectral wave model STWAVE version 4.0 (Smith, Sherlock, and Resio, 2001), developed by the U.S. Army Corps of Engineers Waterways Experiment Station, was employed to evaluate changes in wave propagation across the nearshore region fronting Nantasket Beach. STWAVE is a steady state, spectral wave transformation model, based on a form of the wave action balance equation of Jonsson (1990) and is regularly used, and widely accepted in coastal design and studies. The model can simulate wave refraction and shoaling induced by changes in bathymetry and by wave interactions with currents. The model also includes wave breaking, wave growth, and influences of wave white capping on the distribution and dissipation of energy in the wave spectrum. STWAVE simulates the behavior of a random sea surface by describing wave energy density as a function of direction (directional spectrum) and frequency (frequency spectrum). The two-dimensional wave spectrum is discretized into separate wave components, which constitute an essential part of the input for STWAVE. Through a combination of the various wave directions and frequencies, STWAVE is able to simulate the behavior of a natural, random sea. In addition, detailed analysis and selection of input spectra allows the model to assess the impact of different seasonal conditions, varying wave approach pathways, and storms. By simulating numerous wave components that propagate towards the Nantasket shoreline, a spectral wave model is superior to a monochromatic wave model, which would include only one specific wave. A comprehensive discussion of the theoretical background of STWAVE can be found in Smith, Sherlock, and Resio (2001).

The STWAVE model also allows for grid nesting (Smith and Smith, 2002). Grid nesting involves using multiple grids to transform waves from an offshore location to nearshore and coastal regions. A coarse (lower-resolution) offshore STWAVE grid is used to transform the waves to the boundary of a nearshore STWAVE grid with a higher spatial resolution. The nearshore grid is considered the "nested" grid. The output wave spectra from the coarse grid are saved at several locations and interpolated onto the nearshore grid boundary. Grid nesting is a useful technique for larger regional applications where a coarse grid is sufficient offshore while complex bathymetry and current fields in the nearshore require a finer resolution grid to give a more accurate simulation of the wave field and wave-induced currents.

Using offshore wave data from the Nantasket Beach region, appropriate offshore wave conditions were developed and used as input data to specify the wave boundary conditions for the STWAVE model (discussed in Section 4.4). Then, using local bathymetry, three separate grids were created, each with a different resolution (discussed in Section 4.3). Using the grid nesting methodology, the model was able to propagate waves to the Nantasket Beach region at the coastline.

4.3 Bathymetry and Grid Generation

Existing bathymetric data in the vicinity of Hull were acquired from two government sources (the National Oceanographic and Atmospheric Administration [NOAA], and the U.S. Army Corps of Engineers [USACE]). In addition, a contemporary survey was performed in the nearshore region to supplement the existing data. Topographic LIDAR survey data were also obtained from a government source (NOAA Coastal Services Center) to help define the coastline and shoreward features. The various data sources were combined to create grids that consist of a mesh of points with resolutions ranging from 100 meters (328 feet) in the offshore grid to 10 meters (33 feet) in the nearshore grid. The model domain, which includes two subgrids, encompasses the entire shoreline of Nantasket Beach in Hull, MA and extends offshore to a water depth of approximately 70 meters (230 feet). The orientation of the reference grids was selected to closely represent a shore parallel contour line, while the offshore boundary was chosen at a water depth deep enough that waves would not sense the seafloor, and to align with the location of the offshore wave information.

4.3.1 Existing Bathymetric/Topographic Information

NOAA Bathymetric Data

Existing National Oceanographic and Atmospheric Administration (NOAA) data were obtained from the National Ocean Service (NOS) Office of Coast Survey Hydrographic Survey Geophysical Data System (GEODAS). The GEODAS data can readily be obtained online at http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html. Ten (10) separate bathymetric surveys were combined to define the seafloor topography offshore of Nantasket Beach. The ten surveys and the year when they were performed are:

- Hingham Bay and Nantasket Beach (1940)
- Approaches to Boston Harbor (1940)
- Outer Boston Harbor (1945)
- Black Rocks, Massachusetts Bay (1952)
- Cohasset-Scituate, Minots Ledge to Marble Head (1953)
- Cohasset Harbor (1953)
- Stellwagen Ledges (1953)
- Massachusetts Bay (1967)
- Outer Approaches to Boston Harbor (1969)
- Cohasset, Massachusetts Bay (1970)

The compilation of these surveys was used to provide data for grid creation in the offshore regions. Figure 4-1 presents the complied NOAA bathymetric data for the region offshore Nantasket Beach. Although many of these surveys are from the middle of the century, these data were only used in the deeper waters well offshore of Nantasket Beach, where bathymetric change, if occurring at all, is minimal. In addition, if a there were multiple observations at the same location, the most recent bathymetric value was assigned in the model grid. To define the nearshore regions, where bathymetric changes are potentially more probable, contemporary surveys were utilized, as described below.

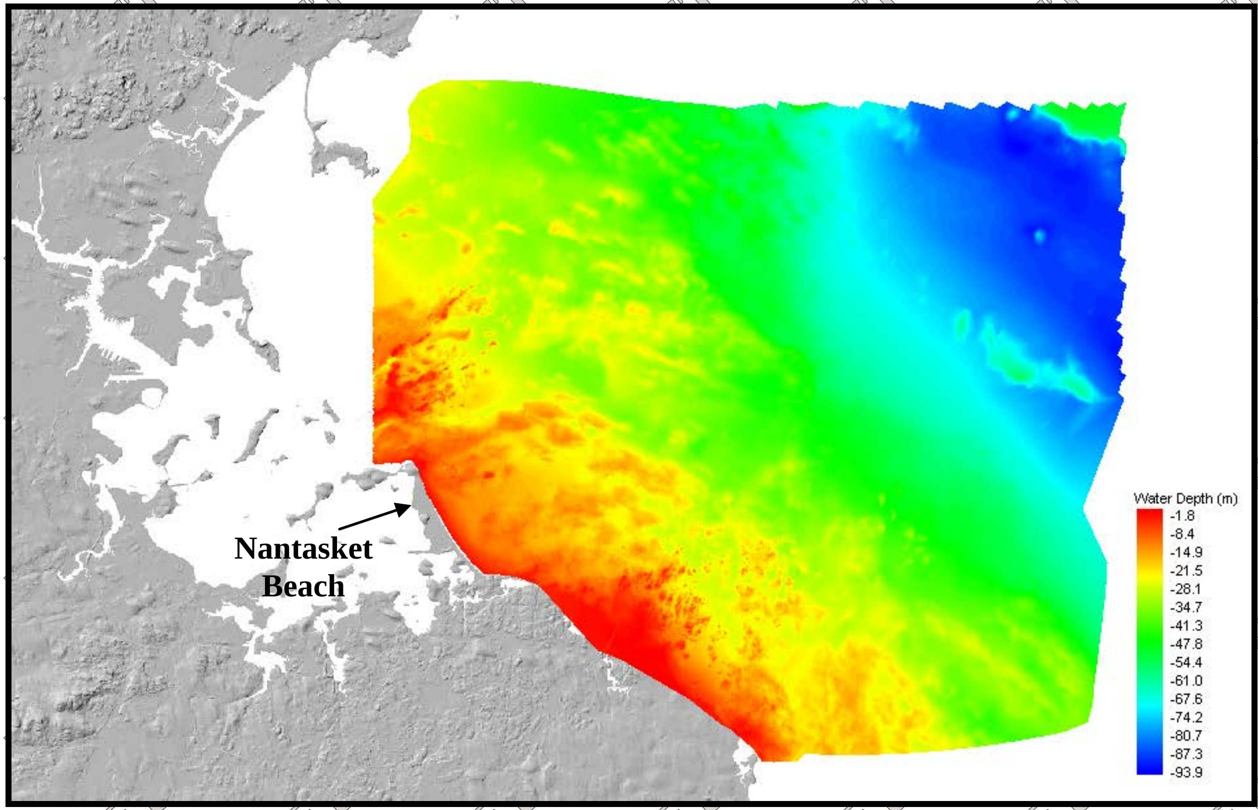

Figure 4-1. NOAA bathymetry offshore Nantasket Beach (meters relative to Mean Tide Level [MTL]). Not to be used for navigational purposes.

NOAA Coastal Services Center LIDAR Survey

Existing topographic data were acquired from the Coastal Services Center (CSC). LIDAR (LIght Detection And Ranging) survey data are readily available on the World Wide Web at http://www.csc.noaa.gov/crs/tcm/. The CSC completed a survey of the Nantasket Beach region on September 27, 2000 as part of their efforts to map coastal change. LIDAR is an active sensor, similar to radar, which transmits laser pulses to a target and records the time it takes for the pulse to return to the sensor receiver. Laser beach mapping involves using this pulsed laser ranging system mounted onboard an aircraft to measure ground elevation and coastal topography. The data were collected in partnership with the CSC, the NASA Wallops Flight Facility, the U. S. Geological Survey (USGS) Center for Coastal and Regional Marine Geology, and the NOAA Aircraft Operations Center. Figure 4-2 presents a map of the LIDAR data obtained along the shoreline of Nantasket Beach. The LIDAR data represents a more recent data set that helped to establish the coastline in creating the grids as well as to define coastal structures and features.

USACE Shoreline Profiles

In order to supplement the shallower nearshore regions in the model domain, a USACE cross-shore profile data set was utilized. The USACE data were obtained from survey work completed in September of 2005 as part of the 2005 Nantasket Beach Characterization Study (USACE, 2006). The USACE data were collected using real time kinematic (RTK) GPS for both the shore-

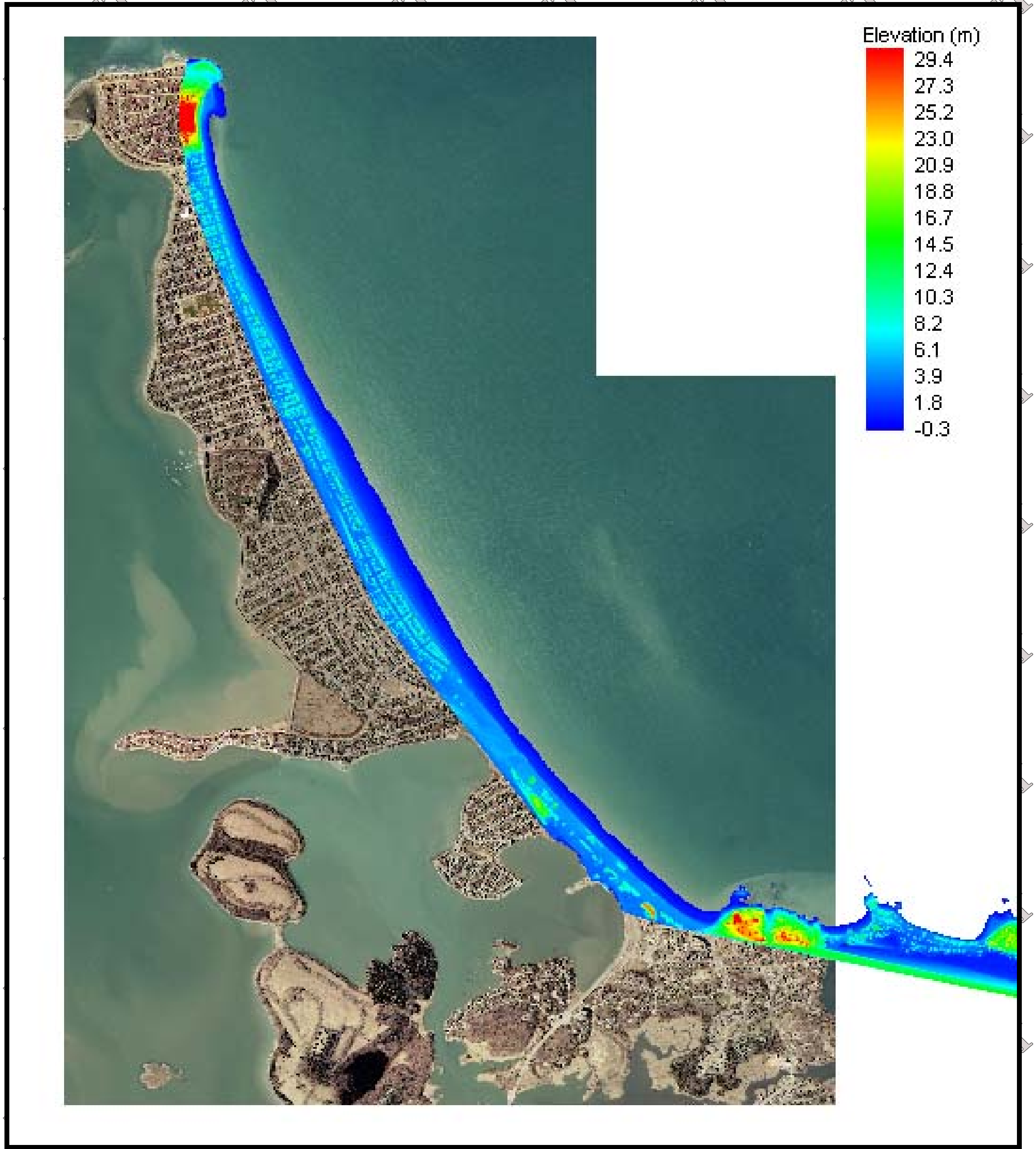

Figure 4-2. CSC LIDAR topography data (meters relative to MTL).

based and hydrographic portions of the survey. Eight cross-shore profiles were surveyed extending from the dune or seawall to a water depth of 35 feet (10.7 meters) NAVD88 or a distance of 5,500 feet (1,676 meters), whichever came first. The horizontal and vertical accuracies for the shore-based survey were +/-1.0 and +/-0.2 feet, respectively, while the hydrographic survey horizontal and vertical accuracies were +/-3.0 and +/-0.2 feet, respectively. The USACE survey profile lines are shown in Figure 4-3.

Figure 4-3. USACE cross-shore profile survey transects.

4.3.2 2006 Site Survey

In order to supplement the existing bathymetric and topographic information, a field survey was conducted by CLE Engineering, Inc. as a part of this project in the most critical nearshore region (DCR Nantasket Beach Reservation). Topographic data were obtained in a shore-based survey that extended along the shoreline from Phipps Street to Atlantic Hill and across the shoreline from 10 feet landward of George Washington Boulevard to 500 feet (152 meters) seaward of the existing seawall structure. In addition, a hydrographic survey was completed along the same extent of shoreline to approximately 1,000 feet (304.8 meters) offshore. Results of the survey are presented in Figure 4-4.

4.3.3 Grid Generation

To simulate wave propagation from the offshore observation locations to the nearshore region of Nantasket Beach, grid nesting was used within STWAVE to provide for an adjustable level of resolution (more detail in the nearshore region). In STWAVE, a grid consists of a mesh of points with dimensions NI and NJ, as shown in Figure 4-5. At each point within the grid domain, water depth, as well as ambient current data, can be specified. Reference points are separated by spacing DX (x-direction) and DY (y-direction). For the Nantasket Beach simulation, three separate grids were created: an offshore grid, an intermediate grid, and a nearshore grid. The modeling grids were created using the bathymetric data sets discussed in the previous sections. The offshore boundary of the offshore grid was chosen at the location where the offshore wave data was acquired, at a water depth deep enough that waves would not sense the sea floor. The orientation of the grids was selected to closely represent a shore-parallel contour line. The grids were rotated to be closely perpendicular to the shoreline, such that a comprehensive range of directional approaches could be simulated. STWAVE is a half plane model (directional approaches relative to a 180-degree half plane). Therefore, rotation of the grid allowed for simulation of all wave approach directions for the Nantasket Beach shoreline that would impact potential sediment transport (waves arriving from 329 to 149 degrees relative to true North).

The offshore boundary of the offshore grid was selected to fall at the WIS 52 wave station (Section 4.4), at approximately the 70 meter (229.7 feet) depth contour. The offshore grid ranges 22 km (13.7 miles) in the cross-shore (x) direction and 17 km (10.6 miles) in the alongshore (y) direction, having a cell size of 100 m by 100 m (328 ft by 328 feet; NI=221, NJ=170). Interpolated depths at each grid intersection point were obtained from the bathymetric data in the gridding process. Figure 4-6 shows the offshore bathymetric grid, for which the offshore boundary was rotated approximately 31 degrees counter-clockwise from true north to be closely oriented with the shoreline.

An intermediate grid was created with the offshore boundary located at approximately the 30-meter contour. The grid has a cell size of 25 meters (82 feet) and extends 9,075 meters (29,774 feet) in the cross-shore direction and 6,175 meters (20,259 feet) alongshore (NI=363, NJ=247). Figure 4-7 shows the bathymetric grid for the intermediate region. The offshore extent of the grid was selected to fall seaward of the majority of the bathymetric features that can be observed offshore Nantasket Beach. Due to the presence of these features, this intermediate grid with good spatial resolution was developed to capture the effects of the changing bathymetry on the wave field.

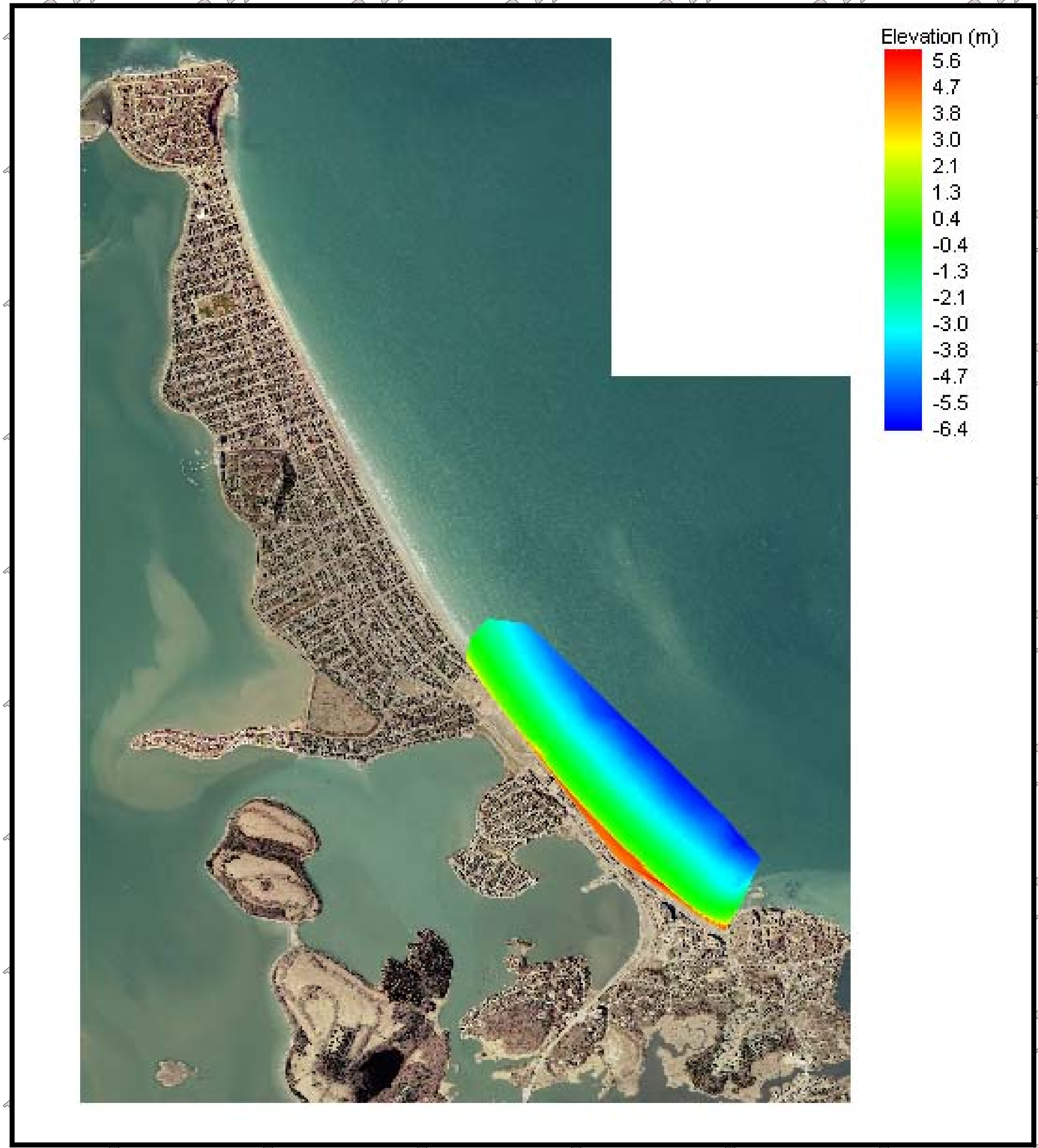

Figure 4-4. 2006 bathymetry and topography data (collected by CLE Engineering) in the vicinity of Nantasket Beach DCR Reservation (meters relative to MTL). Not for navigational purposes.

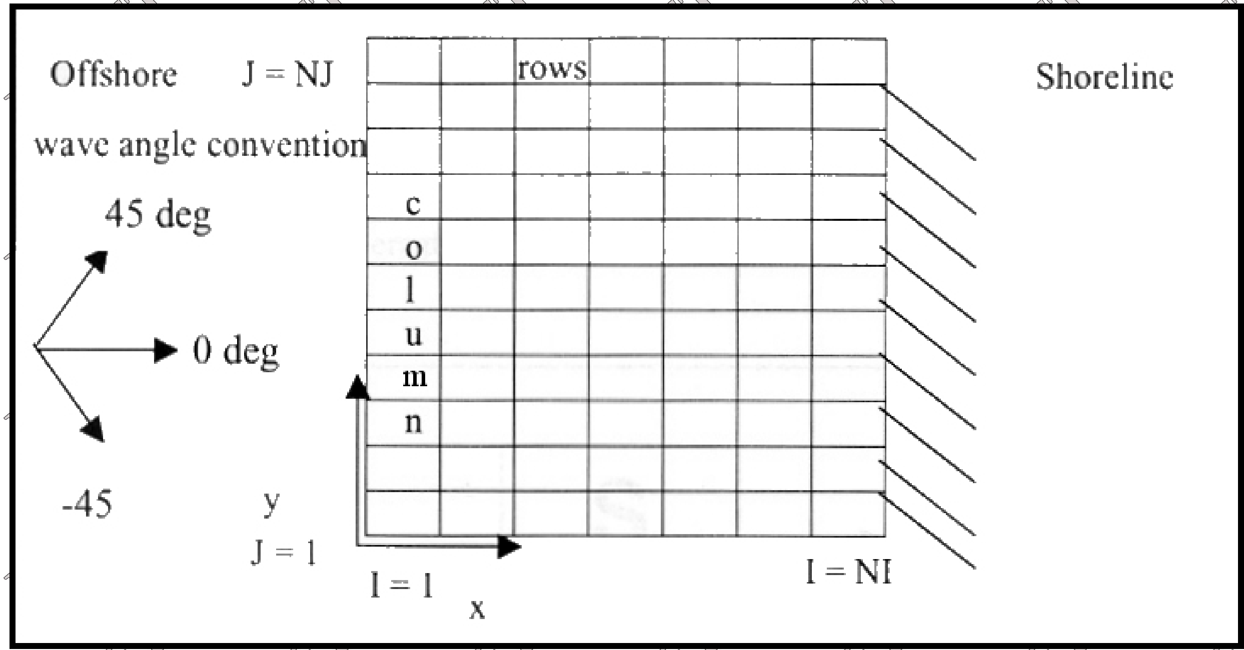

Figure 4-5. Illustration of reference grid notation (Smith, Sherlock, and Resio, 2001).

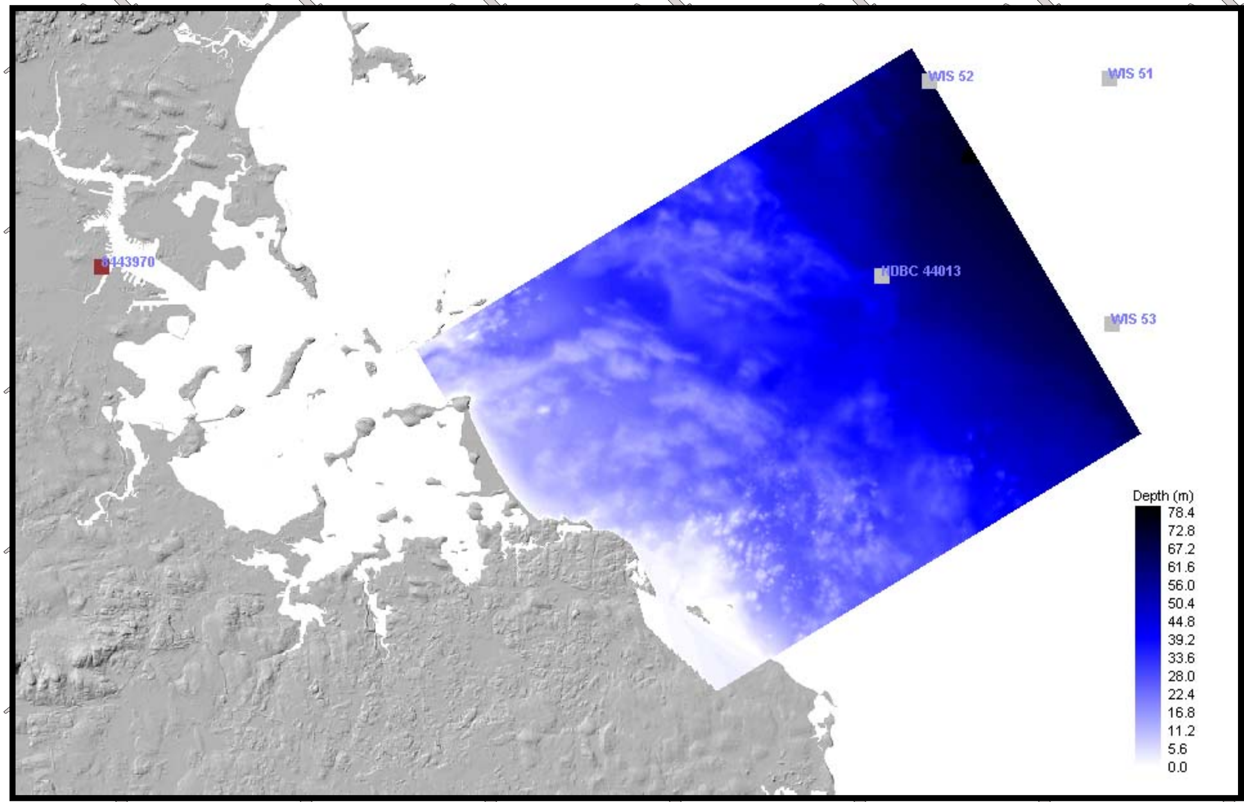

Figure 4-6. Offshore bathymetric modeling grid. Depths are in meters relative to MTL. Not for navigational purposes.

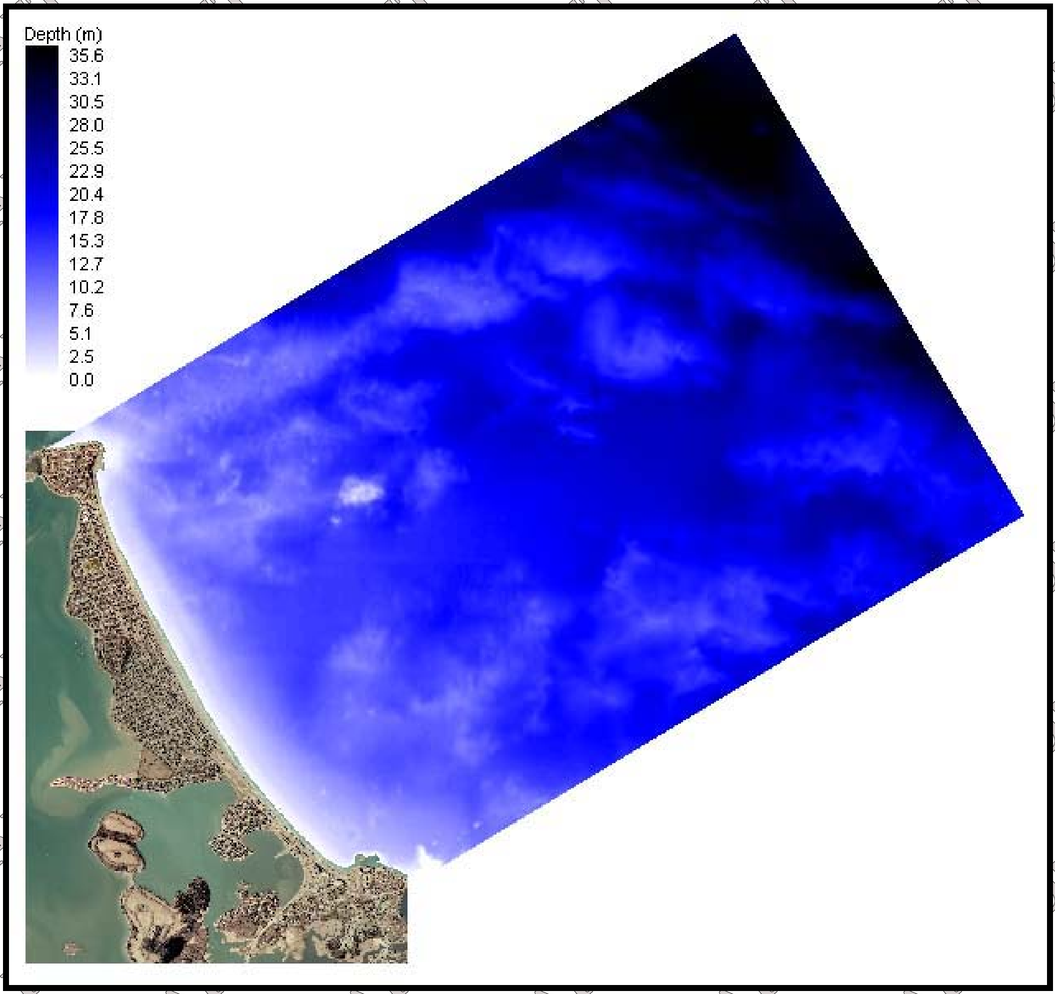

Figure 4-7. Intermediate bathymetric modeling grid. Depths are in meters relative to MTL. Not for navigational purposes.

The bathymetric features in closer proximity to Nantasket Beach are more clearly displayed in Figure 4-8, where the depth contours are limited to 0 to 13 meter (0 to 42.7 feet) range (referenced to MTL) and certain named features are identified. In the northern portion of the grid, Thieves Ledge, with depths of 10-11 meters (32.8-36.1 feet), is the most prominent offshore feature offshore Allerton Hill. Ultonia Ledge extends from Allerton Hill as part of the submerged headland formation in the nearshore with depths of 8-9 meters (26.2-29.5 feet). The most visible, shallow feature is Harding Ledge, a rocky formation offshore the northern portion of Nantasket Beach with depths of 2-3 meters (6.6-9.8 feet). Directly offshore Strawberry Hill is Strawberry Ledge, a nearshore formation with depths of 8-9 meters (26.2-29.5 feet). Unnamed bathymetric features exist offshore the southern portion of Nantasket Beach, offshore of the DCR reservation. Another rocky formation exists at the start of the Black Rocks near the southern boundary of the grid, offshore Atlantic Hill and Gun Rock with depths of 8-9 meters (26.2-29.5 feet). All of these offshore features influence the waves as they propagate towards Nantasket Beach. As such, a high resolution nearshore grid was specified to gain better resolution in the nearshore region for sediment transport calculations. The grid extends 1,920 meters (6,298 feet) in the cross-shore direction, and 6,170 meters (20,237 feet) alongshore, having a high resolution

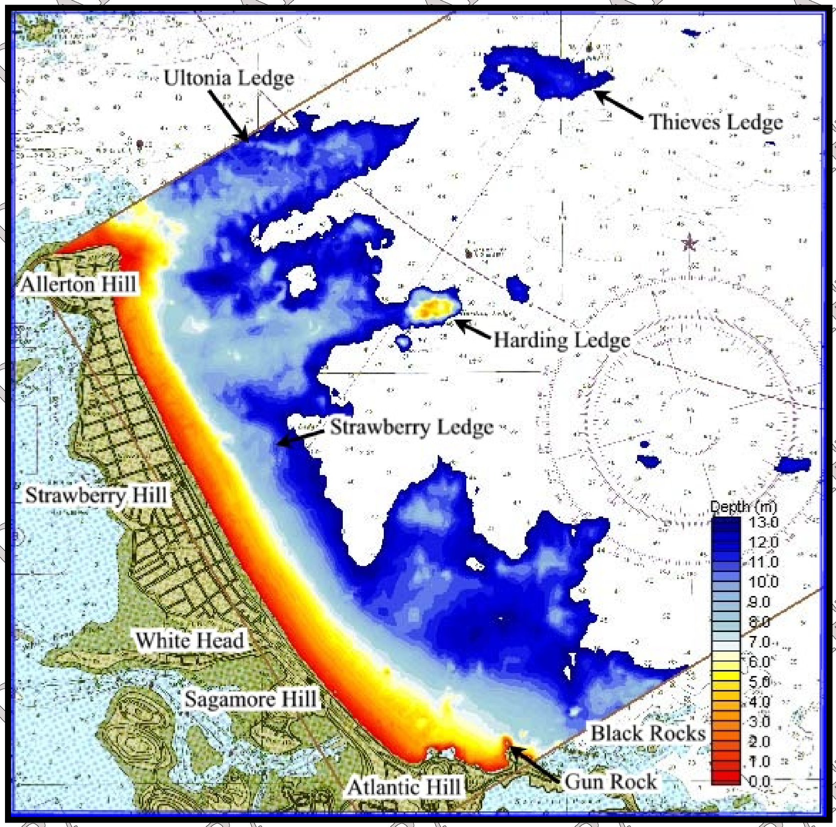

Figure 4-8. Bathymetric features offshore Nantasket Beach. Depths are in meters relative to MTL. Not for navigational purposes.

cell size of 10 meters (33 feet). The offshore extent of the grid was selected to include the 7 meter (23 foot) contour along the entire length of shoreline. The nearshore grid is further discussed along with the sediment transport model in Chapter 5.

4.4 WAVE CHARACTERISTICS AND INPUT SPECTRA

A key component of accurate wave modeling is the analysis and selection of input wave data. The results derived from numerical wave transformation modeling, as well as the subsequent movement of sediment in the coastal zone, are controlled by the selected wave input conditions. This section describes the offshore wave climate and selection of input wave parameters for the wave transformation modeling.

4.4.1 Offshore Wave Climate

For this project, the Wave Information Study (WIS) time series of wave and wind data were used to describe the wave climate offshore the Nantasket Beach region. Long-term time series of wave climate observations are typically not available for most shorelines, and although National Data Buoy Center (NDBC) station 44013 exists offshore Nantasket Beach in 55 meters (180 feet) of water (Figure 4-6), the buoy is not equipped to measure wave directionality, which is crucial to developing wave spectra that accurately characterize the wave climate. The WIS, performed by the USACE, has met a critical need for wave information in coastal engineering studies since the 1980s and is widely accepted for design purposes for United States shorelines by many coastal engineers and scientists. WIS contains time series information of spectrally-based, significant wave height, peak period, peak direction, and wind speed and direction produced from a computer hindcast (prediction) model. The hindcast wave model, WISWAVE (Resio and Tracy, 1983) is simulated using wind information (speed and direction) at selected coastal locations around the United States. The model predicts wave climate based on local/regional wind conditions. Wave measurements made by NOAA during the 1980s made verification of the WIS results possible by comparing the statistics and the distributions of wave heights and periods from different time periods (Hubertz et al., 1993). The availability of long-term records makes WIS data attractive when considering average or seasonal wave conditions. Since the data are widespread and continuous, adoption of the generally accepted WIS data for development of spectral wave conditions is applicable. Previous studies and design projects have used WIS data as an accurate measure of wave climate and input to nearshore wave transformation models (Kraus et al., 1988; Byrnes et al., 1999; Byrnes et al., 2000). Although direct, *in situ* measurements might show some difference in detail, the WIS data set provides an accepted and widely used long-term wave data set, which is a significant improvement over representing the sea state with a single wave condition. In addition, this WIS data used in this study were validated to actual wave height observations at the NOAA 44013 station to verify the relative performance of the WIS and STWAVE models.

The WIS stations were evaluated for this study are shown in Figure 4-6 near the offshore boundary of the modeling domain. Three WIS stations were evaluated to help understand the spatial variability of wave conditions offshore Nantasket Beach and to ensure appropriate selection of wave input conditions. Each WIS station has 20-years worth of spectral wave data, spanning from 1980 to 1999. Figure 4-6 also indicates the location of NDBC station 44013, which provided wave height measurements within the model domain for wave model verification purposes (Section 4.5). Table 4-1 presents a summary of the relevant wave stations used in this study. The most recent WIS simulations (Phase III-type) were used for this study and provide wave parameter results every hour for a twenty-year time period (1980-1999). The Phase III-type WIS data represent the most up-to-date wave generation and wave parameter development and are considered more accurate than the older Phase I-type and Phase II-type data sets. Details on the differences between the various Phases of USACE wave generation can be found on the WIS website (http://frf.usace.army.mil/wis/wis_main.html). Each WIS station is located near the offshore boundary of the modeling domain in 40 to 63 meters (131 to 207 feet) of water depth.

Table 4-1. Summary of relevant stations in the modeling domain.

Station	NDBC 44013	WIS 51	WIS 52	WIS 53
Latitude	42.35°N	42.42°N	42.42°N	42.33°N
Longitude	70.69°W	70.58°W	70.67°W	70.58°W
Depth (m)	55	40	63	56
Time Period (yrs)	1985-2005	1980-1999	1980-1999	1980-1999

The three 20-year WIS data sets offer a synopsis of the wave climate offshore of Nantasket Beach. A closer examination of the data identifies the variability in wave energy and approach direction, parameters that typically have a significant impact on sediment movement in the nearshore. Figure 4-9 presents wave rose plots, which illustrate the distribution of significant wave height, for each of the WIS stations. The grayscale colors indicate the magnitude of the wave height, the circular axis represents the direction of wave approach (coming from) relative to True North (0 degree), and the extending radial lines indicate percent occurrence within each magnitude and directional band. The majority of the waves are shown to be arriving from north-northeast to south-southeast. The direction and magnitude of the 20-year wave data are similar throughout stations 51-53; therefore, there is little spatial variability in wave climate among the WIS stations. The lack of spatial variation can be further illustrated by the comparison of the mean wave period distribution (Figure 4-10), the percent occurrence directional distribution (Figure 4-11), and the percent wave energy directional distribution (Figure 4-12). Figures 4-10 through 4-12 only present wave directions that propagate towards Nantasket Beach, where 90 degrees represents a shore-normal wave (perpendicular to the shoreline). For each of these parameters, there is little variation between the individual WIS Stations. Since each WIS station near the domain boundary has similar wave data, Station 52, which is located most directly offshore Nantasket Beach, was selected as the offshore wave data source to generate spectral input conditions.

Offshore, the most common wave approach direction is from the east (90 degrees in Figure 4-9 or 120-130 degrees in Figure 4-11, which represents direction relative to the rotated model domain). The most wave energy is associated with waves coming from the northeast (70-80 degrees in Figure 4-12). Figure 4-13 compares the basic percent occurrence and the percent energy across the directional distribution for WIS station 52. The percent occurrence distribution simply presents the percent of time waves come from each direction, while the percent energy presents the amount of energy coming from each direction. The asymmetry between the distributions indicates that although there are a lower percentage of waves arriving from the northeast than the east, the northeast waves are more energetic. This can be explained by the high number of nor'easter storms that are common to the New England area. Therefore, to properly represent the offshore wave conditions that drive the wave model and help estimate longshore sediment transport at Nantasket Beach, it is clear that the wave conditions cannot be defined by one single set of wave parameters, or even by a series of specific wave conditions, but rather a compilation of a variety of waves that occur over a longer time frame. It is also likely that the wave field experiences significant changes as the waves advance towards the coastline. The results of the wave transformation modeling will explore the changes that occur to the wave distribution as they propagate towards the coast, and specifically in the vicinity of the Nantasket Beach and the DCR reservation.

Rather than selecting the most common wave heights and directions, a detailed analysis was conducted to compile and summarize the existing WIS data into detailed input spectra for the wave transformation model. Each spectral simulation contains distinct differences in the distribution of wave energy between directional and frequency bands, and consequently produces varying impacts in the transformation and sediment transport patterns.

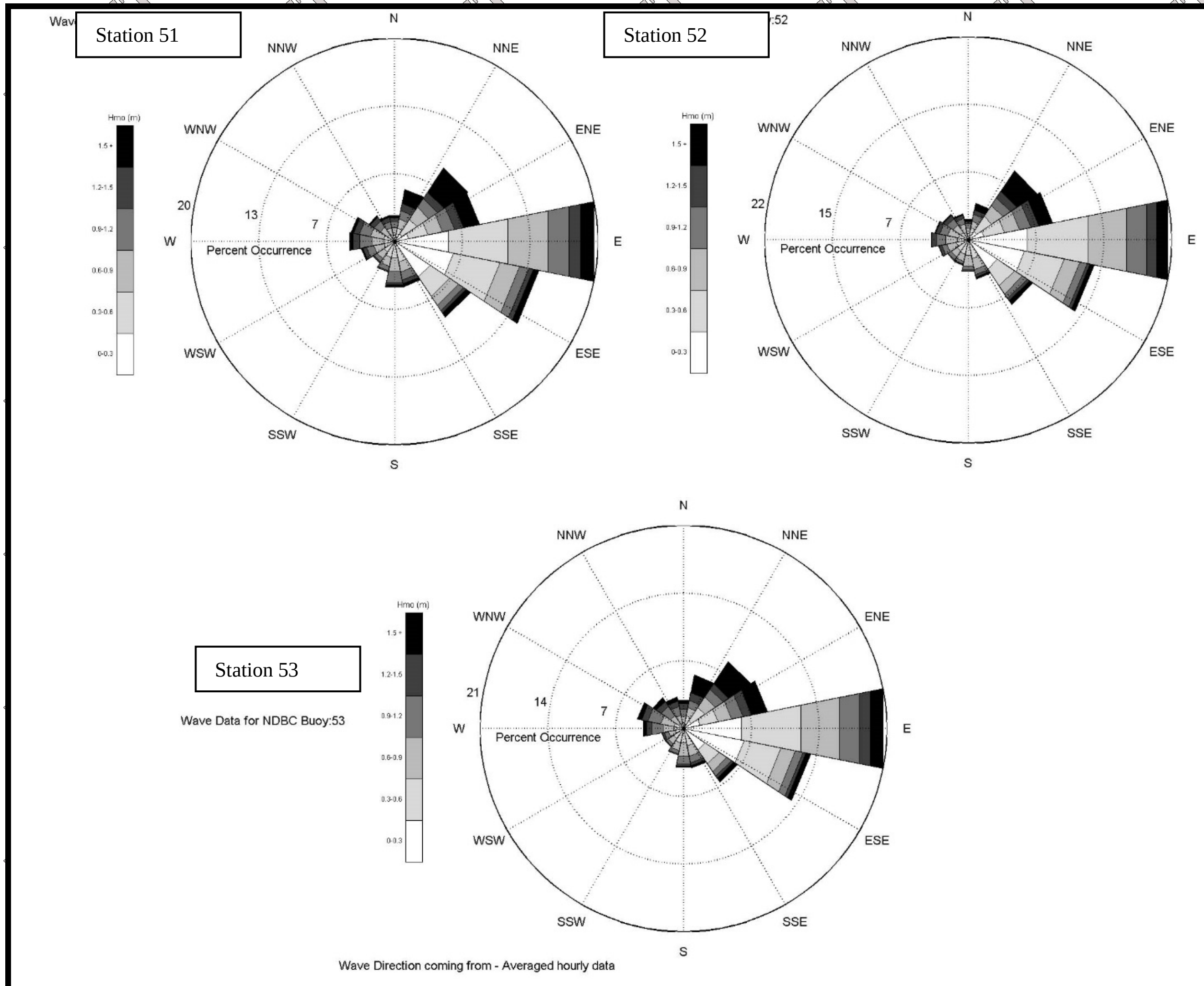

Figure 4-9. Twenty-year, hourly-averaged wave roses for WIS Stations 51-53. Wave height in meters.

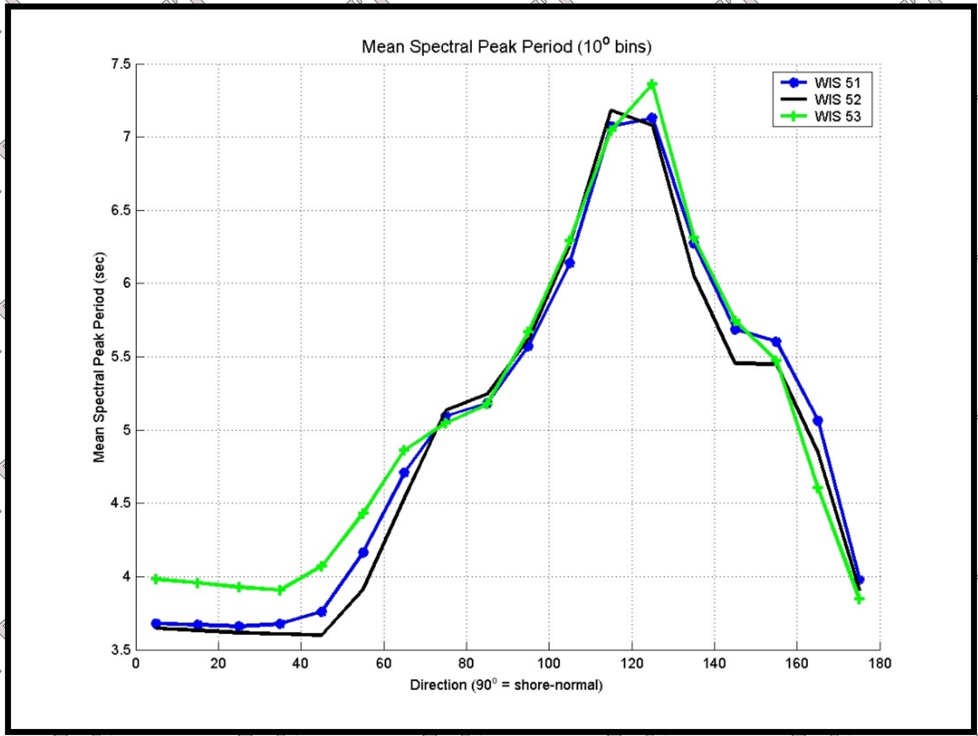

Figure 4-10. Directional distribution (wave directions propagating onshore in 10 degree bins) of mean wave period for WIS Stations 51-53.

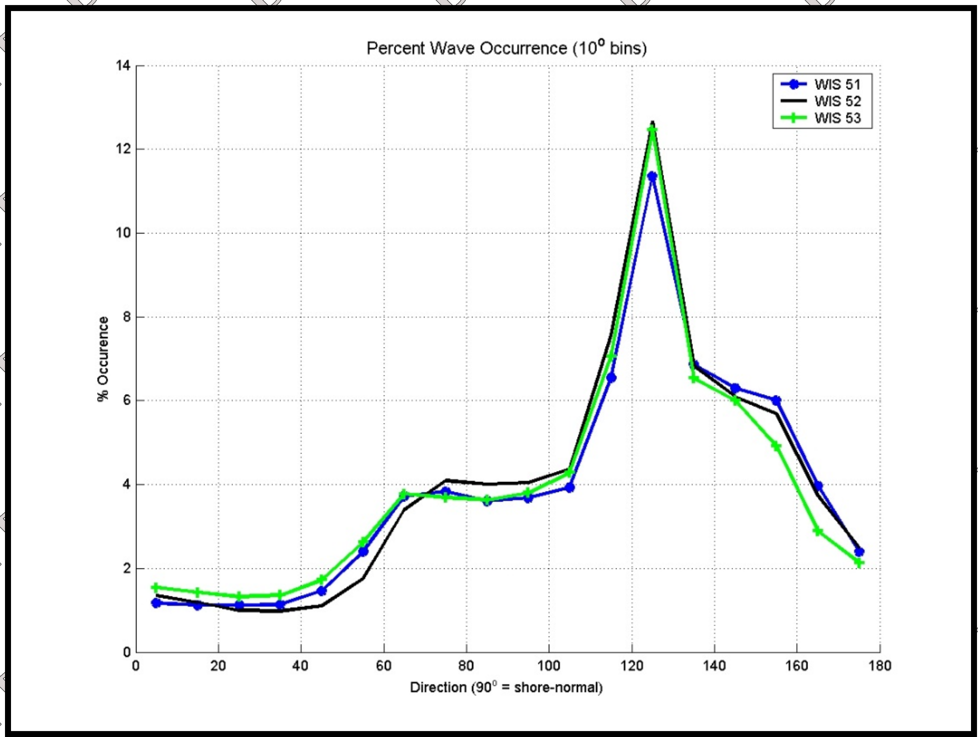

Figure 4-11. Directional distribution (wave directions propagating onshore in 10 degree bins) of percent wave occurrence for WIS Stations 51-53.

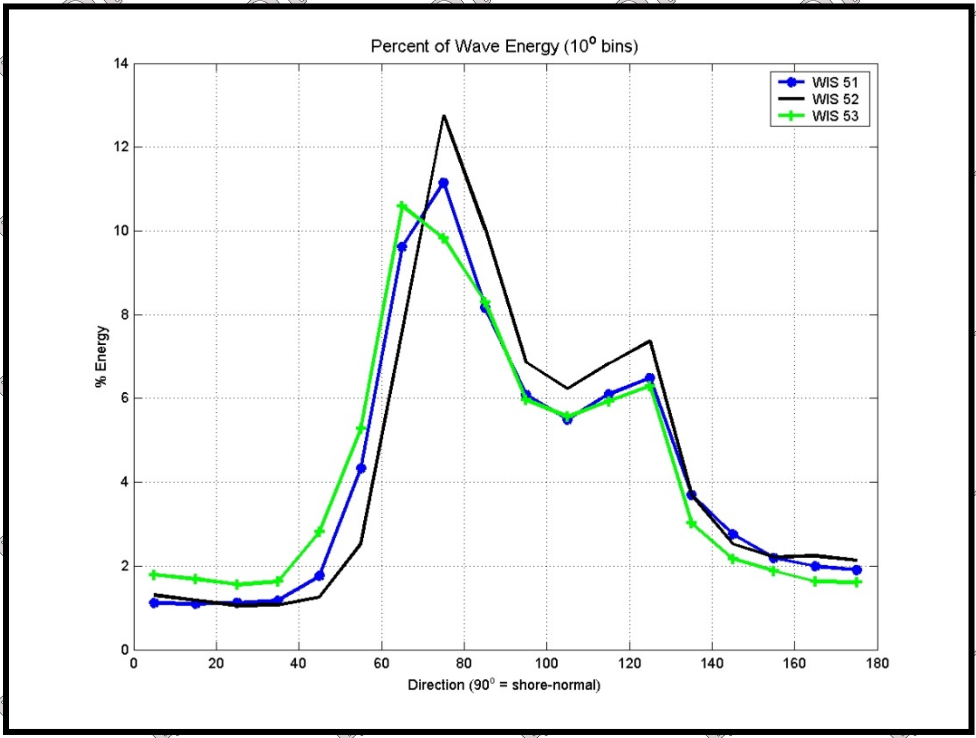

Figure 4-12. Directional distribution (wave directions propagating onshore in 10 degree bins) of percent wave energy for WIS Stations 51-53.

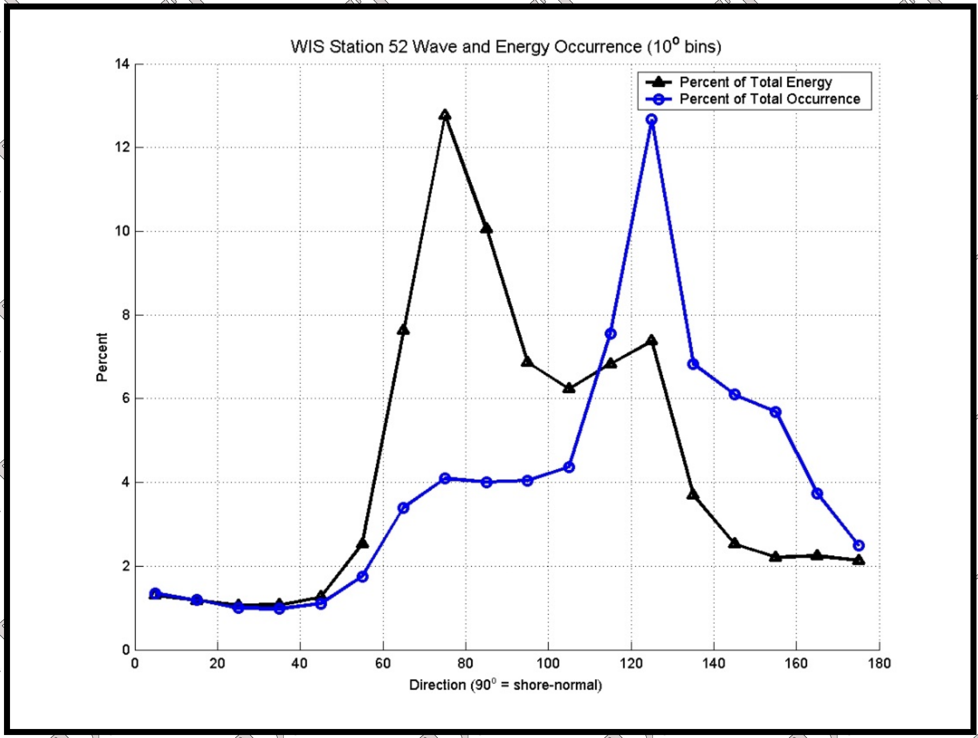

Figure 4-13. Comparison of percent occurrence and the percent energy across the directional distribution for WIS station 52.

4.4.2 Input Wave Conditions

STWAVE requires input of a directional wave spectrum, which represents the distribution of wave energy in the frequency and direction domains. The two-dimensional wave spectrum is given as the product of the energy and directional spectra. The directional spreading function provides the relative magnitude of directional spreading of wave energy, while the frequency spectrum provides the absolute value of wave energy density. Input wave conditions were developed for average annual conditions, a representative year (simulation of every hour during 1987), and specific storm events.

Average Annual Directional Approaches

In order to determine long-term wave conditions and wave statistics at the coastline, as well as for potential use in sediment transport calculations, spectral data from WIS Station 52 were used to derive energy-conserving annual average directional spectrum. Data were segregated by direction of approach, and an energy distribution, as a function of frequency, was generated from all the waves in each directional bin. The energy associated with each frequency was then summed to create an energy distribution for each approach direction. In essence, a representative two-dimensional spectrum was generated for each approach directional bin based on the sum of all the WIS spectra approaching from that mean direction. This can then be combined with the percentage of occurrence to create a long-term (20 year) evaluation of wave impacts at the shoreline. This energetic directional bin approach has been successfully utilized in transformation modeling (Byrnes et al., 2000; Woods Hole Group, 2008) and identifies all potential approach direction, including those that may occur only a small percentage of time during a typical year, but potentially have significant impacts on the shoreline and sediment transport (e.g., the higher wave energy approaches from the northeast). Table 4-2 presents the cases that were simulated in STWAVE to represent the complete wave climate offshore of Nantasket Beach. The table also presents the percent occurrence and wave energy associated with each approach direction. The frequency and directional energy spectra were tailored to match the energy distribution of each approach bin that occurred in the WIS data. Therefore, the directional and frequency distributions matched the data directly. Each of the directional bins presented in Table 4-2 were simulated in the wave transformation model.

Since STWAVE is a half-plane model, only waves propagating towards the coastline are represented. Waves that may be reflected from the coastline and waves that are generated by winds blowing offshore are not included. Waves headed offshore would represent a calm period along the coastline, and this period of time is also presented in Table 4-2.

Representative Year Simulation

In addition to the average annual directional spectra presented in Table 4-2, which are derived from 20 years of WIS hindcast wave data, a full year long time span was also simulated to provide additional insights into the wave field transformations and the wave statistics in the vicinity of Nantasket Beach. Simulations of an entire year of wave data, where wave spectra is simulated every hour, provide a significant data set in the nearshore zone that represents the annual wave climate. A representative year of wave data was selected by comparing individual year statistics to the overall 20-year wave statistics. This comparison allows for selection of a representative year of wave data with wave heights, periods, directions, and energy similar to the magnitude and form of the entire 20-year wave data set. Figure 4-14 shows the percentage of wave energy that occurred in each year over the 20-year period, from 1980 to 1999. Figure 4-15 shows the distribution of wave energy averaged for each directional bin over the 20-year time period compared to the same directional distribution for 1987. Figure 4-15 indicates that the directional distribution of energy for 1987 compares well to the 20-year energy distribution. Therefore, 1987 was selected as a representative year for simulation. Associated wind data were included with the wave spectra as input into the wave transformation model. Therefore, both the waves generated in the regions outside of the model grid (Atlantic Ocean) and locally generated wind waves are included in the simulation. Tidal data obtained from NOAA station 8443970 located in Boston Harbor were also included as input to the year-long simulation to correctly represent fluctuations in the water elevation.

The simulation of every hour during 1987 was also used to verify the performance of the STWAVE wave transformation model. Modeled wave transformation results for 1987 were compared to the observed wave heights at NDBC station 44013. The validation of the wave model is presented in detail in Section 4.5.

Table 4-2. Input conditions and scenarios for the wave transformation numerical modeling.

Directional Bin	Approach Direction	% Occurrence	% Wave Energy	Sig. Wave	Sig. Wave	Peak Period	Peak Direction

(0°=N)				**Height (m)**	**Height (ft)**	**(sec)**	**(0°=N)**
329 to 351.5	NNW	2.14	2.11	0.87	2.84	3.6	342.2
351.5 to 14	N	2.23	2.44	0.89	2.94	3.6	2.7
14 to 36.5	NNE	4.74	7.77	1.01	3.31	4.1	27.8
36.5 to 59	NE	9.10	25.88	1.21	3.98	5.1	47.7
59 to 81.5	ENE	9.74	14.72	0.89	2.92	6.1	70.7
81.5 to 104	E	22.58	14.67	0.60	1.97	7.0	92.4
104 to 126.5	ESE	13.57	5.77	0.45	1.48	5.6	115.0
126.5 to 149	SE	6.40	3.95	0.54	1.76	4.8	133.9
Calm	--	29.49	--	--	--	--	--

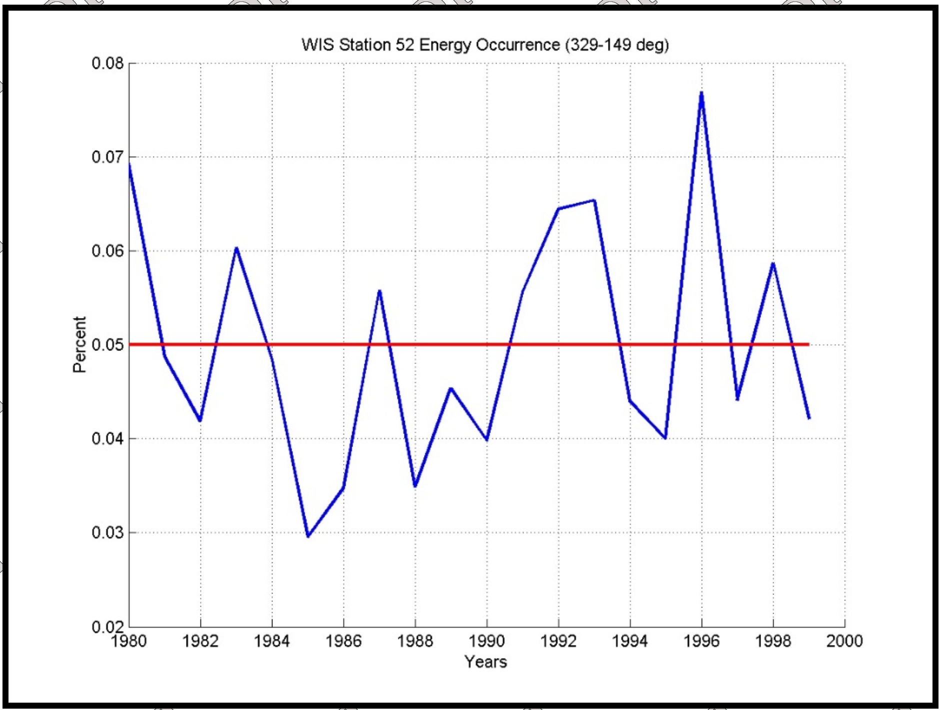

Figure 4-14. Percent energy occurring each year over the 20 years at WIS station 52 (blue line) with average percentile indicated by red line (for wave directions propagating onshore, 329 through 149 degrees where 0°=N).

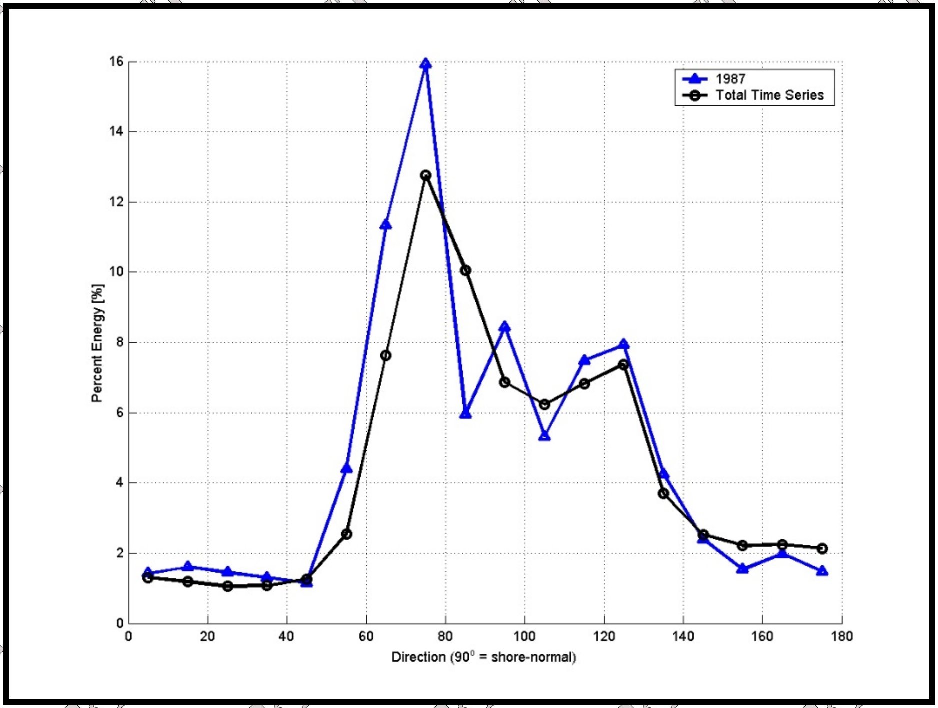

Figure 4-15. Comparison of the percent energy across the directional distribution (wave directions propagating onshore in 10 degree bins) for 1987 (blue line) and for the 20 years of wave data (black line) at WIS station 52.

High Energy Events

Since high-energy events have a significant impact on many physical processes (and in most cases significantly contribute to sediment transport), it is crucial to include storm simulations in the wave modeling to determine extreme storm wave characteristics and assess the associated potential impacts on the shoreline along Nantasket Beach. High energy events were evaluated by reviewing existing literature on hurricanes and northeast storms that affected the coast of Massachusetts and by performing an analysis of storm events from the WIS data.

Several historical storm events in the New England area over the past century have had an impact on Nantasket Beach. The New England Hurricane of 1938 was a Category 3 hurricane on the Saffir-Simpson Scale that caused extensive damage along the coastlines of Connecticut, Rhode Island, and Massachusetts. The Blizzard of ’78 was another infamous storm that produced heavy coastal flooding and hurricane-strength winds. More recently, in the past 25 years, other storms that have had an impact on the New England coastlines include: Hurricane Gloria in 1985, Hurricane Bob in 1991, the “Perfect Storm” in October of 1991, a no-named Northeaster storm in December of 1992, the “Storm of the Century” in March of 1993, the Blizzard of ’96, and the April Fools’ Day Blizzard in 1997. Selected storm events were simulated in the wave transformation model based on available data and the historical impact on Nantasket Beach. Some of the more famous historical storms (e.g., the Blizzard of ’78) did not have limited data coverage, and therefore were not selected for simulation.

Wave data from the WIS 52 Station was used to conduct an analysis of storm events. The wave data were examined and high-energy wave events were characterized based on a set of criteria. A storm event was defined when the significant wave height was greater than 3 meters (9.8 feet) for at least 12 hours. Separate events were defined by requiring a window of 18 hours between wave heights that exceeded the 3 meter (9.8 feet) threshold value. The high-energy wave events were then cross-referenced with a list of known historical storm events for the New England area.

In addition, return-period storm event conditions (10-year, 50-year and 100-year) were developed in order to provide a complete array of extreme events that could be expected to occur at this location. The return-period storm wave heights were determined using the Generalized Extreme Value (GEV) method. This method provides reliable estimates of extremes without assuming the distribution type is known (Resio, 1989). The GEV method uses asymptotic methods to fit sampled maxima to the tail of a parent distribution, whose characteristics are estimated from the original sample. The original sample was taken from the WIS 52 data set. Table 4-3 presents the wave heights estimated by GEV. The return period storms peak wave periods were derived using the following relationship (USACE 2002b) for extreme wave parameters:

$$T_p = \sqrt{10.25 H_{mo}} \qquad (4\text{-}1)$$

where H_{mo} is the extreme wave height. Since the exact wave direction of extreme events is unknown for return-period storms, the most common storm approach and highest energetic direction (northeast 45°) was assumed based on the average approach direction of all the storms in the hindcast data. Therefore, a 45° approach was selected to represent the return period storms, since it represented the average direction of the storms found within the WIS 52 data set.

Storm surge values were also included in the wave modeling simulation to represent the increased water level experienced during the passage of a large storm event. Elevated water levels, even with moderate wave heights, can result in significant erosion along the shoreline. Surge values reported by a variety of sources were used to determine the water level associated with these storm events. For return-period storms, storm surge data were taken from Tidal Flood Profiles of the New England Coastline (USACE, 1988). For the known specific storm events, storm surge elevations were determined from the NOAA station 8443970 located in Boston Harbor and local observations and historical accounts.

Table 4-3 presents the storm events and their associated wave and storm surge characteristics. Storm spectra were developed for the STWAVE simulations from these storm parameters using standard parametric methods (e.g., TMA spectra, $\cos^n$ directional distribution), since the observed spectra during these events are unknown.

Table 4-3. Extreme storm event characteristics offshore Nantasket Beach used to define input spectra.

Storm Event	Significant Wave Height (m)	Significant Wave Height (ft)	Peak Wave Period (sec)	Avg. Wave Direction (degrees)	Storm Surge (m above MTL)
10-year	7.0	23.0	10.2	45	2.71

50-year	8.6	28.2	11.3	45	2.96
100-year	9.3	30.5	11.8	45	3.05
Perfect Storm (10/31/1991)	5.6	18.4	10.0	49	2.80
Nor'easter (Dec. 11-14, 1992)	7.6	24.9	12.5	62	2.75
April Fools' Day Blizzard (April 1, 1997)	6.4	21.0	11.1	42	2.14

4.5 MODEL VALIDATION

In order to verify the performance of the wave model, model results were compared to the wave measurements from NDBC station 44013 for every hour of 1987. Figure 4-16 shows comparisons of the modeled (red) and measured (blue) wave heights for 1987, with each panel presenting a quarter of a year of data. Figure 4-17 shows a comparison of the modeled (red) and measured (blue) wave period for 1987, with each panel also presenting a quarter of a year of data. Portions of the time series without a blue line indicate time periods when the NDBC station was not recording. Visually, the modeled wave heights compare favorably to the observations, and specific wave and storm events were accurately simulated, as well as calm periods. Both average and storm conditions are well represented throughout the entire year. For example, the large event in the middle of November is accurately predicted, as is the entire month of July (smaller waves). The comparison of the modeled and observed wave periods shows there are greater discrepancies, but the simulated wave periods generally follow the trend of the observations. In order to quantify the model performance, error statistics (bias and root-mean-square error) were used to quantify the performance of the wave model.

The bias and root-mean-square (RMS) error are defined as follows where *n* is the number of *P* data points:

$$Bias = \frac{\sum (P_{measured} - P_{simulated})}{n} \tag{4-2}$$

$$RMS\ Error = \sqrt{\frac{\sum (P_{measured} - P_{simulated})^2}{n}} \tag{4-3}$$

The error statistics computed for the model results and observations made at NDBC station 44013 are shown in Table 4-4. Bias is a measure of the average deviation of the measured values from the simulated values. A positive bias means the model is under predicting while a negative bias means, on average, the model over predicted the results. The performance of the model can be evaluated using the RMS error value. The smaller the RMS error value, the better the model performed. The computed statistics show that the model is slightly under predicting wave height and period at the NDBC station, but the deviation is relatively small. The modeled wave height is within 0.15 meters (0.5 feet) of the observed values, while the wave period is within 0.14 seconds. The RMS error indicates that the model does a better job at simulating the wave height than the wave period.

Table 4-4. Computed error statistics for simulated and observed wave parameters at NDBC 44013.

	Wave Height (m)	Wave Period (s)
Bias	0.15	0.14
RMS Error	0.44	2.18

4.6 Nearshore Wave Transformation Modeling Results

4.6.1 Average Annual Directional Approaches

Model simulations were performed for the typical wave conditions represented by the directional bin spectra presented in Table 4-2. Wave focusing and divergence occur at several locations throughout the modeling domain, which results in variations in the wave energy propagating towards the coastline of Nantasket Beach for each directional bin.

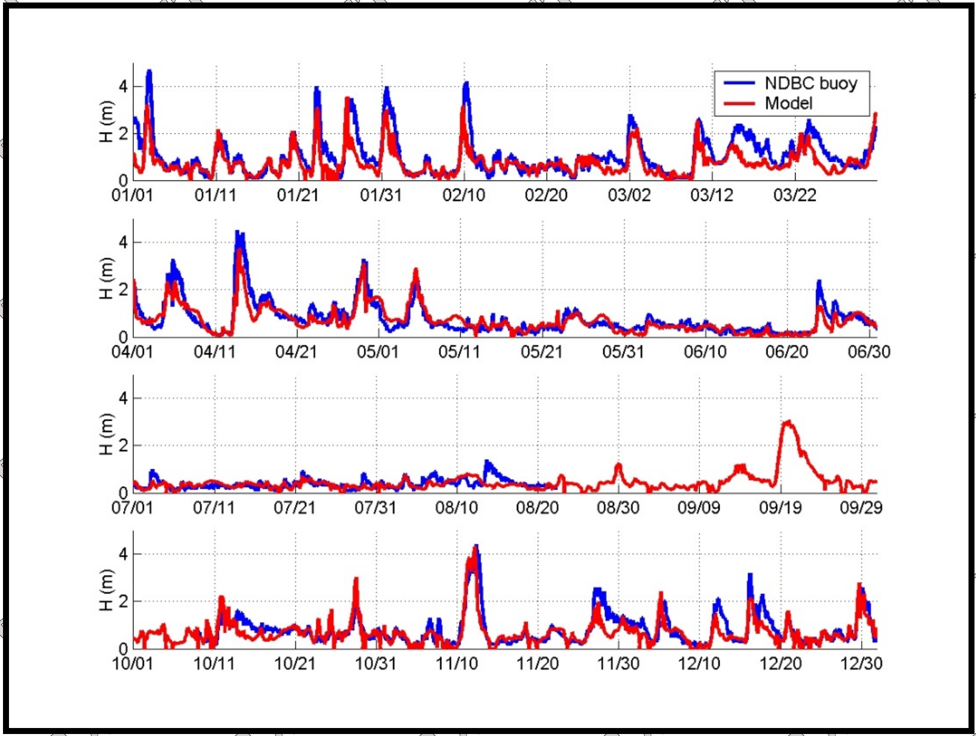

Figure 4-16. Comparison of observed (blue line) and modeled (red line) wave height (m) for 1987 at NDBC station 44013.

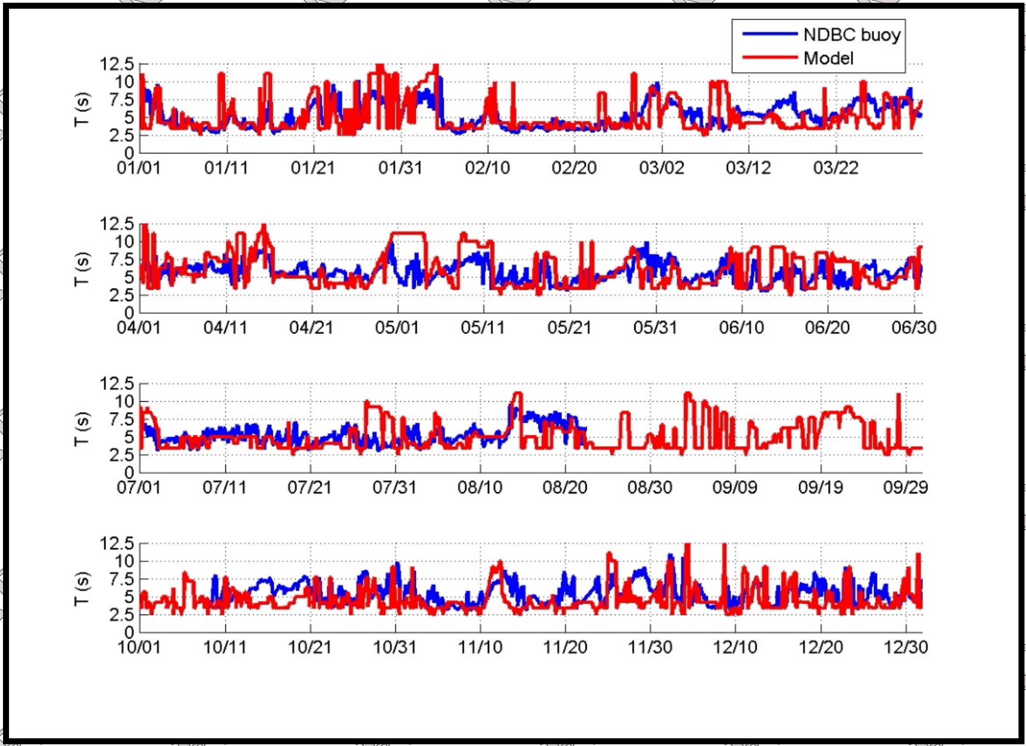

Figure 4-17. Comparison of observed (blue line) and modeled (red line) wave period (s) for 1987 at NDBC station 44013.

Figure 4-18 illustrates STWAVE results for the intermediate grid modeling domain, for waves approaching from the northeast (36.5 to 59 bin), the most energetic approach direction of the typical condition cases. The color map corresponds to the distribution of significant wave height (meters) throughout the modeling domain. Reds indicate higher wave heights, while blues indicate small wave heights. The model simulation was conducted at depths and shoreline positions corresponding to mean water level. Arrows on the figure represent the modeled wave direction as they propagate and approach the shoreline. The directions become more shore-normal as the waves get closer to the coastline and are affected by the irregular bottom bathymetry. The last visible arrow row indicates significant redirection towards the coastline, as the waves become more shore-normal. Figures for all approach directions for the intermediate grid modeling domain are presented in Appendix A.

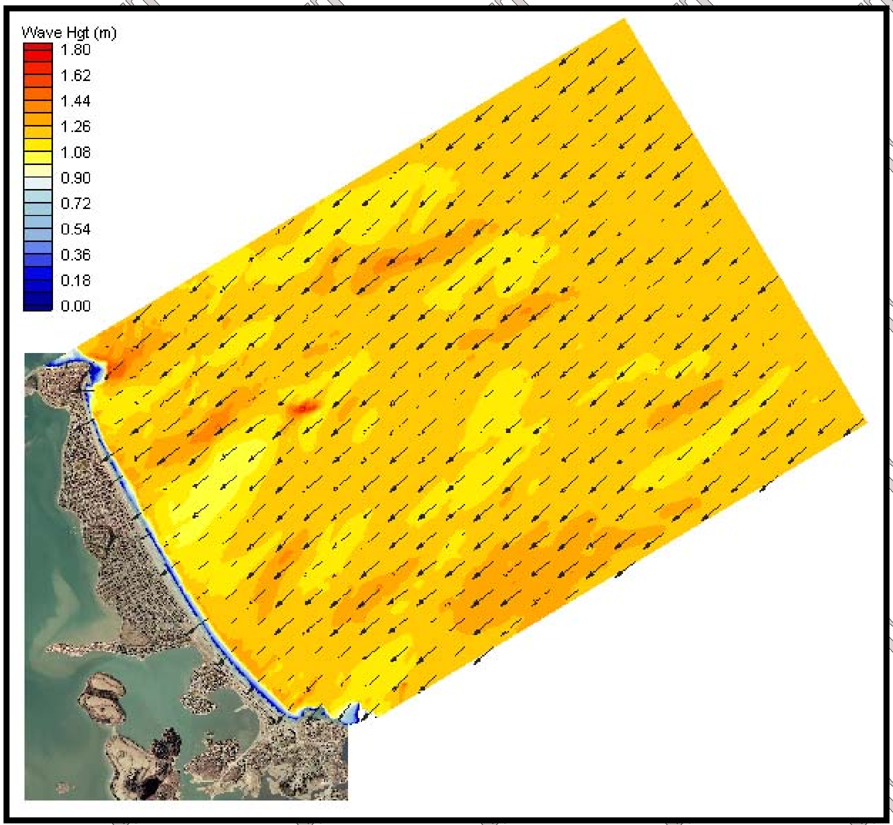

Figure 4-18. Spectral wave modeling results for a northeast approach direction (36.5-59 degree bin). Wave height is presented in meters.

Figure 4-18 shows how the bathymetric features along the Nantasket shoreline affect wave energy for this specific approach direction. For example, wave focusing is shown to occur at Allerton Hill due to wave refraction. To the south, wave shadowing is shown to occur in lee of Ultonia Ledge and Allerton Hill. In between Ultonia Ledge and Harding Ledge, larger waves are allowed to penetrate toward the shoreline (as illustrated by the darker orange region). With its shallow water depths, Harding Ledge causes wave shoaling and diffraction offshore Strawberry Hill. The wave energy in lee of Harding Ledge is reduced, as is shown by the pale yellow coloring extending from Harding Ledge southwest toward the coastline. Offshore the DCR region, south of White Head, more wave energy is allowed to penetrate toward the shoreline as can be observed by the dark orange streaks and dark orange region close to the shoreline. Of course, this example only represents one specific approach direction, and all average annual approach directions must be considered to represent the overall dynamics along Nantasket Beach. The variability in the wave climate is clearly indicated by the differences in nearshore wave patterns arising from the various input spectra approach directions. In order to arrive at an accurate estimation of the sediment transport in the region, results from the wave model can be used to generate the sediment transport flux. This includes waves coming from all directions and having various wave heights and periods. Figures for the remaining approach directions for the Nantasket Beach region are presented in Appendix A.

4.6.2 High-Energy Events

The wave transformation model was also used to simulate high energy events, as discussed in Section 4.4.2. The simulation of specific storm events was important to quantify the short-term impacts that occur during these energetic scenarios. Sediment transport along the coastline can be significant during these short episodic events. Figures 4-19, 4-20 and 4-21 show the spectral wave model results for the 10-, 50-, and 100-year return period storm events, respectively. Wave heights are significantly higher than the annual average directional cases, as the offshore wave heights range from 6.7 m (22 feet) for the 10-year storm to 8.5 m (28 feet) for the 100-year storm. All storm event model results are plotted using the same color scale for wave height so that a comparison of the storm waves offshore Nantasket Beach can be made. The storm event spectral model results were passed along to the nearshore, refined model grid to assess direct impacts on Nantasket Beach, as they were for the annual average directional bin cases.

Figures 4-22 through 4-24 show the spectral wave model results from the April Fools' Day Blizzard (April 1, 1997), Perfect Storm (October 31, 1991), and the Nor'easter storm (Dec. 11-14, 1992) simulations, respectively. The wave model results in each figure are plotted on the same color scale as the return period storm model results were, for inter-comparison. The waves associated with the April Fools' Day Blizzard and the Perfect Storm are similar to those simulated for a 10-year return period event with the April Fools' Day storm having the largest offshore waves (exceeding 7 meters or 23 feet). The simulation of the Nor'easter storm which occurred in December of 1992 produced the largest waves offshore of Nantasket Beach (up to 8.9 meters or 29.2 feet) due to the larger wave period and the wave orientation (62 degrees relative to North), which is close to shore-normal.

Overall, the storm simulations show that the region offshore of Nantasket beach can become a high-energy environment conducive to large wave events (both in wave height and period). These large wave events, although short-lived, can potentially have the most impact on the shoreline of Nantasket beach in mobilizing sediments and inflicting damage on the existing coastal infrastructure.

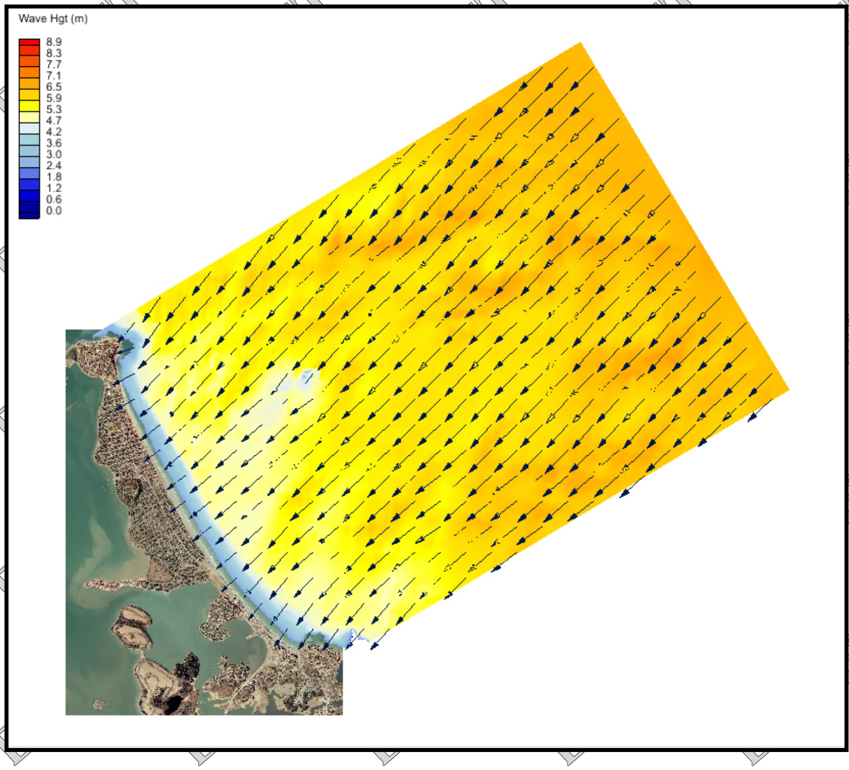

Figure 4-19. Spectral wave modeling results for a 10-year return period storm in the Nantasket Beach region. Wave height is presented in meters.

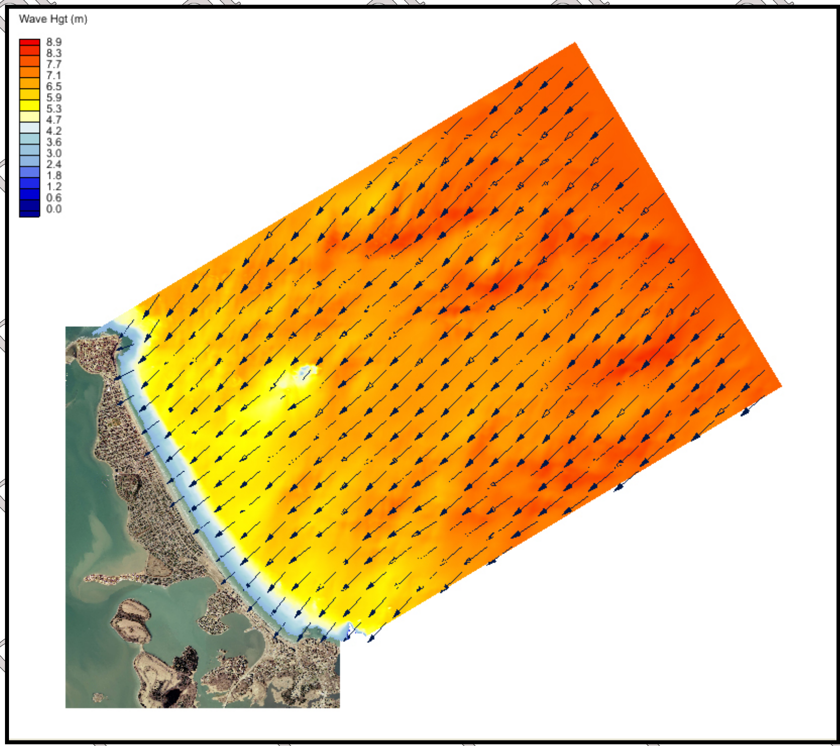

Figure 4-20. Spectral wave modeling results for a 50-year return period storm in the Nantasket Beach region. Wave height is presented in meters.

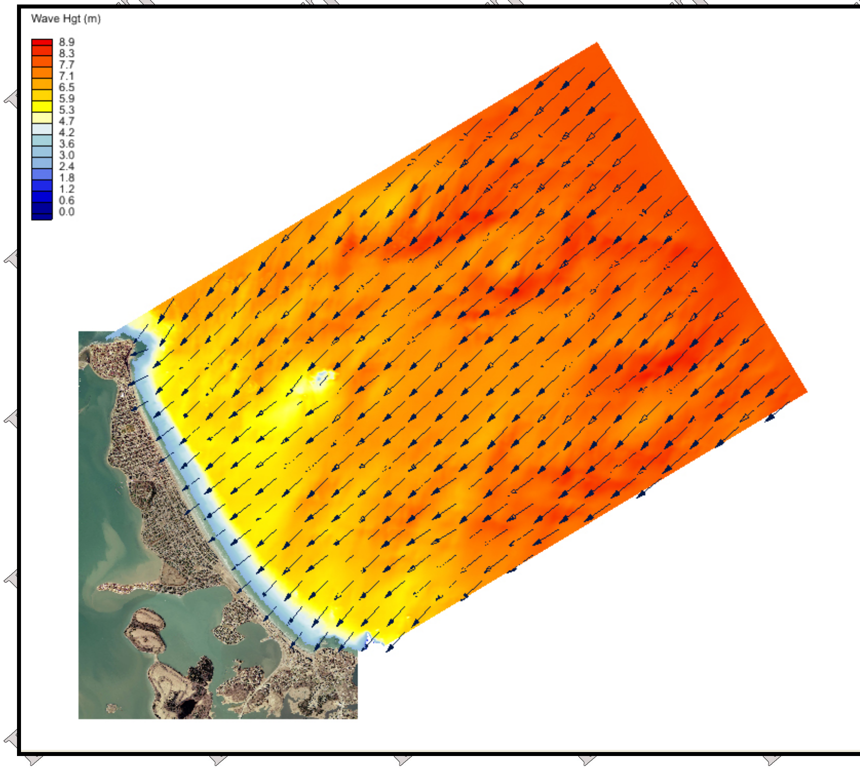

Figure 4-21. Spectral wave modeling results for a 100-year return period storm in the Nantasket Beach region. Wave height is presented in meters.

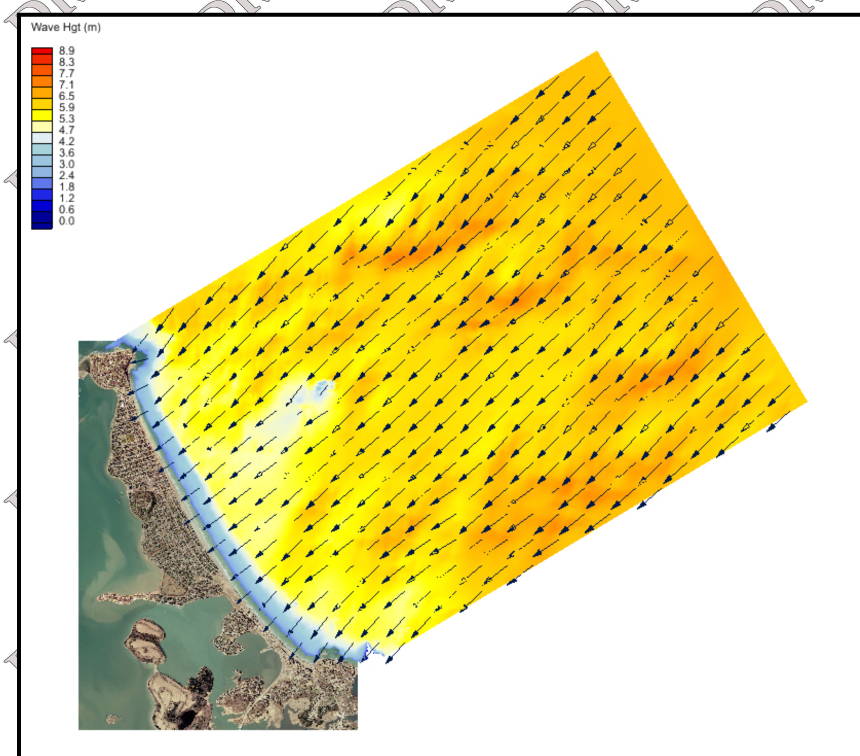

Figure 4-22. Spectral wave modeling results for the April Fools' Day Blizzard (April 1, 1997) in the Nantasket Beach region. Wave height is presented in meters.

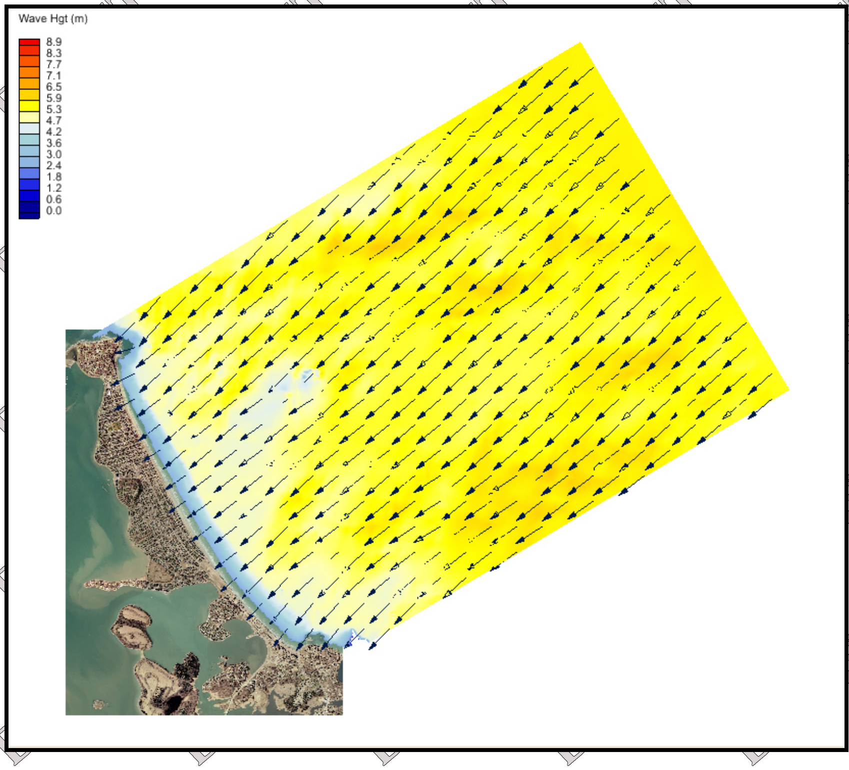

Figure 4-23. Spectral wave modeling results for the Perfect Storm (October 31, 1991) in the Nantasket Beach region. Wave height is presented in meters.

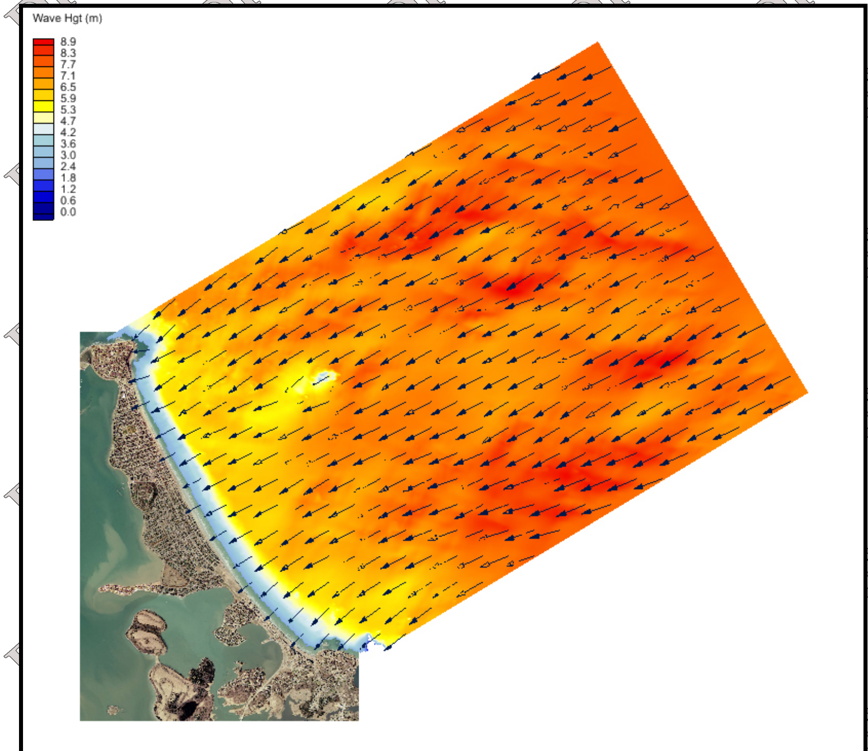

Figure 4-24. Spectral wave modeling results for the Nor'easter storm (Dec. 11-14, 1992) in the Nantasket Beach region. Wave height is presented in meters.

4.7 SEA LEVEL RISE

Another important consideration in the wave transformation simulations, as well as the long-term planning for Nantasket Beach, is potential sea-level rise. The potential impacts of sea-level rise present an additional natural hazard risk for developed areas within the coastal zone. The impacts are similar to those caused by shoreline erosion, and include increased flooding and wave activity in areas previously not affected, as the shoreline moves increasingly further inland.

Scientific research indicates that global (eustatic) sea level has risen approximately 6 to 8 inches (15 to 20 cm) over the last century (EPA, 2000). This eustatic rise in sea level has occurred in part due to glacial isostasy, warming of the world oceans, and melting of continental glaciers. Along most of the US coast, tide gage data show that local sea levels have been rising 2.5 to 3.0 mm/yr, or 10 to 12 inches over the past century. Because the tide gage stations measure sea level relative to the land, which includes changes in the elevations of both water levels and the land, tide gages measure relative sea level rise, and not the absolute change in sea level. Therefore, the rates of relative sea level rise have greater relevance to the evaluation of coastal hazards from sea level rise, than do changes in eustatic sea level.

While the topic of accelerated sea level rise is still heavily debated, the Intergovernmental Panel on Climate Change (IPCC) has undergone a considerable effort to analyze and review the current state of knowledge and provide an estimated range of predicted sea level rise into the next century. For Nantasket Beach, sea level rise estimates were evaluated from a number of sources, including NOAA (2008) and IPCC (2007) estimates. Model simulations were conducted for predicted sea level rise using the projected service life of the proposed alternative and a range of potential rates. The model simulations were relatively insensitive to the use of various rates of sea level rise (i.e., the results were not impacted by changing the rate of sea level rise). Therefore, sea levels based on historical rates of measured sea level rise (NOAA, 2008), which provide a reasonable median estimate of sea level rise predictions, were used in all model simulations.

Long-term tide gage data collected at the NOS (National Ocean Service) station in Boston Harbor, MA provide the closest measurements to Nantasket Beach (NOAA, 2008). Rates of rise computed from the Boston Harbor data set spanning the period from 1921 to 2006 indicate a relative rise in sea level of 2.63 mm/year, or 10.4 inches over the past century (Figure 4-25). This rate of sea level rise (2.63 mm/yr) was included in all model simulations, including assessment of the alternative(s) performance. These estimates help determine potential impacts of rising sea levels on future conditions at Nantasket Beach. Ultimately, the range of potential sea level rise scenarios do not have a significant impact on the model results over the expected service life of the various alternatives (both structural and beach nourishment).

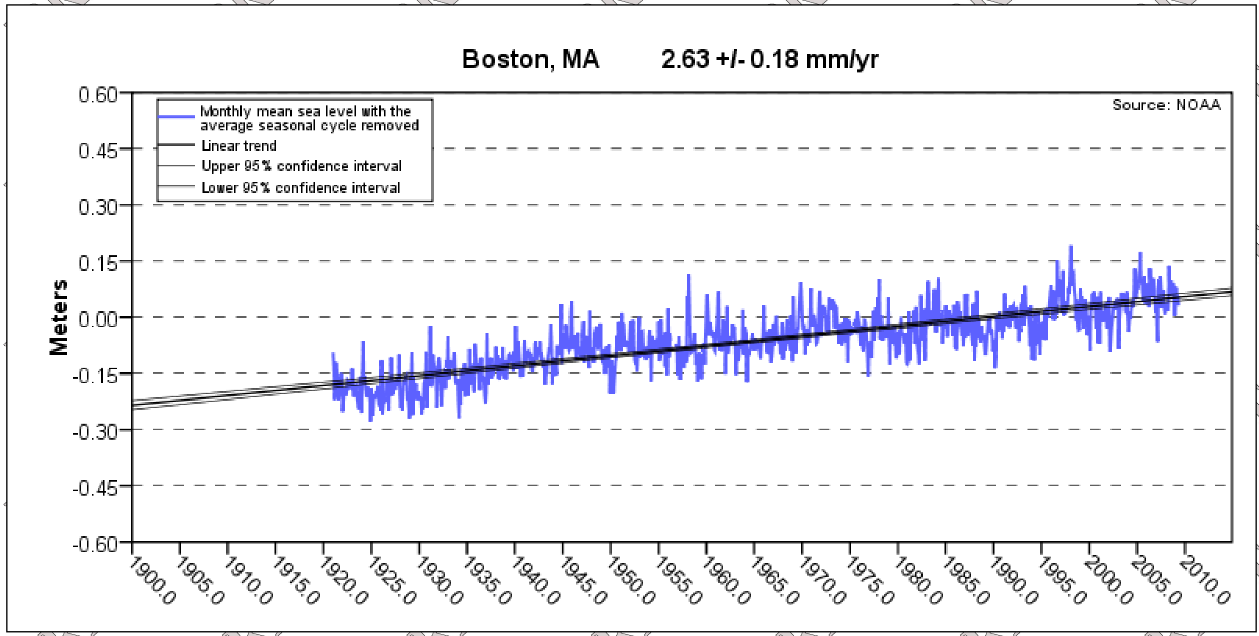

Figure 4-25. Long-term tide data from NOS gages at Boston Harbor showing relative rise in sea level (NOAA, 2008).

5.0 SEDIMENT TRANSPORT

Understanding the wave transformations is a critical step in the determination of shoreline processes and sediment transport in the nearshore region. In order to evaluate and assess any alternative that may be considered in the coastal region along Nantasket Beach, the sediment transport dynamics for the current conditions must be understood. This chapter obtained estimates of the alongshore sediment flux integrated across the surf zone, and subsequently estimated the regional sediment transport for Nantasket Beach. The sediment transport model was also used to determine the performance of various seawall alternatives for Nantasket Beach.

5.1 SEDIMENTS

The characterization of natural sediments at Nantasket Beach is an important first step in evaluating littoral processes and the movement of sediments along the shoreline. In addition, knowledge of the grain size of the beach sediments help to define the design grain size for any shore protection alternative involving beach nourishment.

The Nantasket Beach Characterization Study (USACE, 2006) was utilized to provide information on the type of sediments and grain sizes that exist along the beach and within the surf zone. The USACE obtained 64 vibracore and ponar samples along five cross-shore profiles. The samples were taken in the fall of 2005 (September 30 to October 8) along the cross-shore profiles numbered 1, 3, 5, 7, and 8 (Figure 4-3). The sample depths were to be four feet unless penetration was restricted, and the samples were then subdivided into upper and lower portions. The actual depth range for the upper samples was 0.7 to 2.2 feet (0.2 to 0.7 meters). Grain size analyses showed that the sediments were generally fine-grained (0.15 to 0.25 mm) with coarser sediments found on the landward portion of the profiles and offshore at the deeper sampling locations.

The study also quantified the cobble/gravel (>4.76 mm) and sand fractions (4.76 to 0.074 mm). In general, relatively less sand was found in the lower samples (2 to 4 feet below the surface) compared to cobble and/gravel. The average percentage of sand for all of the lower samples was 73%, while the average percentage of sand for the upper samples was 82% (Table 5-1). Profile #8 had the lowest percentages of sand at 56% and 62% for the upper and lower samples, respectively.

Table 5-1. Average cross-sectional profile sand fractions (USACE, 2006).

Profile Number	Lower Sample Average % Sand	Upper Sample Average % Sand
1	89.0	94.9
3	82.5	90.2
5	66.0	80.7
7	66.5	80.9
8	56.2	62.1

For the sediment transport modeling, a mixed grain size approach was utilized to incorporate the presence of the combined cobble/gravel/sand material found nearshore and on Nantasket Beach. This approach is further detailed in the sections to follow. For this modeling, it was necessary to determine a representative median grain size (D_{50}) for both the cobble/gravel and sand fractions. For the sand fraction, the median grain sizes determined in USACE (2006) for each of the upper samples were averaged to define a representative sand D_{50} equal to 0.25 mm. The median grain sizes of the cobble/gravel fraction for each of the upper samples were averaged to define a representative cobble/gravel D_{50} equal to 28 mm. The analysis was conducted on the upper samples in evaluating sediment transport, since this layer is subjected to the mobilization forces of waves and currents. The spatial distribution of the cobble/gravel and sand fractions was used in the sediment transport modeling presented in the chapter.

5.2 ANALYSIS APPROACH

Sediment movement in the coastal zone, as well as the effects of coastal structures on shoreline processes, can be estimated by using various types of sediment transport models. These models may differ in their detail, in their degree of representation of the physics of the problem, in their complexity, and in other manners. Process-based sediment transport models are those that directly address the fundamental physics of waves and sediment transport. These models which focus on those essential physics are able to encompass a variable wave field. Such sediment transport models may not represent all the details exactly, but they can be used to demonstrate regional sediment transport trends and the spatial influence of coastal structures on adjacent shorelines. The sediment transport model presented herein is a process-based model which determines regional sediment transport trends in the presence of time-variable (in direction and height) waves.

The goal of this model is to provide a physically-based representation of alongshore currents and sediment transport driven by breaking waves in the surf zone. The specific objective is to obtain estimates of the alongshore sediment flux integrated across the surf zone. To achieve this physically-based representation, it is important to understand what longshore processes may cause erosion or accretion of sediments. Typically, a section of shoreline can be represented with a cell, having a finite length along the shore. Sediment enters this cell from the updrift side (i.e., the side that alongshore currents are directed towards), and leaves the cell from the downdrift side. The net sediment balance will vary depending on the height, period, and direction of the nearshore waves.

A wave passing a cell may have the following effect on sediment:

(1) The same amount of sediment enters a cell as leaves the cell.

(2) More sediment enters a cell than leaves the cell.

(3) More sediment leaves a cell than enters the cell.

The first scenario leads to a stable cell shoreline. The shoreline neither erodes nor accretes. The second scenario leads to accumulation of sand in the cell, causing accretion (i.e., building out of the shoreline). This scenario is referred to as sediment convergence, as sediment converges in the cell. The final scenario leads to a net loss of sediment in the cell, causing erosion. This possibility is referred to as sediment divergence, as sediment diverges from that cell. Thus, shoreline erosion or accretion can be thought of as a simple divergence or convergence of sediment moving alongshore. Of course, storms also can move sand offshore and other waves may move sand onshore; however, the focus of this chapter is on the alongshore movement of sand, which results in a majority of the net changes of the shoreline.

The regional sediment transport model requires the results of the wave field presented in Chapter 4. The sediment transport model consists of a hydrodynamic component to determine the wave-induced currents, and a sediment transport component to quantify the amount of sediment moved by those wave-induced currents. The hydrodynamic component is based on a standard set of equations that are widely accepted and generally used, more specifically known as the steady-state, depth-averaged mass and momentum equations for a fluid of constant density. These equations are standard in many surf zone applications (e.g., Mei, 1983) and provide a state-of-the-art representation of the alongshore current. The sediment transport component is based on a recent peer-reviewed and published formulation by Haas and Hanes (2004), which has been shown to be consistent with recent complex formulae for wave-driven sediment transport and with the Coastal Engineering Research Center (CERC) formula (USACE, 2002) for the total (laterally-integrated) alongshore sediment flux.

For Nantasket Beach, a high-resolution bathymetric grid was generated using the nearshore bathymetry/topography (Figure 5-1). The grid for the sediment transport model is the same high-resolution nested grid used for the STWAVE wave transformation model, with 10 m (32 ft) cells spanning 1,920 m (6,300 ft) in the cross-shore direction and 6,170 m (20,243 ft) in the alongshore direction. The wave transformation model was executed for the average annual conditions and the high-energy events on this high-resolution grid. The results from the STWAVE simulations are then applied as input into the sediment transport model.

Given the native geology of the New England area, many beaches consist of a mixture of sand, gravel and cobble. The analysis of sediment transport along Nantasket Beach includes this mixture of grain sizes. The sediment transport model includes an assessment of the potential mobilization of sediments of different grain sizes (i.e., the ability of the waves to initialize movement), as well as the amount of sediment available for transport. Specifically, simulations of sediment transport used the following two grain sizes based on USACE (2006): (1) a fine-to-medium grained sand having a d_{50}=0.25 mm, and (2) a coarse-grained pebble having a d_{50}=28 mm.

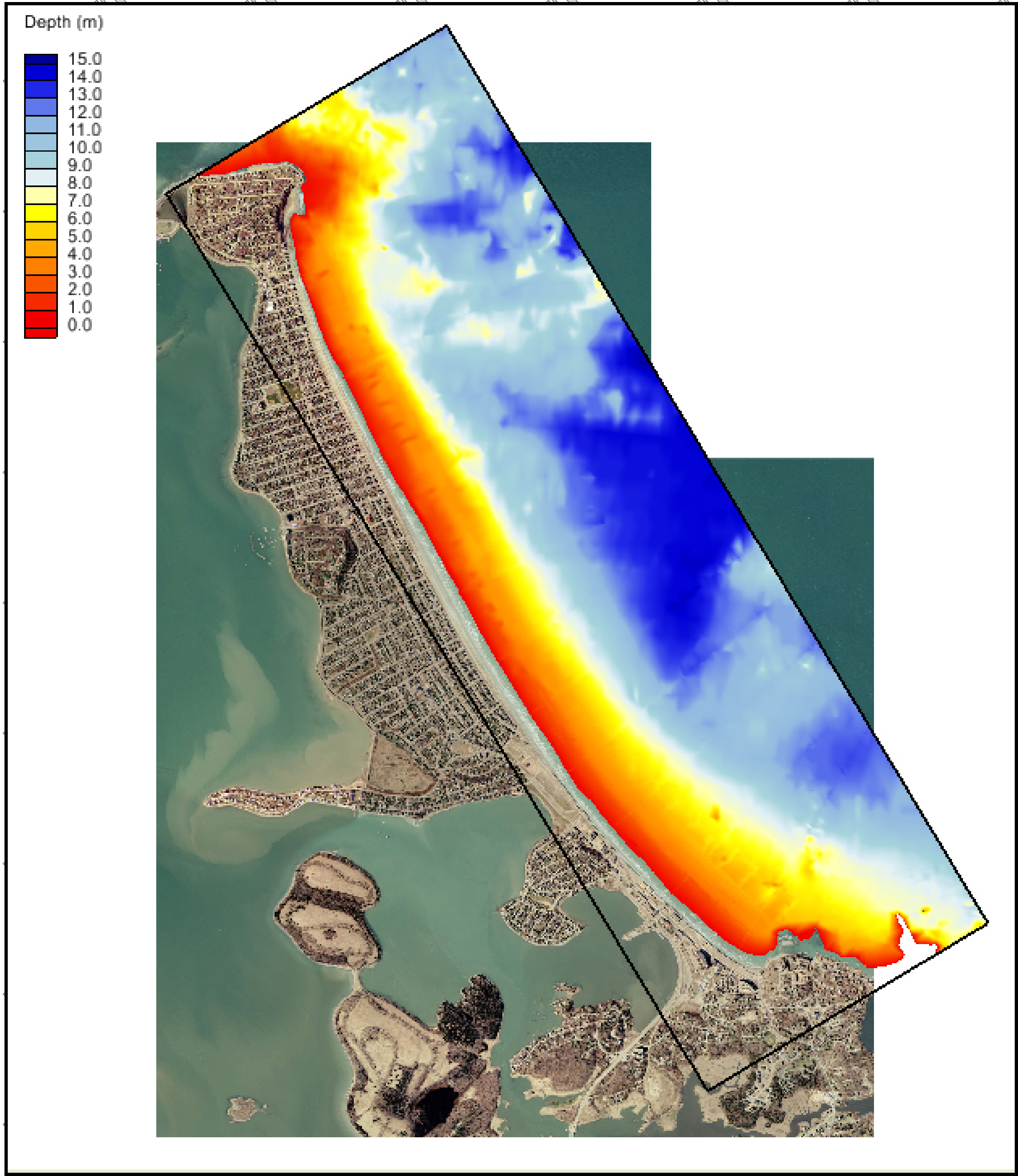

Figure 5-1. Nearshore, refined bathymetric grid for Nantasket Beach used in wave transformation and sediment transport models. Depth shown in meters relative to Mean Tide Level. Nopt for navigational purposes.

5.3 MODEL DESCRIPTION

As stated above, the sediment transport model used for the analysis of Nantasket Beach is a process-based model that uses standard steady-state, depth-averaged mass and momentum equations for the hydrodynamics, in conjunction with calculations of longshore sediment transport based on a methodology by Haas and Hanes (2004). The following subsections present in detail the model theory and formulation of the various model components, but it is not critical that the reader becomes familiar with the concepts presented below to understand the results of the modeling.

5.3.1 Hydrodynamic Component

<u>Governing Equations</u>

The wave-averaged, depth-integrated, mass-conservation equation for a constant-density fluid with a rigid lid is

$$\frac{\partial(Hu)}{\partial x} + \frac{\partial(Hv)}{\partial y} = 0, \qquad (5\text{-}1)$$

and the wave-averaged, depth-averaged momentum equations for a non-rotating system are

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -g\frac{\partial \eta}{\partial x} - \frac{ru}{H} + \frac{\tau_x}{(\rho H)} \qquad (5\text{-}2)$$

and

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -g\frac{\partial \eta}{\partial y} - \frac{rv}{H} + \frac{\tau_y}{(\rho H)}. \qquad (5\text{-}3)$$

Here x and y are the horizontal coordinates, t is time, u and v are the x and y components of the wave-averaged and depth-averaged horizontal velocity, g is the gravitational acceleration, η is the surface displacement, r is the bottom resistance coefficient, H is the water depth, ρ is the fluid density, and τ_x and τ_y are $-(1/H)\partial S_{xx}/\partial x - (1/H)\partial S_{xy}/\partial y$ and $-(1/H)\partial S_{xy}/\partial x - (1/H)\partial S_{yy}/\partial y$, respectively, where S_{xx}, S_{xy}, and S_{yy} are the components of the wave-induced radiation stress tensor (Mei, 1989).

A stream function (ψ), which defines the two-dimensional flow, can be defined by

$$(u,v) = H^{-1}\left(\frac{\partial \psi}{\partial y}, -\frac{\partial \psi}{\partial x}\right), \qquad (5\text{-}4)$$

which satisfies (5-1) identically, and an equation for the wave-averaged potential vorticity ξ, defined by

$$\xi = \frac{1}{H}\left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right) = -\frac{1}{H}\frac{\partial}{\partial x}\left(\frac{1}{H}\frac{\partial \psi}{\partial x}\right) - \frac{1}{H}\frac{\partial}{\partial y}\left(\frac{1}{H}\frac{\partial \psi}{\partial y}\right), \quad (5\text{-}5)$$

is obtained by taking the curl of (5-3) and (5-4) and dividing the result by *H*, which yields

$$\frac{\partial \xi}{\partial t} + u\frac{\partial \xi}{\partial x} + v\frac{\partial \xi}{\partial y} + \lambda\xi = \lambda\xi_0 + \frac{v_0 - v}{H}\frac{\partial \lambda}{\partial x} - \frac{u_0 - u}{H}\frac{\partial \lambda}{\partial y} \quad (5\text{-}6)$$

where $\lambda = r/H$, $u_0 = \tau_x/(\rho r)$, $v_0 = \tau_y/(\rho r)$, and $\xi_0 = H^{-1}(\partial v_0/\partial x - \partial u_0/\partial y)$.

In the present application, *H* is known, *r* is assumed to be given in the linear long wave approximation by $c_d[H_s/(4H)](gH)^{1/2}$ (e.g., Mei, 1983), and τ_x and τ_y are output from the wave transformation model. Here c_d = 0.003 is the drag coefficient for the surf zone under breaking waves (Feddersen et al., 1998) and *H* is the significant wave height, defined to be four times the standard deviation of the wave-induced oscillatory surface displacements, which is also given by the wave model. With this information, (5-4), (5-5) and (5-6) determine the coupled evolution of ξ, ψ, *u* and *v*.

Boundary Conditions

The coordinate system is defined so that *x* is positive onshore, $x = 0$ defines the offshore boundary of the computational domain, $y = 0$ and $y = L_y$ denote the alongshore boundaries of the computational domain, and the shoreline is a potentially irregular boundary in $x > 0$. In the present application, there can be only one shoreline, and *H* is restricted to be positive and nonzero everywhere in the domain. Boundary conditions are required for ψ on all boundaries and for ξ on inflow boundaries. The following boundary conditions are intended for applications in which the offshore boundary is well seaward of the surf zone and the shoreline at the alongshore boundaries is approximately straight and parallel to the *y* axis.

At the offshore boundary, the forcing and velocity fields are assumed to be weak, so that the alongshore velocity and potential vorticity are negligibly small and the offshore boundary conditions become

$$\frac{\partial \psi}{\partial x} = 0 \text{ and } \xi = 0 \text{ at } x = 0. \quad (5\text{-}7)$$

At the alongshore boundaries, the velocity field is assumed to be approximately confined to the *y* direction and approximately independent of *y*, so that the alongshore boundary conditions become

$$\frac{\partial \psi}{\partial y} = 0 \text{ and } \frac{\partial \xi}{\partial y} = 0 \text{ at } y = 0, L_y. \quad (5\text{-}8)$$

The shoreline is a streamline, so that ψ on the shoreline must be a constant, which may be set to zero, without loss of generality:

$$\psi = 0 \text{ on the shoreline.} \tag{5-9}$$

The shoreline is not an inflow boundary, so that the shoreline potential vorticity does not affect the solution.

Numerical Solution

Equations (5-4), (5-5) and (5-6) are solved by means of a standard numerical procedure described, for example, by Roache (1998). Spatial derivatives are represented using finite differences on a rectangular grid with equal spacing *dx* in the *x* and *y* directions. The representation of the spatial derivatives is second-order-accurate except that the advective terms in (5-6) are represented by a first-order upwind scheme. The time derivative in (5-6) is represented by an explicit first-order scheme with time step *dt*. The solution for each application begins from rest and advances in time until it reaches an asymptotic steady state. At each time step, the potential vorticity ξ is advanced according to (5-6), the elliptic equation (5-5) is then solved for the stream function ψ using Jacobi iteration (e.g., Lynch 2004), and finally the velocities *u* and *v* are calculated according to (5-4). Attainment of an approximate steady state requires that the solution advance until *t* is approximately equal to 3 times the maximum value of λ. Stability requires that the Courant number $(u^2+v^2)^{1/2}dt/dx$ based on the maximum flow speed be less than approximately unity.

5.3.2 Sediment Transport Component

Haas and Hanes (2004) proposed a simple formula for the alongshore sediment flux, which is, in the present notation,

$$q_s = \left(\frac{2c_1 c_d}{g}\right) < |\boldsymbol{u}|^2 > u_s \tag{5-10}$$

where q_s is the alongshore component of the sediment flux, c_1 is an empirical constant approximately equal to 1.3, brackets denote an average over many wave periods, $\boldsymbol{u}$ is the instantaneous velocity vector (including both the wave-induced oscillatory velocity and the current), and u_s is the alongshore component of the current velocity.

In the present application, $\boldsymbol{u}$ is assumed to be dominated by wave-induced oscillatory velocities and to be related to wave-induced surface displacement by linear long wave theory, so that $<|\boldsymbol{u}|^2>$ approximates $[H_s/(4H)]^2 gH$. In addition, a right-handed coordinate system (s,n,z) is defined so that *s* is locally alongshore, *n* is locally shore-normal, and *z* is vertical and positive upward. In this coordinate system, $Hu_s = \partial\psi/\partial n$. Equation (5-10) can therefore be written as:

$$q_s = 2c_1 c_d \left[\frac{H_s}{4H}\right]^2 \frac{\partial \psi}{\partial n} \tag{5-11}$$

In the surf zone, H_s/H is approximately constant (H_s/H < 0.63 is explicitly assumed by STWAVE), so that (5-11) can be integrated with respect to *n* across the surf zone to yield

$$Q = \frac{c_1 c_d}{8}\left[\frac{H_{sb}}{H_b}\right]^2 \psi_b \tag{5-12}$$

where *Q* is the alongshore sediment flux integrated across the surf zone and subscript *b* denotes evaluation at the break point, (i.e., at the seaward edge of the surf zone). In the present application, (5-12) is used to determine the sediment flux integrated across the surf zone after the stream function has been computed from the hydrodynamic component.

In determining sediment mobility, the threshold for mobility was established using the criterion parameter θ_{cr}, defined by Soulsby (1997) as:

$$\theta_{cr} = \frac{0.30}{1+1.2D_*} + 0.055\left[1-\exp\left(-0.02D_*\right)\right] \tag{5-13}$$

where D_* is the dimensionless grain size given by:

$$D_* = \left[\frac{g(s-1)}{\nu^2}\right]^{1/3} d_{50} \tag{5-14}$$

with *g* being the acceleration due to gravity, ν is the kinematic viscosity of water, d_{50} is the median grain size, and $s = \rho_s/\rho$.

The computation of the maximum bed shear stress due to the combined waves and currents, employed the algebraic expression by Soulsby (1997), which best fits the analytical model of Grant and Madsen (1979). The drag coefficient c_d of steady current in absence of waves and the wave friction factor f_w for waves in absence of current were determined as:

$$f_w = 1.39\left(\frac{A}{z_o}\right)^{-0.52} \tag{5-15}$$

$$c_d = \left[\frac{\kappa}{1+\ln(z_o/h)}\right]^2 \tag{5-16}$$

where $A=U_wT/2\pi$, the bed roughness length $z_o=d_{50}/12$, $\kappa=0.40$ is von Karman's constant, and *h* is the water depth.

5.4 Sediment Transport Results

5.4.1 Average Annual Directional Approaches

This section discusses the use of the regional wave model in determining the nearshore hydrodynamics, and subsequently the average annual sediment flux (i.e., the rate of sediment moving along the coast) along Nantasket Beach between Point Allerton and Atlantic Hill. The computed sediment transport rates are presented for the average annual wave conditions for the evaluated directional approaches.

The regional wave modeling results (Chapter 4) were used as input into the non-linear sediment transport model. Wave results from each of the average annual directional spectra bin simulations were used to develop the complete summary of sediment movement for various wave conditions. Simulations of sediment transport were conducted using a multi-grain size representation (d_{50}=0.25 mm and 28 mm) and the results were assessed to define the average annual sediment transport regime throughout the Nantasket region.

Model simulations were performed for the wave conditions represented by the directional bin spectra presented in Table 4-2. Figure 5-2 illustrates the sediment transport results for waves approaching from the northerly (351.5 to 14 degree) approach bin. Northwest (Point Allerton) is located towards the top of the plot; southeast (Atlantic Hill) is located to the bottom of the plot. Figure 5-2 presents the local bathymetry (left hand panel), the resultant wave height from the regional wave transformation model (center panel), and the associated sediment flux (right hand panel). The sediment flux represents the rate of sediment moving along the coast. Negative values indicate movement towards the northwest (from bottom to top of the figure); positive values indicate movement towards the southeast (from top to bottom of the figure). The rates are presented in units of 100,000 cubic yards per year (cy/yr) and can be used to quantify the annual sediment transport at Nantasket Beach. These calculations assume that sediment is available on the beach for transport (e.g., potential transport). If the shoreline is armored (e.g., revetment), or doesn't have a sediment source readily available, then the sediment transport rates may vary compared to the values presented herein.

As is expected for this northerly wave approach scenario, the sediment flux in Figure 5-2 shows sediment transport in a southeast direction along nearly the entire stretch of Nantasket Beach (i.e., a positive sediment flux corresponds to sediment transport from the top of the plot [Point Allerton] towards the bottom of the plot [Atlantic Hill]). The sediment transport rate is reduced relative to the rest of the beach just south of Point Allerton, due to the wave sheltering provided by the rocky formation. Advancing towards the southeast, the rate of gross transport increases, varying between 38,000 and 76,000 cy/yr, with the maximum reaching near 92,000 cy/yr.

As was presented in Table 4-2, this approach direction (351.5 to 14 degrees) contains a low amount of wave energy and has a small percentage of occurrences, and therefore produces smaller rates of sediment transport compared to other approach directions. This directional approach was shown to clearly indicate how the directionality of the transport correlates with the directionality of the waves. This represents only a single approach direction, and is only representative of times when waves are arriving from the north. All approach directions must be evaluated and aggregated to determine the net sediment transport movement at Nantasket Beach.

Figures 5-3 and 5-4 display the sediment transport model results from two additional wave approach directions, the northeast (36.5 to 59 degree bin) and east (81.5 to 104 degree bin), respectively. As in Figure 5-2, the local bathymetry is presented in the left hand panel, the resultant wave height is shown in the center panel, and the associated sediment flux is shown in the right hand panel. The results presented in Figures 5-3 and 5-4 correspond to the wave model results presented in Figures 4-18 and 4-20, respectively. Figure 5-3 illustrates model results for the wave directional bin having the most wave energy, as indicated by the larger wave heights. Sediment transport for this northeasterly wave direction is again primarily directed towards the southeast; however, the transport rates are much larger. The largest sediment transport rates exist just south of Harding Ledge (Figure 4-8) where the larger waves are also shown to exist. Moving in a southeasterly direction, although the net transport along the DCR reservation is to the southeast, there are areas along the DCR reservation where the transport is directed to the northwest. These changes in direction of transport point to areas where there is either the divergence (erosion) or convergence (accretion) of sediments. These abrupt changes in the directionality of sediment transport along the DCR reservation are an indication the shoreline in this area is dynamic with an active migration of sediments.

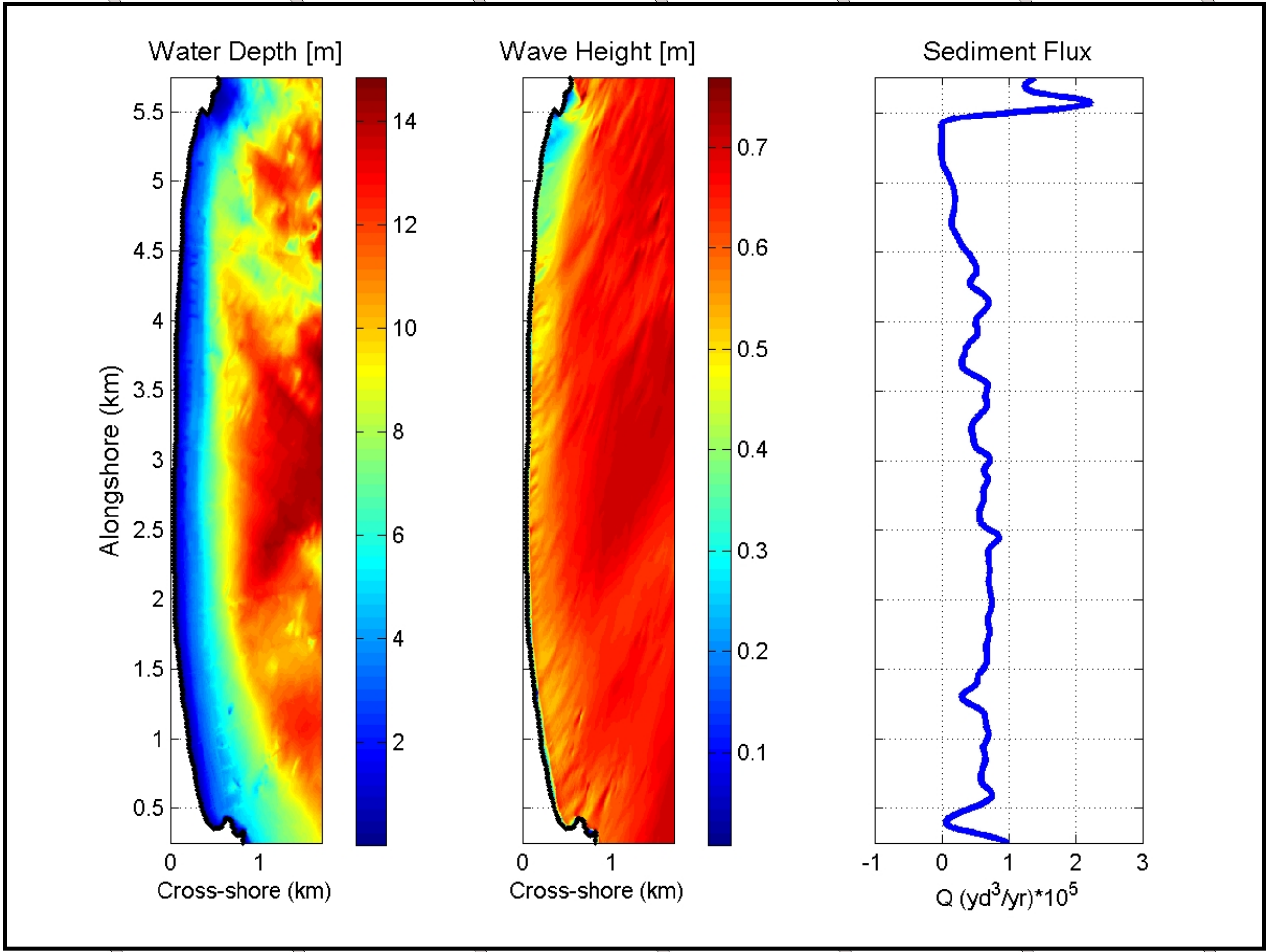

Figure 5-2. Sediment transport model results for a northerly wave approach (351.5 to 14 degrees). Water depth and wave height in meters.

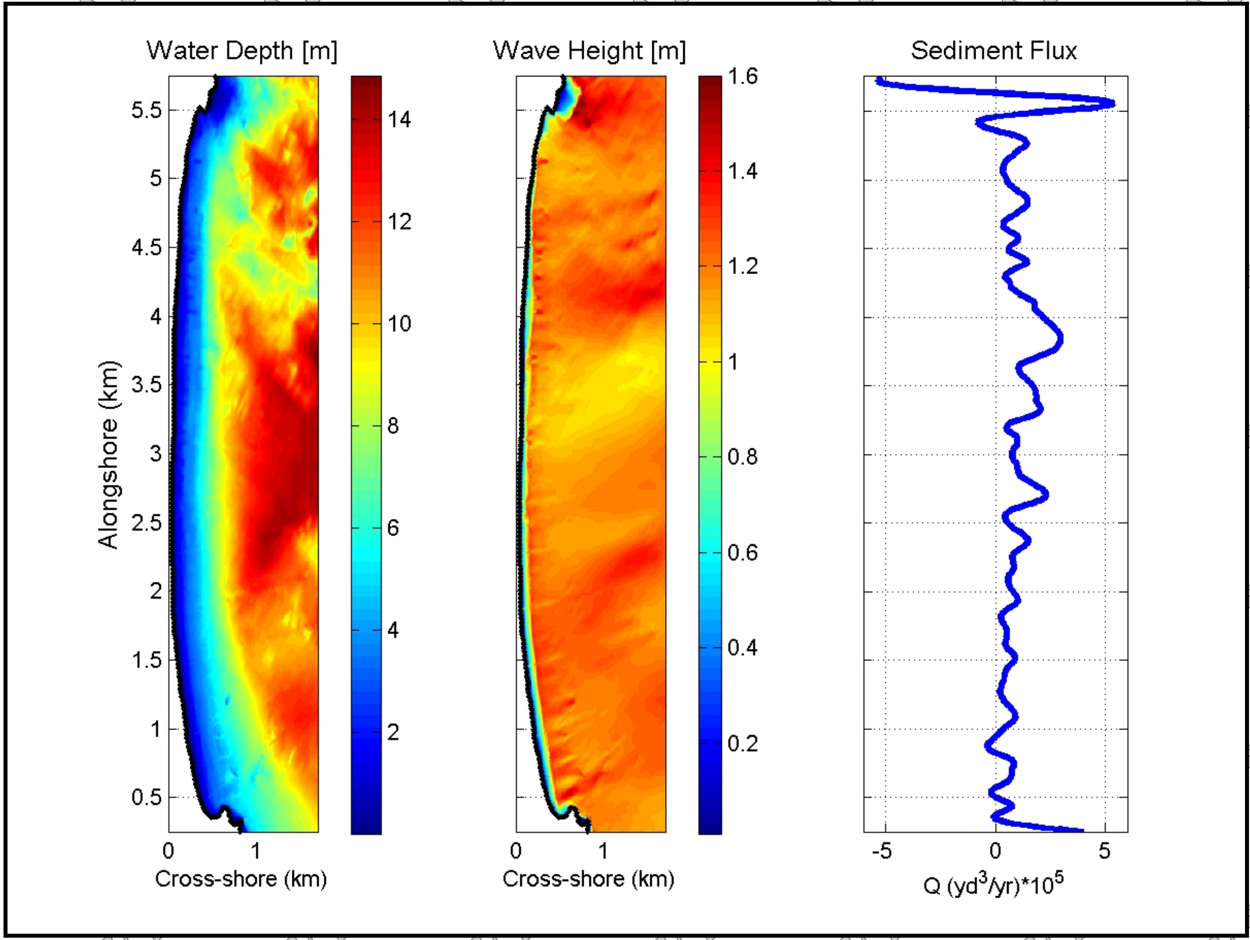

Figure 5-3. Sediment transport model results for a northeasterly wave approach (36.5 to 59 degrees). Water depth and wave height in meters.

Figure 5-4 represents a more easterly wave approach and the sediment transport rate is predominantly from the southeast to the northwest, as would be expected for this approach direction. This wave-directional bin (81.5 to 104 degrees) is the predominant wave direction for Nantasket Beach with the largest percentage of occurrence. In general, waves approaching from the east have an angle that is sufficient to drive the hydrodynamics necessary for sediment transport to the northwest.

Gross sediment transport rates vary significantly for the various average annual approach directions, and reach a maximum of 400,000 cy/yr. The magnitudes of the gross sediment transport rates provide an indicator of the wave energy associated within each wave approach direction.

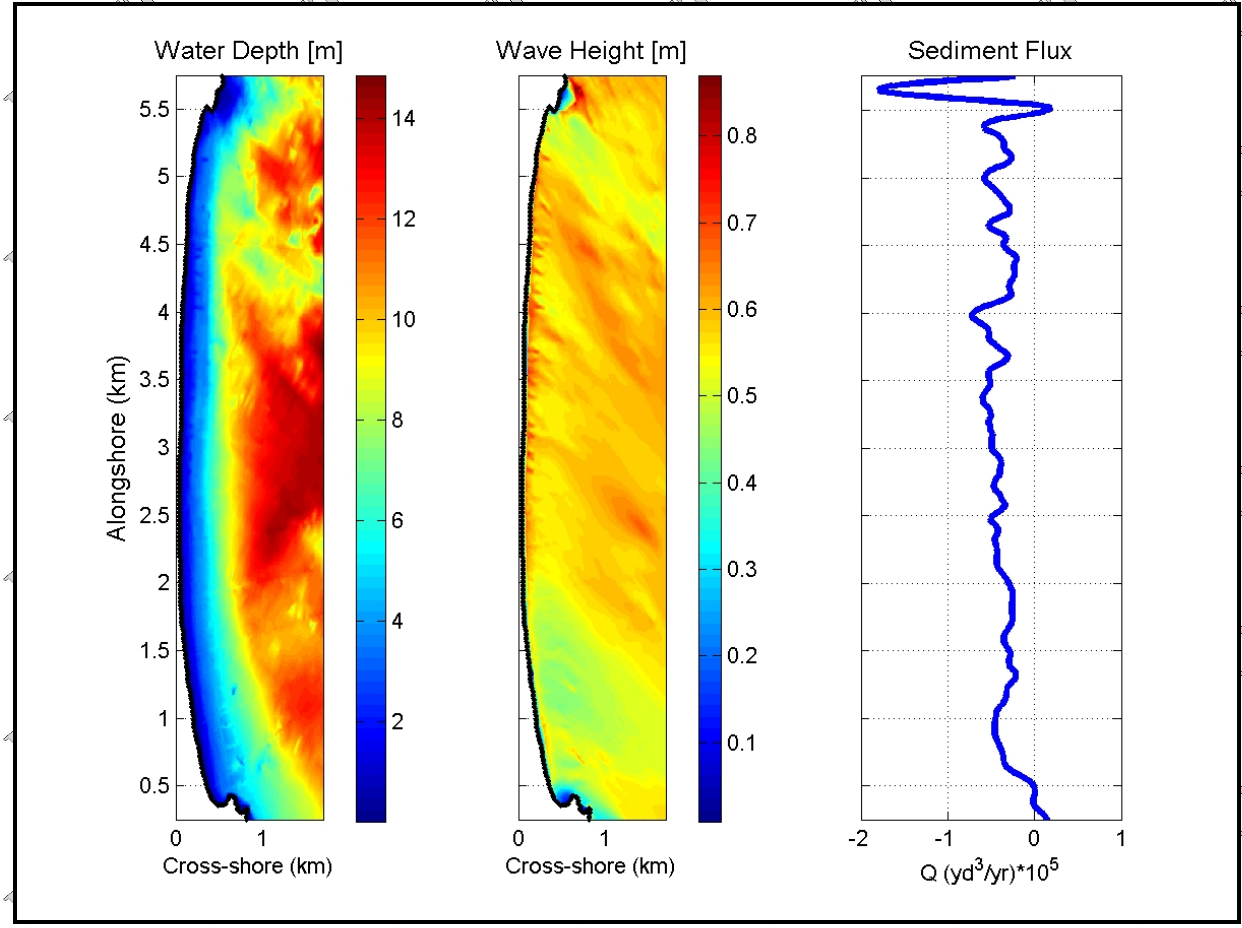

Figure 5-4. Sediment transport model results for an easterly wave approach (81.5 to 104 degrees). Water depth and wave height in meters.

The sediment transport results presented discussed so far focus on single spectral, directional distributions of wave energy. To accurately represent what occurs over an average year, the various wave scenarios need to be combined to represent an average year of wave climate. Using the percent occurrence of wave approach (Table 4-2), the average annual approach directions were normalized and combined to determine the net longshore transport rate. Figure 5-5 presents the average yearly sediment flux determined using the mixed grain size approach. The vertical axis represents distance alongshore. The DCR portion of Nantasket Beach is therefore located toward the bottom of the figure, while Allerton Hill is at the top of the figure. Figure 5-5 presents the local water depth (left panel) from the regional wave transformation model and the associated sediment flux (right panel). The sediment flux represents the rate of sediment moving along the coast; where negative values indicate movement toward the north/northwest (from bottom to top of the figure), and positive values indicate movement toward the south/southeast (from top to bottom of the figure). This rate is presented in units of m^3/yr and can be used to quantify the annual sediment transport in reaches along Nantasket Beach. The solid black line shown in the sediment flux figure is a fit of the flux results, indicating the general movement of sand along the coastline.

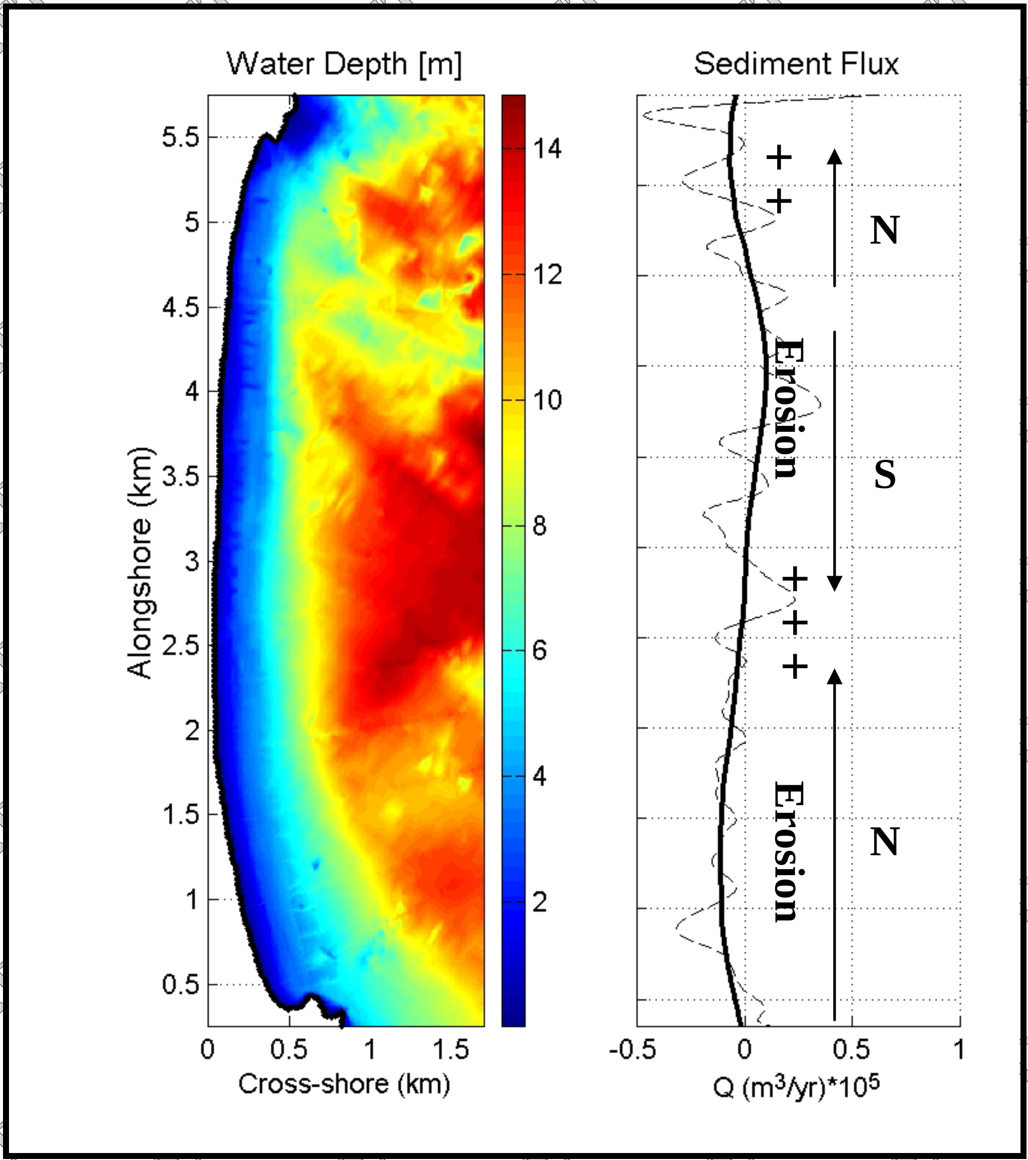

Figure 5-5. Sediment flux results for an average annual year at Nantasket Beach. Water depth in meters.

The sediment flux indicates that, along the southern portion of Nantasket Beach (0.5 to 3.0 km alongshore), the average annual longshore transport is directed to the northwest (negative flux value) at an average rate of approximately 4,060 cy/yr, with maximum rates ranging from 10,000 cy/yr to 50,000 cy/yr. The center portion of Nantasket Beach (3.0 to 4.5 km alongshore) experiences sediment transport to the southwest at an average annual rate of approximately 3,800 cy/yr, while the northernmost section of Nantasket Beach (4.5 to 5.5 km alongshore) indicates transport to the northwest at a minor mild rate. As such, net sediment transport along the Nantasket shoreline is relatively small and is directed towards the north/northwest. These relatively small transport rates, and reversals in transport direction along the shoreline, support the historically relatively stable nature of the Nantasket Beach shoreline, as presented in Chapter 3. For example, the northward sediment transport ranges from 10,000 to 50,000 cy/yr in the

DCR portion of Nantasket Beach (as shown in the dashed line). This is a relatively small flux of sediment, indicating that on an annual basis, not much sand is moved to either the north or the south.

The movement of sediment is further illustrated by the arrows expressing direction of sediment transport, as well as the subsequent convergence and divergence of the flux (creating areas of accretion and erosion, respectively). As shown, the sediment in the DCR portion of Nantasket Beach is transported to the north, and since there is no major source of sediment to the beach (due to the Atlantic Hill headland), an area of erosion is created. North of the DCR portion of the beach, there is an area of accretion (identified by '+++' on Figure 5-5) caused by a convergence of southward and northward moving sediment. The model also indicates a region of erosion north of the accretion near the center of Nantasket Beach, and an area of accretion at Allerton Hill (identified by '++' on Figure 5-5).

In general, the larger-sized cobble material is not mobilized during a majority of the average annual wave conditions. The more commonly occurring, but less energetic, wave approach directions arriving from the east and east-southeast (Table 4-2) are not capable of mobilizing the cobble material. During these conditions, only the sand portion of the beach is mobilized and transported to the north-northwest. The cobble component of the distribution is only mobilized during the more energetic wave conditions (e.g., northeast north-northeast). During these conditions, both the sand and cobble components are mobilized and transported to the southeast. In addition, during storm events, which also typically arrive from the northeast, both cobbles and sand are mobilized to the southeast. Therefore, in the alongshore direction at Nantasket Beach, cobbles are more consistently transported to the southeast, while the net movement of sand is more consistently to the northwest. This dissemination of the natural sediment distribution at Nantasket Beach is consistent with the observations of sediment types at the beach, where relatively more cobble based material is generally located in the southeast portion of Nantasket Beach, while the northwest portion of Nantasket Beach contains relatively more sand (USACE, 2006).

The sediment transport results were also compared to the historical shoreline change rates to determine the relative performance of the model. Figure 5-6 overlays the model sediment flux results against the historic rates of shoreline change. The red line indicates the sediment flux results, while the black line shows the historic rate of shoreline change (in terms of ft/yr). Negative values of sediment flux (red line) indicate movement of sand to the north, while positive values of sediment flux indicate movement of sand to the south. Negative values of shoreline change indicate erosion, while positive values indicate accretion. The areas of erosion and accretion shown in Figure 5-5 (caused by the convergence and divergence of the flux) match the observed shoreline change well. For example, sand moving from the southeast to the northwest in the DCR portion of Nantasket Beach would result in a loss of sediment in this region, therefore, the observed erosion that occurs in this region.

5.4.2 Representative Year Simulation

In addition to the average annual directional bin cases, a 1-year simulation of longshore sediment transport was conducted to provide additional insights into the wave–driven transport patterns in the vicinity of Nantasket Beach. Results from the representative yearlong STWAVE simulation (see Section 4.4.2.2) were used as input conditions to the sediment transport model. Hourly results of sediment transport flux were compiled for the year long simulation and then summed to give an annual rate of transport for the representative year. Figure 5-7 shows the representative year (1987) sediment flux (red line in right hand panel), and results show similar trends to the average year simulations.

Figure 5-6. Sediment transport flux from modeling results (red line) compared to historic rates of shoreline change (ft/yr black line).

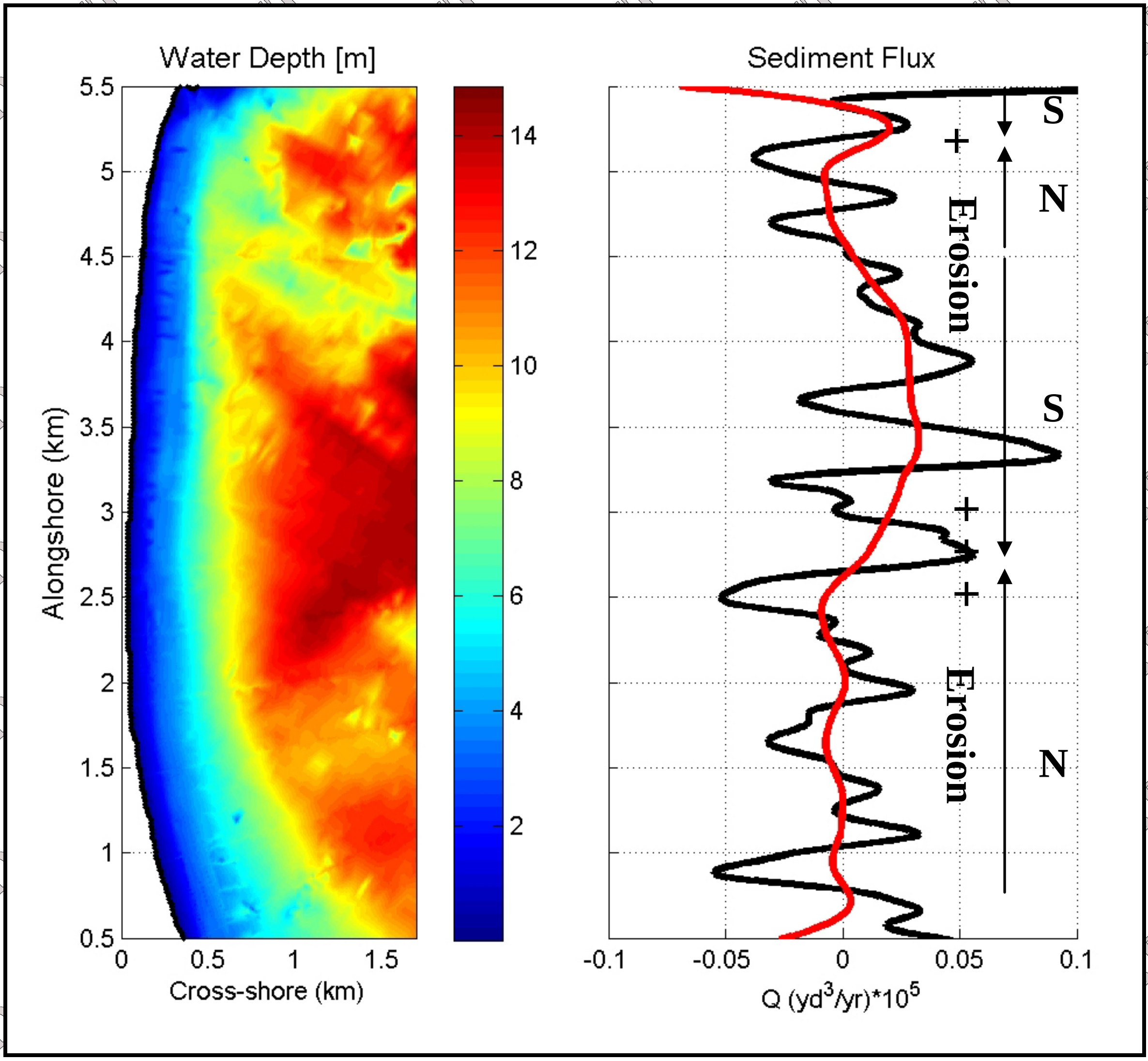

Figure 5-7. Representative year sediment flux for Nantasket Beach. Water depth in meters.

5.4.3 Sediment Transport during Storms

In order to put in context the amount of material that may be temporarily moved during a significant storm event, the sediment transport model was also used to evaluate the sand movement for significant storm events. For example, during a 10-year storm event, sediment transport rates average 60,000 cy/yr to the southeast, with maximum flux rates exceeding 200,000 cy/yr. This is significantly larger than the average annual conditions. Similarly, for the 50-year case, sediment transport flux rates average approximately 800,000 cy/yr, with maximums of over 2,000,000 cy/yr. Although these storms obviously don't last an entire year, and therefore move only a fraction of that amount, these high-energy storm events result in a significant amount of sediment movement at Nantasket Beach and play an important role in the overall consideration of alternatives for erosion mitigation. For example, a 1 day 50-year storm event could transport as much or more material as an entire average year (approximately 2,000 cy).

6.0 DEVELOPMENT OF ALTERNATIVES

Ocean waves, currents, tides, storm surges, and relative sea-level rise contribute to the erosion of sandy shorelines and the destruction of coastal property. Traditionally, attempts to combat these erosional pressures consisted of hard structures, such as groins, breakwaters, seawalls and revetments, and/or soft solutions such as artificial beach fills. Each of these established erosion mitigation measures has proven effective when used under favorable conditions; yet, none is suitable for every location, and implementation under the wrong conditions may have severe negative impacts on a coastal community.

During the past several years, new shoreline erosion mitigation measures have been developed; these measures are often referred to as alternative technologies. In the context of this analysis, the term alternative technology refers to any erosion control measure that has not been extensively used in the northeastern United States. Dozens of alternative technologies have been implemented throughout the United States during the past several years; however, only a few have proven to be effective. Many of these technologies are based on principles similar to more accepted engineering methods. Some alternative technologies are based on sound scientific principles, and for certain conditions will induce accretion along a beach face. However, care should be exercised in applying these methodologies since each stretch of shoreline is unique. In the following sections, the more promising of these methods of erosion control have been evaluated.

Decisions regarding management of shoreline erosion at Nantasket Beach can only be made after a thorough evaluation of available erosion mitigation alternatives. The following chapter describes a variety of established coastal engineering methods for erosion mitigation, as well as several less traditional approaches. The ideas upon which these methods were developed are explained, and their particular application at Nantasket Beach is discussed. Therefore, this chapter provides the preliminary alternatives analysis for Nantasket Beach by evaluating a range of commonly used coastal protection alternatives.

6.1 OVERVIEW

An alternatives analysis is the basis for determining the optimal solution and assessing potential impacts, both physical and environmental. A variety of factors are considered when evaluating the various alternatives (e.g., cost, feasibility, performance, environmental impacts, constructability, etc.), with the overall objective focused on selecting the optimal solution. As such, the goal of the assessment is to evaluate reasonable, practicable, and feasible alternatives that will achieve the goals and objectives of the project, while minimizing the short and long-term adverse effects, if any. The alternatives analysis procedure developed for Nantasket Beach, including a comprehensive list of the alternatives evaluated and the alternatives developed for more comprehensive evaluation, is presented in this chapter.

The studied alternatives were geared towards determining a long-term solution for creating and maintaining a functional recreational beach, improved storm damage protection for upland infrastructure, and fitting within the overall Master Plan for the DCR reservation property. Ultimately eight specific alternatives, including both structural (e.g., revetment, seawall, etc.)

and non-structural (e.g., retreat, beach nourishment, etc.) were determined jointly between the Department of Conservation and Recreation (DCR), the Town of Hull, the Citizens Advisory Committee (CAC) for Nantasket Beach, the Louis Berger Group, Inc. (Berger), and the Woods Hole Group (WHG). These alternatives are presented in Section 6.3 and were developed to work in concert with the existing coastal protection measures, while meeting the goals of the community for Nantasket Beach.

The alternatives were chosen at a meeting on January 31, 2007, during which all viable long-term solutions were discussed and considered, and an initial series of site-specific alternatives were selected for analysis that were developed as the most feasible solutions for the DCR portion of Nantasket Beach. Careful consideration was given to all factors associated with each alternative. For example, potential impacts on the neighboring shoreline, engineering feasibility, likelihood of success, cost, etc. were all considered in the final selection process. All members of the alternative development team (DCR, Berger, and WHG) agreed upon the final alternatives that were selected for consideration. The evaluation of these alternatives is presented in greater detail in Chapter 7.

6.2 Typical Coastal Protection Alternatives

Prior to the development and selection of the final alternatives to be assessed in the detailed alternatives analysis, a range of traditional coastal protection alternatives were considered to determine potential solutions that may be feasible at Nantasket Beach. These alternatives, in addition to the no action alternative, were considered in the initial evaluation of potential solutions for Nantasket Beach. Types of alternatives that were considered included:

- No action
- Non-structural "soft" solutions (beach nourishment, dune reconstruction, nearshore berms)
- Structural "hard" solutions (revetments, groins, jetty modifications, breakwaters, and seawalls)
- Combinations of solutions (perched beach, beach nourishment with groins, etc.)
- Alternative technologies (beach dewatering, nearshore berms, submerged offshore reefs, and other alternative technologies)

Table 6-1 presents a list of the alternatives that were considered in the preliminary analysis. The table identifies if the alternatives were established shore protection methods (standard) or alternative technologies (non-standard), hard or soft solutions, and if they could be applicable at Nantasket Beach.

Table 6-1. Alternatives considered in the preliminary alternative analysis procedure.

Alternative	Method	Hard/Soft	Applicable for Nantasket
No action	N/A	N/A	No
Retreat/relocate	N/A	N/A	Maybe
Beach nourishment	Established	Soft	Yes
Perched beach	Alternative	Hard	No
Dune Reconstruction	Established	Soft	Yes
Revetments and seawalls	Established	Hard	Yes
Groins	Established	Hard	No
Breakwaters	Established	Hard	No
Beach dewatering	Alternative	Hard	No
Nearshore berms	Alternative	Soft	No
Offshore reefs	Alternative	Hard	No
Other alternative technologies	Alternative	Hard	No

6.2.1 Passive Alternatives

No Action

The no action alternative implies there would be no change to the present conditions at Nantasket Beach. This alternative is considered unacceptable by the project team as the existing seawall is currently at risk for failure in certain areas, the existing shorefront would continue to be eroded, a sustainable recreational beach would not exist, no protective action would be taken, and the upland infrastructure would face increased risk for potential damage or loss. The current water-dependant function of the Reservation would be compromised as the beach would not be maintained. Therefore, the "no action" alternative was not recommended; however, it is considered in the more detailed alternatives analysis (Chapter 7) as a baseline comparison for the other alternatives.

Retreat/Relocation

This alternative is similar to the no action alternative in that the beach is allowed to continue to erode; however, the seawall would either be removed or relocated further landward. This would directly impact current parking facilities, as well as some reservation infrastructure (MJM bathhouse) and local businesses. This retreat option may be combined with other coastal protection alternatives/techniques to create additional beach seaward of the removed or relocated seawall. Changes to the utilities and parking lot would also occur to account for the new structure location. Variations of this potential alternative were considered for further evaluation and details are presented in Section 6.3.

6.2.2 Established Shore Protection Alternatives

Beach Nourishment

One of the primary causes of coastal erosion is a deficit of sediment within the coastal littoral cell. To offset this deficit, nourishing the beach with compatible sediment placement is a logical means for improving the longevity of the shoreline where such a project is economically feasible. Beach nourishment does not stop erosion. Rather, the beach width is increased, recreational area is improved, and potential damage to upland infrastructure is postponed by extending the shoreline toward the ocean. As such, periodic renourishment must be anticipated. At a site like Nantasket Beach, the increased beach area also provides a major recreational and economic stimulus benefit.

Beach nourishment is typically the most non-intrusive technique for coastal protection and involves placing sand, from an offshore or upland source, in a designed template on an eroding beach. Figures 6-1 and 6-2 present examples of beach nourishment projects being constructed. Beach nourishment is intended to widen the beach, as well as provide added storm protection, increased recreational area, and in some cases, added habitat area. Although nourished sand is gradually displaced alongshore or transported offshore, the nourished sand that is eroded takes the place of the upland area that would normally have been lost or eroded during a storm event. Therefore, beach nourishment serves a significant role in storm protection. In addition, beach nourishment is the only alternative that introduces additional sand into the system. For coastlines with a dwindling sediment supply, such as Nantasket Beach, this is critical for long-term success. Solutions that do not involve beach nourishment typically involve rearranging the existing sand in a manner that will only benefit a portion of the beach or provide hardened protection that does not offer an improved beach area with no longevity.

Environmental concerns with beach nourishment projects include the potential for temporarily decreased water quality when sediments are dredged and deposited, and disturbing natural habitat when removing or depositing the dredged material. These concerns can be addressed by adhering to dredging time windows that avoid periods of shellfish, finfish, and shorebird activity. Grain size compatibility between the borrowed and native beach sediments should be maximized in order to avoid disturbance of nearshore resources such as shellfish and submerged aquatic vegetation, as well as to increase the lifespan of the nourished beach. For example, large differences in grain size between the native and borrow material may lead to changes in beach slope through natural adjustment of the new grain size introduced to the beach.

The many benefits of beach nourishment, and the ability to control environmental impacts with careful design and planning, make beach nourishment a viable alternative for the Nantasket Beach area. A beach fill project for this area would mitigate the on-going erosion, improve storm damage prevention and flood protection to infrastructure, and improve the recreational resource of both the DCR and neighboring beaches.

Figure 6-1. Beach nourishment project under construction.

Figure 6-2. Beach nourishment project under construction in Virginia Beach, VA (photo courtesy of Virginia Beach).

Beach nourishment was recommended for further evaluation, and a range of potential design layouts, including various lengths, beach widths, etc., are detailed further in Chapter 7. In addition, beach nourishment was also considered in concert with several other alternatives since nourishment meets a critical need for Nantasket Beach by providing a functional, useable beach during all stages of the tide.

Perched Beach

A perched beach is an alternative method of sand placement designed to reduce the amount of sand required, and to help retain the material for a longer time period. The nourishment volume is reduced by using a submerged sill to hold up or "perch" the beach above the natural bottom, significantly reducing the amount of sand required for beach construction and maintenance. The submerged sill is also designed to limit the loss of nourished sand seaward of its location. A perched beach is no longer solely a soft solution (e.g., beach nourishment only), since the sill is typically composed of rocks. Figure 6-3 presents a schematic drawing of a perched beach, while Figure 6-4 shows an example of a perched beach on Martha's Vineyard, MA decades after construction. The perched beach is not a common engineering solution implemented in the US and there is limited design information available. The USACE has recently indicated that model studies and calculations of life-cycle costs demonstrated that a perched beach was as expensive as repeated beach nourishments with no sill construction over a 30-40-year period (USACE, 2003). The perched beach alternative is not recommended for further evaluation at Nantasket Beach, since this would significantly change the beach usage. Although a perched beach can provide significant storm damage protection, it is not an ideal solution for a recreational beach setting. Swimming and water based activities become unsafe in such a setting, due the large rocks offshore that are hidden from view.

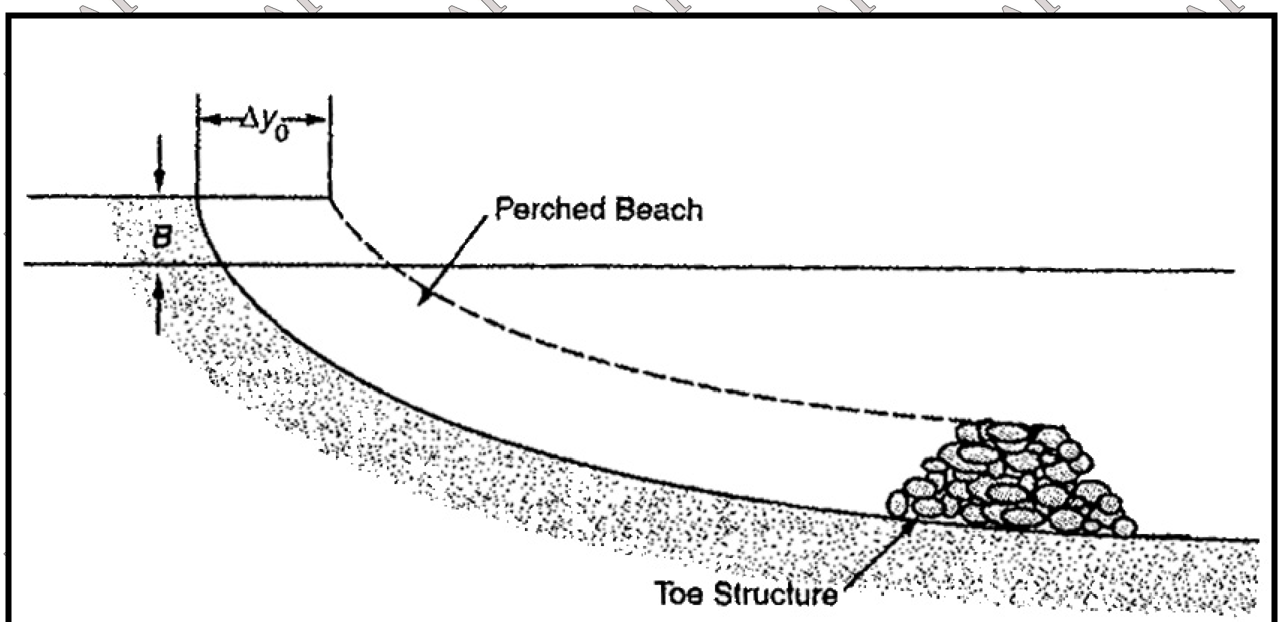

Figure 6-3. Schematic of a perched beach with a rubble mound sill. B is the berm height and Δy_0 is the increase in berm width (Dean and Dalrymple, 2002).

Figure 6-4. Example of a perched beach in Martha's Vineyard, MA. The perched beach has eroded behind the sill and is in need of replenishment.

Dune Reconstruction

Dune reconstruction is a rebuilding of the dunes landward of the beach. Protective dunes are useful when combined with nourishment distributed over the beach face. A coastal dune provides a vertical buffer that protects the landward property from storm waves. Additionally, the coastal dune provides a source of sediment for the beach as it slowly erodes during larger wave events. Figure 6-5 presents an example of a dune reconstruction project. Construction of a dune, which currently does not exist along the DCR portion of Nantasket Beach, is complicated due to the presence of the seawall and overall space restrictions. A dune could be placed in front of the existing seawall, or the seawall could be removed or relocated to allow for placement of a coastal dune similar to those located along the northern portions of Nantasket Beach. Dune reconstruction, by itself, is not recommended for DCR portion of Nantasket Beach; however it was combined with potential other alternatives in the overall alternatives assessment.

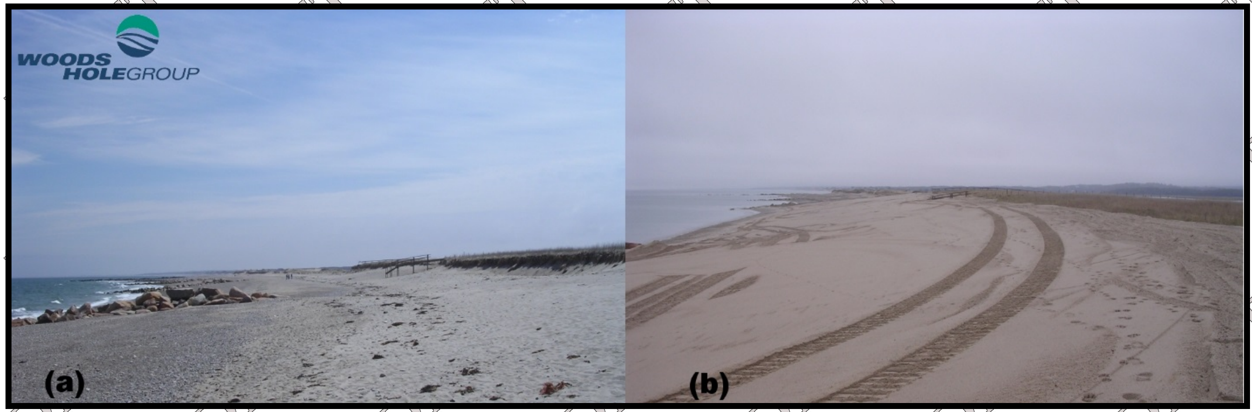

Figure 6-5. Example of a dune reconstruction project in Sandwich, MA (a) pre-construction, and (b) post-construction.

Revetments and Seawalls

Seawalls and revetments separate land from water, with the primary function of reducing wave energy and protecting the upland from the erosional forces of waves and currents. Seawalls are typically vertical structures (Figure 6-6), constructed with steel sheets or concrete. Revetments are sloping (Figure 6-7), constructed of concrete or quarry stones. Higher energy environments generally dictate the use of a seawall instead of a revetment or combination. These two types of structures interact with the nearshore littoral processes in a similar fashion. The DCR portion of Nantasket Beach currently has a seawall and/or revetment that span part of the beach.

Unlike groins and breakwaters, which may protect adjacent updrift beaches or improve the longevity of a beach fill, seawalls and revetments only protect the land directly behind them. If there is no beach fronting the structure, or if the beach is overtopped by storm flooding and wave action, a continual lowering of the profile in front of the structure will generally occur. This is due to the magnified erosional forces of the waves as they reflect from the structure, and to the loss of bank or dune sediments protected by the wall, that otherwise could help replenish the fronting beach. In addition, toe scour and flanking at the ends of the wall may threaten the structure itself as erosion continues. Additional forces threatening the structure may be induced if the structure is overtopped, as soil becomes saturated and soil pressure is increased behind the wall and reduced by scour in front of the wall.

Considering these complications, a seawall or revetment can benefit the natural coastal environment and the adjoining upland property if the elevation of the structure is sufficiently high to prevent regular wave overtopping and deep enough to resist scour and toppling. With a beach fronting a seawall or revetment to provide wave energy dissipation, the structure can provide protection from rare severe erosive forces. Installing a seawall often requires additional measures to build and maintain a beach in front of the structure. Typically, the combined costs of beach maintenance and seawall construction would be economically prohibitive. However, since the DCR reservation already has a significant seawall and/or revetment structures in place, the continued maintenance of the seawall and/or improvements to these existing structures is a reasonable alternative to consider. Also, given the highly developed nature of the area landward of the exiting seawall and the urban setting of Nantasket Beach, these structures offer much needed storm damage protection that could not be achieved by a natural beach alone. Multiple seawall and revetment alternatives, and combinations with other alternatives, were considered in more detail for Nantasket Beach. These alternatives are presented in Section 6.3 and evaluated in Chapter 7.

Groins

Groins are typically constructed of rubble mound or wooden bulkhead, and are structures built perpendicular to the shoreline. In an environment with longshore sediment transport, a groin reduces erosion by trapping sand in the form of a fillet on the updrift side, although there is usually erosion on the downdrift side. This erosion/accretion trend is shown in Figure 6-8. Often, several of these structures are constructed consecutively along the shore to form a groin field. Since groins may inhibit longshore sediment transport, a groin field is most effective when the downdrift limit is a natural sediment sink, such as a tidal inlet or a naturally terminating headland. Otherwise, the construction of groins may result in severe erosion of the adjacent downdrift beach by denying the natural longshore sediment transport. Additionally, construction of groins typically results in some swapping of a footprint of nearshore habitat area from sandy beach to rocky intertidal in the locations where the groins are constructed.

Figure 6-6. The seawall along the DCR portion of Nantasket Beach.

Figure 6-7. Revetment located along the DCR portion of Nantasket Beach.

Figure 6-8. Existing groin showing updrift accretion fillet (left side of groin) and downdrift erosion zone (right side of groin). These shoreline conditions are typical in areas of groins.

Specific groin types that were considered at Nantasket Beach were groin fields (a series of groins along the shoreline), a terminal groin (a singular groin located at the downdrift end of a beach nourishment), and "T-head" groins. T-head groins are comprised of a standard shore perpendicular groin fitted with a shore-parallel T-head at their seaward end. The T-head is often built to interrupt the seaward flow of water and sand in rip currents that often develop along a groin's axis. The T-head may also act as a breakwater and shelter a sizeable stretch of beach behind it. This alternative would attempt to hold the beach nourishment in place by preventing losses in both the seaward and alongshore directions. In addition, the T-heads would afford additional wave protection by breaking wave energy.

When implemented under favorable natural processes, a properly designed groin or groin field can be effective in preventing beach erosion. However, natural conditions that are conducive for successful groin implementation, such as a sufficient sand source and dominant direction of longshore sediment transport, do not exist everywhere. Groins are not recommended for use at Nantasket Beach since they would significantly interfere with beach and water usage (e.g., surfing). Groins may also result in significant negative impact to the neighboring beaches to the north of the DCR reservation and would have high construction costs and environmental concerns. Therefore, groins are not a preferred alternative for Nantasket Beach.

Breakwaters

Breakwaters are designed to reduce wave action in the area leeward of the structure to retard beach erosion. Typically, this type of shore protection is provided from a single large offshore rubble mound (rock) structure, or a series of shorter segmented breakwaters oriented parallel to the shoreline (Figure 6-9). A segmented breakwater dissipates wave energy in its lee, and each breakwater allows for sediments to be deposited on the adjacent shoreline, forming a bulge in the beach defined as a salient. The wave climate and distance between the shoreline and the breakwater govern the salient growth. If the accreted sand makes contact with the breakwater, the formation is termed a tombolo.

The sources of the trapped sediment behind each breakwater are derived from the ambient littoral drift and the sediment transport induced by the diffraction pattern of the waves around the ends of the breakwater, which forces sediment toward the shadow zone. Trapping the natural littoral drift is a concern because erosion of the downdrift beaches may result. Artificially filling the salients to an equilibrium planform (adding extra sediment seaward of the shoreline and landward of the breakwater) may prevent downdrift erosion for some finite period of time (until more nourishment is required), and the longshore transport may continue, unaffected by the breakwater.

Determination of this equilibrium planform requires an accurate prediction of the salient growth behind a breakwater. A myriad of variables, spanning the natural littoral processes and wave conditions, as well as the properties of the structure, govern the shoreline response. For a single detached offshore breakwater, the reduction in sediment transport from the wave shadowing effect of the breakwater, the transport induced by the diffracted wave pattern, and the effects of wave energy transmitted through the structure must be weighed against the ambient sediment transport conditions to determine the shoreline response. A further consideration for a series of segmented breakwaters is the design geometry. The interrelated effects of each structure's length, distance from shore, and the gap between each structure relative to the incident wavelength determine the post-construction shape of the shoreline.

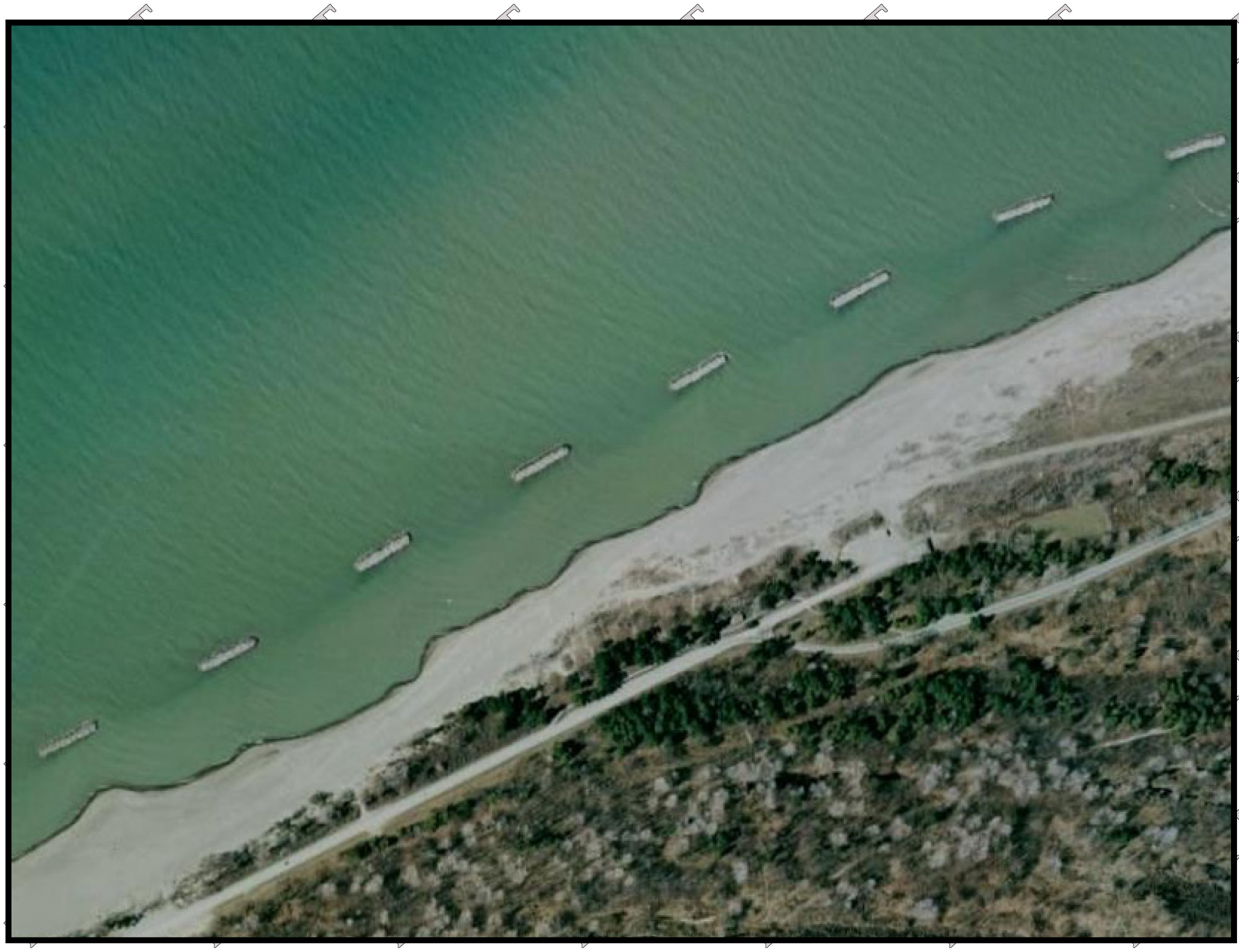

Figure 6-9. Detached breakwaters offshore of Presque Isle State Park, Erie, PA (Image from Google Earth).

As with groins, breakwaters are a viable means of stabilizing the shoreline; however, there are adverse effects. Physically, there is the potential for downdrift erosion, which may be aggravated by the formation of tombolos that cut off longshore sediment transport completely. Environmentally, alteration of bottom habitat and aesthetic beauty are also drawbacks. However, a properly designed system of breakwaters, where no tombolos form, will not inhibit longshore transport as much as groins.

By understanding the environmental drawbacks of detached offshore breakwaters and designing them to mitigate these concerns, they may be a viable option to control coastal erosion. Unfortunately, the cost of breakwater construction in an open coastal region can be expensive. To ensure that tombolos will not form, the offshore distance must be increased. It is also mandatory to construct the breakwaters far enough offshore to prevent impacts on the natural seasonal cross-shore transport of sand. This increase in offshore distance and water depth will directly affect the structure cost and environmental impact, since a breakwater constructed in deeper water will require more material. For example, for a typical trapezoidal-shaped cross-section rock breakwater, the construction costs are tripled (or more) when the depth is doubled. In deeper water, the footprint of the breakwater increases (at least 50% increase in footprint with doubled depth), and potential adverse environmental impacts are also increased. At Nantasket Beach, the high construction costs, permitting, and interference with many recreational uses (e.g., surfing), outweigh the anticipated benefits, making detached offshore breakwaters infeasible. Therefore, although technically feasible, offshore breakwaters were not recommended for further assessment.

6.2.3 Alternative Technologies

<u>*Beach Dewatering*</u>

The primary goal of beach dewatering is to stabilize the shoreline by lowering the groundwater table. A beach dewatering system contains a series of pipes buried in the beach face through which water from the wave uprush is pumped from the beach. On a typical beach the water table is governed by tidal fluctuations, groundwater flow from land, and the uprush of water in the swash zone (the zone of wave action on the beach, which moves as water levels vary, extending from the limit of run-down to the limit of runup). Lowering the water table through beach dewatering at the shoreline theoretically may mitigate erosion problems in several ways. The process is analogous to the dewatering process used when excavating saturated soils, where the slopes are stabilized as a result of reducing the upward buoyancy force in the sand grains and through slight compaction as water percolates down through the soil. The decreased gradient between the lowered water table and sea level effectively decreases the outflow of water from the beach face, further stabilizing the berm and inhibiting offshore movement of sediment. Additionally, as sediment laden swash zone water is pumped into the beach face, erosion is prevented and small amounts of sediment may be accreted.

Beach dewatering projects using both gravity drainage and vacuum pumping systems have been designed and implemented at a number of sites. The most significant finding of these early cases is that dewatering systems may stabilize the beach, thereby providing an alternative for beach protection. However, the observed success of dewatering systems is limited to areas where an abundance of sediment is available. In the absence of a significant sediment supply, the effectiveness of beach dewatering is in question, and the technique cannot be expected to build a beach. The over-steepening of the beach due to the dewatering process indicates a change in the equilibrium profile shape meaning sand is captured on the upper portion of the profile. If the pumping process is discontinued, the beach profile can be expected to revert to its original equilibrium shape rather rapidly and transport this material offshore. Therefore, the beach that may have been built due to this temporary steepening of the profile, would be quickly lost during a readjustment of the profile. It is likely that this oversteepening may account for much of the accreted volume exhibited at the test sites.

In addition, the idea of beach dewatering raises a number of environmental concerns. First, the available literature does not adequately discuss the effects of dewatering systems on downdrift beaches. In a natural beach system, waves will tend to transport sand in the longshore direction depending on the offshore wave angle with respect to the shoreline. Since beach face dewatering systems accrete sand by interrupting a portion of the natural littoral drift, downdrift erosion should be anticipated. Other concerns include high operational maintenance costs, and the potential for complete destruction of the system during major storm events.

A large beach dewatering project was initiated in the Siasconset area of Nantucket Island in 1994. This project has undergone at least one major redesign effort since its inception, and is still in the evaluation process. The construction and operation costs for this project have been significant, and to date the success of this technology at this site has been limited.

Due to the possible negative environmental impacts, the relatively high cost with respect to the potential benefits, and the unproven performance, this technology is considered experimental and is not recommended for Nantasket Beach. The overall sediment deficit within the Nantasket Beach area also argues against the use of beach dewatering.

Nearshore Berms

As an alternative to beach nourishment, sand may be deposited in the form of an offshore berm to act as a sediment source, or feeder berm for the beach. Although the best use of dredged material for shore protection is directly on the beach face in the form of nourishment, nearshore berms have been designed and implemented to make use of incompatible sediments that would normally have been transported to an offshore disposal site. Theoretically, the feeder berm serves as an offshore supply of sediment and a wave break that moves onshore during periods of low wave steepness, typically during the summer months. Depth of placement and grain size are important parameters for determining the behavior of the berm after placement. Wave forces cannot transport coarse material as readily as fine material. In addition, near-bottom velocities caused by waves are smaller in deeper water; therefore, the berm must be placed in depths where wave forces can transport the sediment.

The advantage of utilizing nearshore berms is their low construction cost. Dredged material can be easily dumped offshore to form a berm; however, the deposition of sediments must be within designed disposal area limits to assure shoreward transport. The deposition depth is also typically limited by the drafts of the fully loaded barges delivering the material.

At this time, monitoring data from nearshore berm projects show that they have little measurable effect on beach stability. In many cases, poor results have occurred due to placing the berm too far from shore to facilitate onshore movement. Although placement of sand in nearshore berms is a better use of incompatible sediments than deep-water disposal, littoral transport of this material does not appear to affect beach erosion rates. Typically, incompatible sediments are too fine, and placement in the nearshore may introduce environmental problems associated with water clarity. For example, water quality may be temporarily reduced, and benthic organisms may be covered as the sediments settle. In cases where the nearshore berm sediments are too coarse, the wave climate is not able to move the sediments into the littoral system. Instead, the berm sediments remain offshore and have little influence over the nearshore sediment transport.

For the Nantasket Beach area, nearshore berms most likely will not be beneficial. Whenever possible, available beach sediments should be placed within the littoral system as beneficial reuse, and directly on the beach for cases where increased beach width is required for recreational purposes. The nearshore berms may also interfere with the recreational surfing activities that are conducted at Nantasket Beach.

Submerged Offshore Reefs

Submerged offshore reefs and breakwaters are a variation of the breakwaters discussed above. In these instances, breakwaters are submerged to eliminate perceived aesthetic impacts. Various types of submerged breakwaters, such as rock structures, artificial reefs, and beach cones, have been developed to reduce erosional forces on the beach and/or prevent the loss of sediment from the nearshore. The theory behind these structures is to reduce the height of incoming waves by reflecting and dissipating energy as the waves propagate over the submerged structure. For sediment trapping purposes, the breakwater acts as a physical barrier blocking sediments from moving offshore.

Submerged offshore breakwaters are often rubble mound rock structures oriented parallel to the shoreline. Other designs include concrete shapes such as the Beachsaver (Creter, 1994) or Prefabricated Erosion Prevention (PEP; Mitchell, 1994) reefs that have been implemented on the Atlantic coast of the United States. Both of these reefs are constructed of prefabricated concrete modules, which can be interlocked to protect large sections of a shoreline. Beachsaver modules have a triangular profile shape, a saw-toothed bottom, and rough "stepped" seaward and landward slopes. Beach cones have been developed for more localized protection in low wave energy environments (Davis and Law, 1994). They consist of concrete cones arranged in pyramidal clusters, interlocked with interstitial wave blocks and anchored to the sea floor with PVC pipes.

A great deal has been learned about submerged breakwaters through laboratory and field testing. Major deficiencies include excessive settlement of the structures and an inability to achieve expected wave height reductions. The latter problem is exacerbated in storms because surge levels increase the water depth above the structure, allowing for higher than normal waves to break on the exposed beach. During storms, as much as 95 percent of wave energy may be transmitted past a submerged breakwater. In addition, laboratory experiments have indicated significant longshore currents develop in the lee of the breakwaters (Browder, 1994). Although details of how this current might affect sediment transport are still being studied, initial indications show a net loss of sediment behind the structure with accretion at either end.

Submerged breakwaters can provide protection for beaches by dissipating wave energy during normal wave conditions, and combined with the advantage of their invisibility, these structures can potentially serve to mitigate beach erosion problems in a way that satisfies community interests. However, issues regarding environmental impacts remain unresolved. Locating "hard" submerged engineering structures within the nearshore zone disturbs bottom habitat, inhibits recreation swimming and water use, and creates a potential navigational hazard. This alternative is not recommended for Nantasket Beach.

Additional Alternative Technologies

Over the last few decades, numerous other devices have been patented to prevent beach erosion. The types of alternative technology devices span a wide range of ideas, including beach cones (Davis and Law, 1994), ultra-low profile geotextiles injected with concrete (Janis and Holmberg, 1994), various geotextile tubes and shapes, fishnets, stabilizers, and artificial seaweed (Stephen, 1994), and a host of additional innovative approaches. These alternative methods often employ nontraditional shapes or materials; however, they are positioned in traditional ways (e.g., to replicate a nearshore breakwater, revetment, or groin). Ultimately, their potential success depends on their ability to resist storm impacts and maintain durability over a design life.

Many of these devices claim to have solved the coastal erosion problem through creation of a beach or capturing sand. In cases, some of these devices can be effective in capturing sediment, and test cases utilizing these alternative technologies have shown beach growth. However, these test cases lack corresponding long-term data documenting the source of the deposited sand. In order for sand to be built up along one stretch of beach, it must have been taken from somewhere else in the system (if sand is not supplied via beach nourishment). Without adding sand to the system, these devices are simply impacting adjacent beaches or the offshore environment by rearranging the existing sand in the active sediment transport zone, similar to groins, jetties, and breakwaters.

In order to compare alternative technologies to standard coastal engineering solutions, the alternative technologies must be thoroughly assessed to ensure that their performance is adequate from a technical standpoint. Technical assessments should include, at a minimum:

- The alternative technology should be shown to maintain continued performance through the seasonal changes at a beach. For example, if a technology is put in place in the winter or spring, following the erosive storm season, the evaluation should consider the natural summer recovery of the beach. As the beach evolves to its summer profile, the build-up of the beach can create a temporary growth that may be misinterpreted as a success.

- Successful performance must be demonstrated with more than just before and after photographs. Long-term and large-scale measurement programs are required to validate the performance of the erosion control devices. This should include monitoring of not only the coastal site where the alternative technology is applied, but also of offshore and adjacent coastal regions to ensure negative impacts are not caused by the technology.

- The alternative technology must be able to withstand the forces of nature in open coastal environments. Engineering design and calculation should indicate that erosion control devices are able to withstand all the forces present during storms and the normal corrosion and fatigue associated with oscillatory wave action. In many cases, the erosion control devices are destroyed during storm events on the open coast.

In order to determine if an alternative technology is a reasonable approach for mitigating coastal erosion at a site, it must be carefully examined in order to ensure it is able to meet its promised function, minimize impact on the environment, survive for a predictable lifetime, and is cost effective. To further the development of innovative technologies, Pope (1997) raised a number of questions that should be considered when evaluating an alternative technology. Most of the technologies developed do not satisfactorily answer these questions. For example, some of the questions Pope (1997) posed include:

- Is the alternative technology heavy enough, especially considering the forces of storm waves?
- If the technology does fail, could the structural components become an environmental or public safety hazard?
- How will the technology perform and will it perform the way it is expected to perform?
- Will the technology be tolerant of erosion and scour effects?
- Will the technology be stable enough and anchored such that it doesn't fall apart?
- Does the technology perform as promised, and are there any adverse impacts to adjacent areas? Has this been documented and shown using long-term data?
- What is the technologies effective life?
- How much will constructing and maintaining the nontraditional or innovative system cost compare to more traditional methods?
- What are the design criteria?
- Is the material that is being constructed from survivable in a high-energy wave environment?
- What will it cost to remove the system (if necessary)?
- Has long-term monitoring of the performance of the alternative technology been conducted both at the site, as well as offshore and at adjacent beaches?

Nontraditional and innovative technologies need to be subject to the same design cost and performance criteria and constraints as the more established traditional methods. Additionally, the alternative technology has the extra burden of overcoming previous shortcomings and proof that they function effectively. These alternative technologies are not recommended for use at Nantasket Beach. Adequate information is not available to support their use at a site of high wave energy such as Nantasket Beach. Additionally, the scale, potential impacts to significant infrastructure if the technology does not perform as expected, and overall value of Nantasket Beach is not conducive to implementation of these alternative technologies. However, certain technologies, specifically the Advanced Coastal Technologies (ACT) ProTecTube™, were considered in concert with other alternative approaches (Section 6.3.8) to supplement traditional methods and to assess a scenario developed by the members of the Citizens Advisory Committee (CAC).

6.3 NANTASKET BEACH ALTERNATIVES SELECTED FOR CONSIDERATION

The previous section presented the traditional alternatives considered to mitigate erosion at a coastal location. Most of the alternatives considered provide the ability to protect the shoreline and upland infrastructure. However, Nantasket Beach, which is a significantly used recreational beach, must be serviceable for a wide range of functions, and the alternative cannot be a protective measure only. The beach must provide area for recreational usage (e.g., sunbathing, swimming, walking, surfing, etc.), while also providing protection. Therefore, most of the alternatives that were determined to be most technically feasible include the addition of new sand to the system through beach nourishment. This is not surprising, since the southern portion of Nantasket Beach has a deficit of sand and a dwindling sediment supply. The development of the upland has eliminated a natural source of sediment from the shoreline, and there is an insignificant amount of sediment supplied from the updrift (to the southeast) region. Chapter 7 will evaluate the most feasible alternatives to a greater extent, and specifically evaluate the performance of the beach for each alternative. The final alternatives selected for evaluation, as developed jointly between the DCR, the Town of Hull, the CAC, Berger, and the WHG on January 31, 2007, were:

- **Alternative 1:** ***No Action.*** This alternative would consist of taking no action at Nantasket Beach and making no changes to the existing seawall or fronting beach.

- **Alternative 2:** ***Seawall Toe Protection.*** This alternative would add stone toe protection in front of the existing seawall in areas where no current toe protection exists (i.e., mid-section of the seawall). Toe protection is similar to a small revetment that would be placed seaward of the existing seawall. This alternative has been implemented along the southern section of the Nantasket Beach seawall (Figure 6-10).

- **Alternative 3:** ***Seawall with Revetment.*** This alternative would place a revetment in front of the existing seawall, providing added protection not only for the existing seawall and upland infrastructure, but also providing an improved wave dissipation structure when compared to a vertical concrete seawall. An example of the revetment proposed along the DCR reservation is presented in Figure 6-7, which consists of the revetment installed along the northern section of the Nantasket Beach seawall.

- **Alternative 4:** ***Beach Nourishment.*** This alternative would consist of adding beach nourishment directly seaward of the existing seawall with no modifications or changes to the seawall itself. Figure 6-11 shows an example of the proposed nourishment alternative, including the new location of the Mean High Water line on the beach.

- **Alternative 5:** ***Seawall Toe Protection and Beach Nourishment.*** This alternative is a combination of Alternatives 2 and 4, where toe protection would be placed in front of the mid-section of the seawall (which is currently unprotected); then the beach nourishment would be placed on top of the toe protection and extending seaward by approximately 180 to 200 feet. The nourishment would initially cover the toe protection completely.

Figure 6-10. Seawall toe protection along the southern section of the Nantasket Beach Seawall.

- **Alternative 6: *Seawall with Revetment and Beach Nourishment.*** This alternative is a combination of Alternatives 3 and 4, where a revetment would be placed in front of the mid-section of the seawall (which is currently unprotected) and then the beach nourishment would be placed in front of the revetment, partially covering the revetment) and extend seaward by approximately 180 to 200 feet. The nourishment would cover a significant portion of the revetment; however the crest of the revetment armor units would remain exposed.

- **Alternative 7: *Retreat and Construct New Seawall, Revetment, and Dune*.** This alternative would remove and demolish the existing seawall, retreat approximately 30 feet landward, construct a new seawall, fronting revetment, and place a dune-like feature in front of the new seawall. Existing parking areas and infrastructure (e.g., MJM bathhouse) would need to be demolished or moved as part of this alternative. The fronting revetment would be similar to the toe protection that currently exists along the southern portion of the current seawall. As such, rock armor units would extend approximately 35 feet seaward from the base of the new seawall. The actual increase in beach width would be minimal (relative to the current beach width). Subsequently, sand would be brought in to cover some of the fronting toe protection material and provide some temporary dune and beach area. This material would be placed at a much steeper slope than the proposed beach nourishment alternatives (4, 5, 6, and 8). This dune-like feature consists of a smaller volume of material and would not extend the beach width by more than approximately 40-45 feet from the toe of the revetment. This alternative would extend along the entire length of the Conservation and replace all existing structures (seawall, STP, and revetment).

- **Alternative 8: *Remove Seawall and Beach Nourishment.*** This alternative would remove and demolish the existing seawall and replace the seawall with a natural dune and fronting beach nourishment. The dune would also utilize ACT ProTecTubes™ as a core of the dune. A significant amount of landward area would be required to create a stable dune system, and this would require removal of nearly all of the current parking areas, roadways, a significant number of public reservation buildings, as well as some business properties and buildings.

Figure 6-11. Example of proposed beach nourishment (conceptual design, not exact proposed design) at Nantasket Beach, the dashed line shows the new location of Mean High Water on the beach.

7.0 COASTAL PROTECTION ALTERNATIVES ANALYSIS

In addition to the development and selection of the alternatives for more detailed analysis, a comprehensive list of evaluation criteria was also developed during the January 31, 2007 meeting. These evaluation criteria were divided into specific subcategories and used to compare the selected alternatives. The evaluation criteria included:

- *Storm Protection and Impacts:* Includes evaluation of the upland flooding potential, the ability of the alternative to provide storm protection for upland infrastructure, and the direct loss of infrastructure due to the construction of the alternative.

- *Service Life:* Performance of the alternatives, including the lifetime of the beach nourishment, as well as the lifetime of the overall shoreline protection system (e.g., including structural lifetime).

- *Socio-Economics:* Includes potential economic benefits or disadvantages to the community, aesthetics, and recreational benefits.

- *Permitting and Construction:* Includes the relative complexity of the environmental permitting, the length required for permitting, and the construction length for each of the alternatives.

- *Costs:* Incurred over the life cycle of the alternative – this includes the initial capital cost, operation and maintenance costs, and upland damage costs and/or savings during a storm event.

In this chapter, each of the eight selected alternatives is analyzed from a coastal processes and performance perspective (which addresses the evaluation criteria of storm protection and impacts), alternatives performance/service life, socio-economic aspects, permitting, and costs.

7.1 STORM PROTECTION AND IMPACTS

In order to assess potential upland flooding and the level of storm damage protection provided to the buildings and upland infrastructure at Nantasket Beach, the impacts of a 100-year return period storm at Nantasket Beach were evaluated for each alternative. The wave run-up and overtopping occurring during a 100-year storm event, using the model results presented in Chapter 4, were determined for each alternative. The rate of overtopping for each alternative provided a quantitative measure of the amount of water that may flood the Nantasket Beach Reservation from ocean storm waves. These values were used to assess the variations in potential flooding associated with each alternative. In addition, the influence on the Federal Emergency Management Agency (FEMA) flood zones was assessed in a qualitative manner to determine if the alternative may impact the location of flood zone lines. Finally, the direct loss of existing infrastructure that would occur due to the construction of the alternative was determined based on a conceptual design for each alternative.

7.1.1 Wave runup and overtopping

Wave runup and overtopping of the potential alternative were determined in order to compare the relative coastal flooding protection afforded by each alternative. Essentially, wave runup is the measure of how high the water propagates up the structure or beach, while wave overtopping is an estimate of how much water gets behind a structure during a given storm.

Wave runup is defined as the maximum water surface elevation (measured vertically) from the still water level. Figure 7-1 illustrates the concept of runup and rundown on a simple smooth slope. The runup depends on the height and steepness of the incoming wave, the slope angle, the surface roughness, and the permeability and porosity of the slope. An increase in the permeability of a slope or the roughness of the slope will decrease the level of runup, as water is allowed to inflow into the structure or greater energy is dissipated, respectively. Figure 7-2 provides an example of the reduction in runup caused by a greater level of permeability.

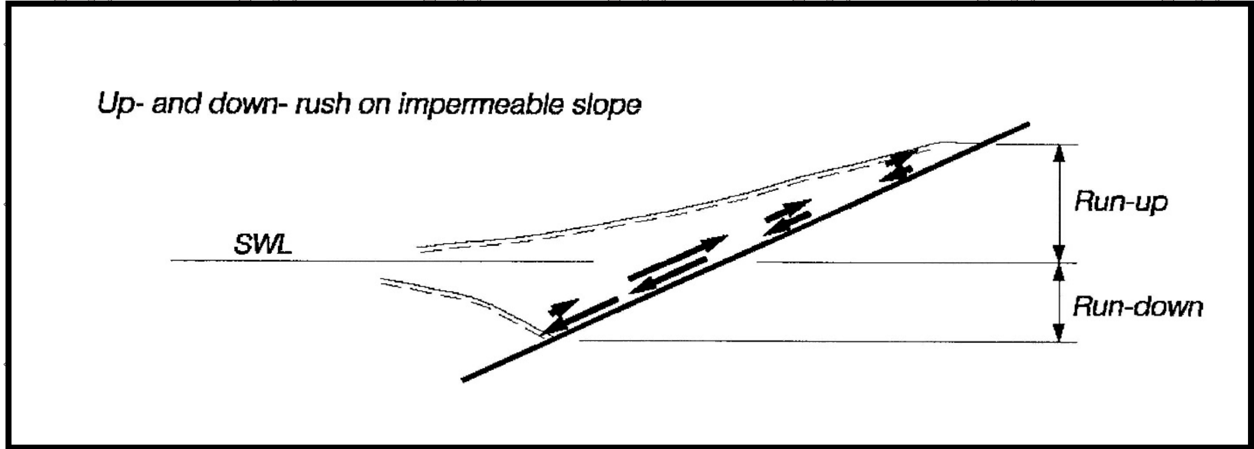

Figure 7-1. Illustration of runup and rundown on a smooth impermeable slope (USACE, 2002).

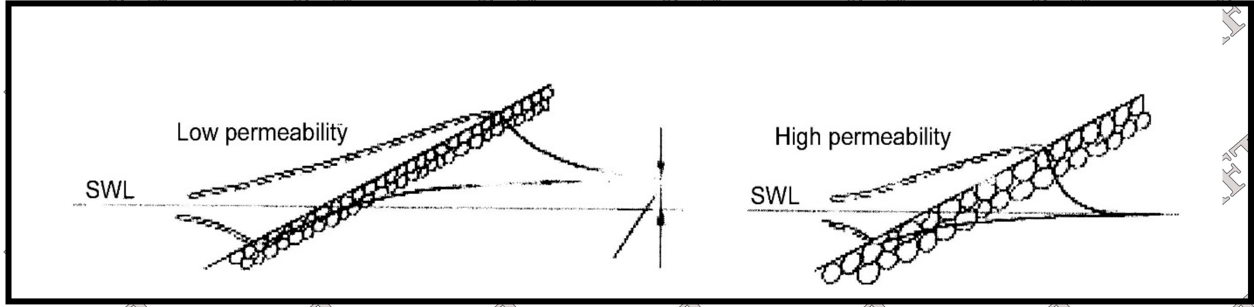

Figure 7-2. Effect of structures permeability on the level of runup. The left hand panel shows a low permeability structure resulting in increased runup, while the right hand panel shows a high permeability structure with decreased runup (USACE, 2002).

Engineering analysis of the wave runup was conducted using standard engineering methodology for both coastal seawalls/bulkheads and revetments. For the vertical seawall alternatives, the methodology was developed by Saville (1955, 1956) as presented in the Shore Protection Manual (USACE, 1984). For the proposed rubble sloping alternatives (e.g., revetment), wave runup was calculated using the method of van der Meer and Stam (1992) as:

$$\frac{R_{u2\%}}{H} = 0.835\xi_{op} \qquad \textit{for } 1.15 < \xi_{op} \leq 1.72 \tag{7-1}$$

$$\frac{R_{u2\%}}{H} = 1.1\xi_{op}^{0.46} \qquad \textit{for } 1.72 < \xi_{op} \tag{7-2}$$

where

$$\xi_{op} = \frac{\tan\alpha}{\sqrt{H/L}} \tag{7-3}$$

with the variables defined as:

$R_{i2\%}$	is the runup level exceeded by 2 percent of the incident waves,
H	is the significant wave height,
α	is the slope of the structure
L	is the wavelength.

Wave overtopping occurs when the highest runup levels exceed the crest of the structure, thereby allowing water to flow over and behind the structure, conceptually shown in Figure 7-3. Wave overtopping can result in significant structural and human safety concerns, as shown in Figure 7-4. Overtopping is presented as a time averaged volume of water that is discharged over the crest of the structure (liters/second for every meter [l/s-m]). The amount of allowable overtopping depends primarily on the type and function of the particular structure. Wave overtopping is unevenly distributed in time and space and a major portion of the overtopping discharge during a storm is due to a small fraction of the waves. Most estimates of overtopping are based on empirical formula developed in field and laboratory studies. Wave overtopping can result in significant upland flooding or erosion landward of the coastal structure. The ability of a structure or beach to reduce wave runup and overtopping is a key component of the overall shoreline protection. Therefore, a key component of the relative effectiveness of each of the proposed alternatives is the relative levels of overtopping allowed.

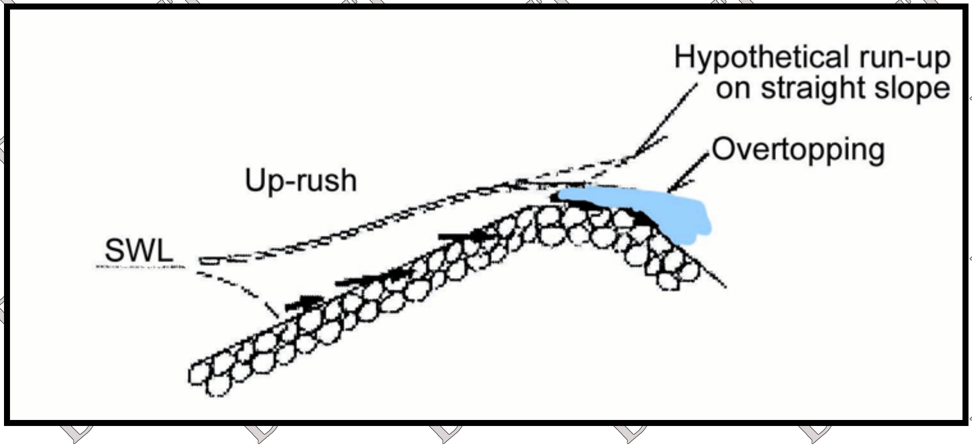

Figure 7-3. Illustration of wave overtopping of a sloped structure. Overtopping occurs when the runup exceeds the crest of the structure (USACE, 2006).

Figure 7-4. Examples of wave overtopping at seawall structures.

For the proposed seawall alternatives, both the methodology of Saville (1958) and the methodology of Franco and Franco (1999) were utilized to predict the overtopping (*Q*) in order to provide a range of potential overtopping rates. Saville (1958) predicted overtopping rate as:

$$Q = (gQ_0^* H^3)^{1/2} e^{-\left[\frac{0.217}{\alpha}\tanh^{-1}\left(\frac{h-d_s}{R}\right)\right]} \qquad (7\text{-}4)$$

while Franco and Franco (1999) predicted the overtopping rate as:

$$Q = (gH^3)^{1/2} * 0.082 e^{\left(-3.0\frac{R_c}{H_s}\frac{1}{\gamma\beta\gamma_s}\right)} \qquad (7\text{-}5)$$

where

- H is the significant wave height at the structure
- R_c is the freeboard (distance between the structure crest and still water elevation)
- D_s is the depth of the structure toe
- Q_0 and α are empirically determined coefficients based on incident wave characteristics and structure types
- γ_s *and* γ_B are geometry and wave crest factors

For the sloped revetment, the methodology of van der Meer and Janssen (1995) was applied.

$$Q = \sqrt{gH^3}\,0.2\exp\left[-2.6\frac{R_c}{H}\frac{1}{\gamma_b\gamma_r\gamma_h\gamma_\beta}\right] \qquad (7\text{-}6)$$

where

- H is the significant wave height at the structure
- R_c is the freeboard (distance between the structure crest and still water elevation)
- $\gamma_r, \gamma_b, \gamma_h$ *and* γ_β are various factors such as the surface roughness, etc.

7.1.2 FEMA Flood Zones

In addition to wave runup and overtopping, which quantify the potential ocean-based flooding that can occur during a storm event, the FEMA flood zones for the Nantasket Beach region were also evaluated to ascertain if potential changes to the delineation of the zones could occur due to each alternative. Figure 7-5 presents the current flood zone delineation at Nantasket Beach. The letters in the different zones represent various levels of flooding that are expected during a 100-year return period storm event. These are defined as follows:

- V zone – Areas of coastal flooding with waves
- AO zone – Areas with flooding with depths between 1 and 3 feet
- A zone – Areas with flooding
- C zone – Areas of minimal flooding

For the alternatives that keep the seawall in place (Alternatives 1 to 6), the flood zones would remain the same. However, for those alternatives that include structural improvements to the seawall or add beach nourishment (Alternative 2 to 6), the flood zones could potentially improve (move seaward). For the cases where the seawall is modified or removed (Alternatives 7 and 8), these flood zones would be expected to move landward and would impact the ability to construct and/or modify buildings and increase insurance rates. For example, Figure 7-6 shows the expected flood zones for Alternative 8. The potential change in FEMA flood zone delineation is summarized in Table 7-1.

Figure 7-5. Existing FEMA flood zone delineation at Nantasket Beach (see previous page for explanation of symbols).

Figure 7-6. Expected location of new FEMA flood zone delineation at Nantasket Beach after the implementation of Alternative 8 (see previous page for explanation of symbols).

7.1.3 Direct Loss of Infrastructure

Construction of some of the alternatives would result in direct loss of existing upland infrastructure. If the seawall remains in its current location (Alternatives 1 to 6), the current infrastructure would not be impacted. However, modifications and/or removal of the seawall would have direct impacts on some of the Nantasket Beach infrastructure. Figure 7-7 shows the impact of Alternative 7 (i.e., moving the seawall 30 feet landward) on the MJM bathhouse. Although some parking area would also be lost, the MJM bathhouse would be the only building impacted in Alternative 7. Alternative 8 would have a much greater impact on the Nantasket Beach infrastructure, since removing the seawall and replacing it with a more gently sloping natural dune would require significantly more cross-sectional space. Figure 7-8 shows the potential impact of Alternative 8 on the same area as shown in Figure 7-7. The direct loss of infrastructure for all alternatives is summarized in Table 7-1. Figures 7-7 and 7-8 are conceptual drawings only.

7.1.4 Summary

Table 7-1 presents a summary of storm damage impacts for each of the eight final alternatives. Specifically, the table provides the wave overtopping results, the potential damage to infrastructure, the expected impact on the FEMA flood zones, and the direct loss of infrastructure. The Shore Protection Manual (USACE, 1984) provides the level of damage to infrastructure associated with the quantity of wave overtopping. Overtopping rates represent the amount of water that is expected to overtop the alternative (seawall, revetment, etc.) during a 100-year storm event with the tide level ranging from mid to high tide. Limiting the amount of overtopping that occurs during the storm event provides some protection benefit. Wave overtopping is typically reduced for a sloping rubble structure or when a beach is fronting the structure since the wave energy is more easily dissipated on the face of the sloping structure or due to the beach.

The rate of overtopping for Alternative 8, which does not include any type of hard coastal structure, could not be directly quantified, since the proposed dune is a dynamic feature that will begin to erode, transport sediment offshore, and overwash (movement of the dune landward) during the storm event. Therefore, the dune evolution during the 100-year storm was simulated using a cross-shore sediment transport model (SBEACH) to determine the potential impact on the dune alternative (Alternative 8). Additionally, Table 7-1 presents the reduction or increase in upland flooding potential (when compared to the no action alternative) and the potential shift in FEMA Flood Zones. Finally, the table also presents the infrastructure that will be directly lost during the construction of each alternative.

Table 7-1. Wave overtopping and upland flooding potential for the final alternatives.

Alternative	Upland Flooding Potential	Impact to Mapped Flood Zones	Overtopping Rate	Expected Impacts due to Large Storm	Direct Loss of Existing Infrastructure
1. No Action	Significant upland flooding	FEMA Flood Zones remain the same	**1-51 l/s-m*** overtopping.	Seawall failure, Significant damage to buildings, Very dangerous to pedestrians, Unsafe vehicular traffic at any speed	No impact unless wall fails
2. Toe Protection	**Small** reduction	FEMA Flood Zones remain the same	**0-34 l/s-m*** overtopping.	Damage to structure, Damage to buildings, Very dangerous to pedestrians, Unsafe vehicular traffic at any speed	None
3. Revetment	**Medium** reduction		**0-20 l/s-m*** overtopping.		
4. Beach Nourishment	**Large** reduction, while nourished beach in place	FEMA Flood Zones remain the same	**0-3 l/s-m*** overtopping.	No damage to seawall, Minor damage to signs, posts, etc., Dangerous to pedestrians on wall, Unsafe vehicular traffic at high speed	None
5. Toe Protection with Beach Nourishment					
6. Revetment with Beach Nourishment					
7. Move Sewall back, revetment and dune	**Medium** reduction	FEMA Flood Zones would shift landward 30 feet.	**0-16 l/s-m*** overtopping.	Damage to structure crest, Damage to infrastructure, Very dangerous to pedestrians, Unsafe vehicular traffic at any speed	MJM Bath house
8. Remove seawall and build dune	**Large** reduction, while nourished beach in place	FEMA Flood Zones will shift landward significantly	Dune migrates approximately **50-75 feet (15.2-22.9 m)** landward	Dune migration into roads & buildings, Damage to buildings, Very dangerous to pedestrians, Unsafe road traffic at any speed	Nantasket Ave, northbound; Tivoli Bathhouse; Bernie King Pav.; MJM Bathhouse; private property; parking areas

l/s-m = liters per second for every meter along the beach

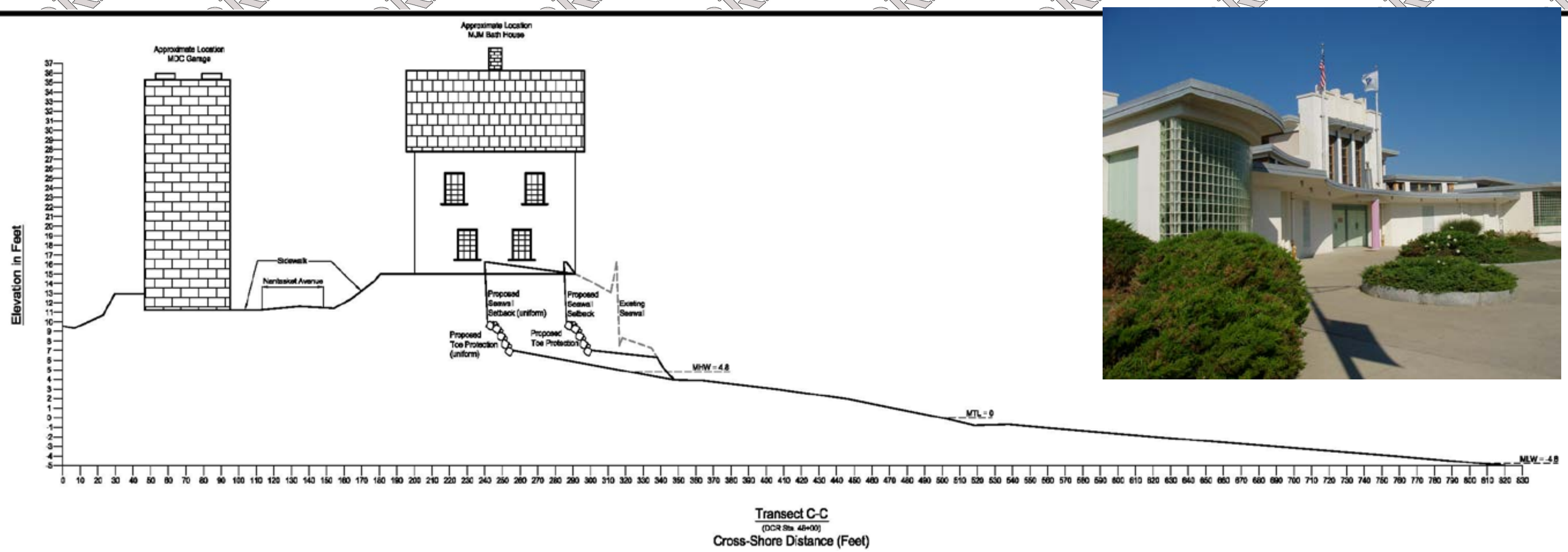

Figure 7-7. Conceptual layout of the new seawall and impact on the MJM bathhouse for Alternative 7 (conceptual layout only, not to scale).

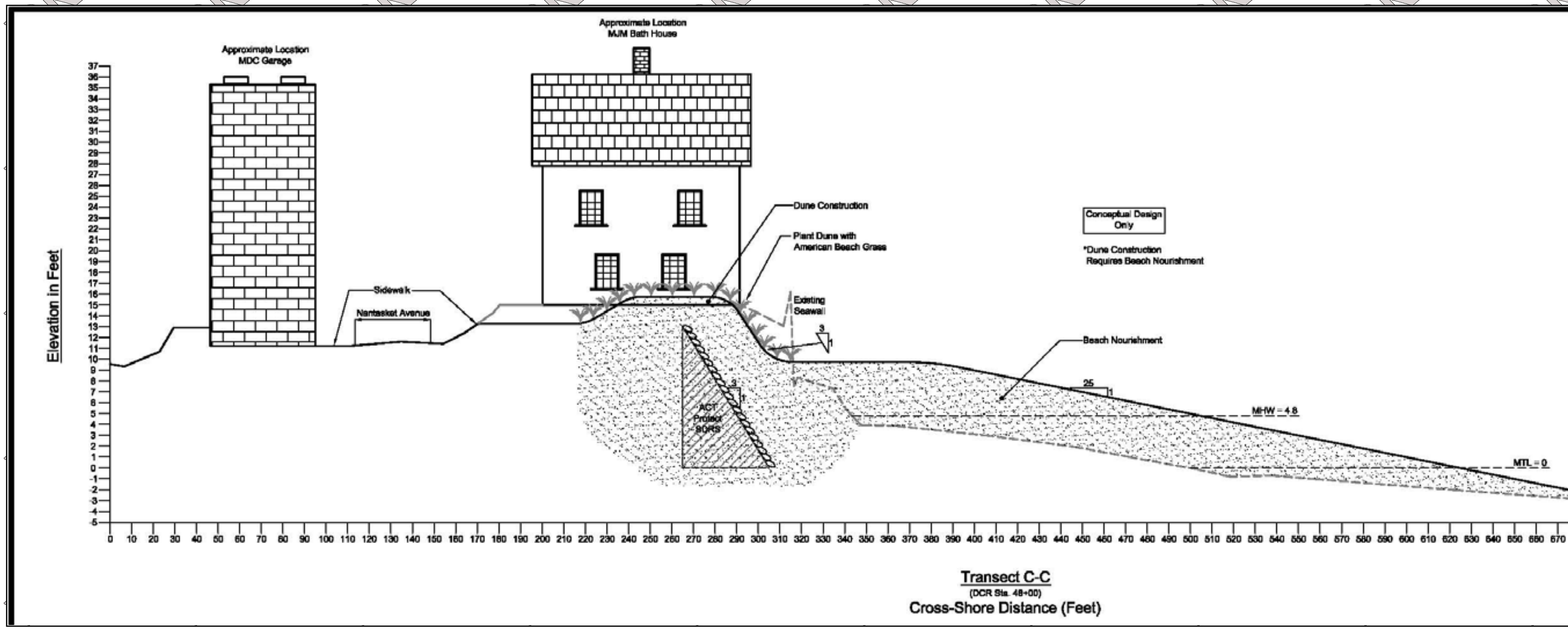

Figure 7-8. Conceptual layout of Alternative 8 and impact on the MJM bathhouse (conceptual layout only, not to scale).

7.2 ALTERNATIVE SERVICE LIFE

Another important criterion in the evaluation of the alternatives is the performance or service life of each alternative. For the long-term solution at Nantasket Beach, this consists of two components:

- *Performance of the beach:* The time long does the beach last before the recreational value returns to the current condition of no high tide beach.
- *Performance of the shoreline protection system as a whole*: How long is protection afforded by the combination of any structure and how does the beach last.

For example, for the no action alternative, there is currently no beach available at high tide, and the existing seawall has a limited lifetime remaining before failure is expected. The U.S. Army Corps of Engineers performed a stability analysis for the seawall, as described in Winkelman and Jones (2005). Calculations were performed in accordance with the USACE's *Engineering Manuals, Retaining and Flood Walls* (EM 1110-2-2502) and *Stability Analysis of Concrete Structures* (EC 1110-2-6058). The analysis evaluated the structure for stability in overturning, sliding, and bearing capacity for the no-storm and 100-year storm conditions. The USACE determined that the seawall requires the following elevations of sand in front of it for stability:

- No-storm conditions: Elevation of +7 feet NGVD
- 100-year storm: Elevation of +9 feet NGVD

Recent beach survey data (September, 2008) show that the elevation in front of the mid-section of the seawall (i.e., the section without rock protection) does not meet the required elevations to withstand a 100-year storm. Further, based on the current elevation of the beach fronting the seawall, as well as the observed rate of erosion from recent surveys (Louis Berger, 2006), the seawall is currently unstable and likely in danger of collapse in less than 10 years for normal conditions, and less than 6 years for storm conditions.

7.2.1 Beach Nourishment Performance

<u>*Beach Nourishment Design*</u>

If beach nourishment is the preferred alternative, or a component of the preferred alternative, the beach nourishment template should be optimized. A successful beach nourishment project is engineered and consists of more than simply placing sediment on a beach. A beach nourishment template, which consists of numerous design parameters, is based on the characteristics of the site and the needs of a project. Every beach nourishment design is unique, since different beaches in different areas have different physical, geologic, environmental, and economic characteristics, as well as different levels of required protection. The design must consider climatology, the shape of the beach, type of native sand, volume and rates of sediment transport, erosion patterns and causes, waves and water levels, historical data and previous storms, probability of certain beach behaviors at the site, existing structures and infrastructure, and past engineering activities in the area. As such, beach nourishment designs must identify the coastal processes at the site. Typically, computer models (Chapters 4 and 5) are used to help design the nourishment template.

The structure of a nourishment template is designed to yield a protective barrier that also provides material to the beach. A higher and wider beach berm is designed to absorb wave energy. Dunes may need to be constructed or existing dunes improved to reduce damage, including potential upland flooding, from storms. Figure 7-9 depicts a beach berm and dune on a typical beach profile. Nourishment length, berm height and width, dune height, and offshore slope are critical elements of a beach nourishment design. Periodic renourishment intervals are also usually a part of the nourishment design. If renourishment is required in less than 5 years, then the nourishment is probably not cost-effective. If renourishment isn't required until after 10 years, then a nourishment project is likely cost-effective. The renourishment interval will vary based on the initial design, wave climate, sand used, number and types of storms, and project age. In addition, beach nourishment is not an exact science; variables and uncertainties exist. Actual periodic renourishment intervals may differ from planned intervals based on conditions at the nourished beach and the frequency and intensity of storms from year to year. This section presents the various beach nourishment designs evaluated for Nantasket Beach. Initially, over 36 different nourishment scenarios were developed and evaluated.

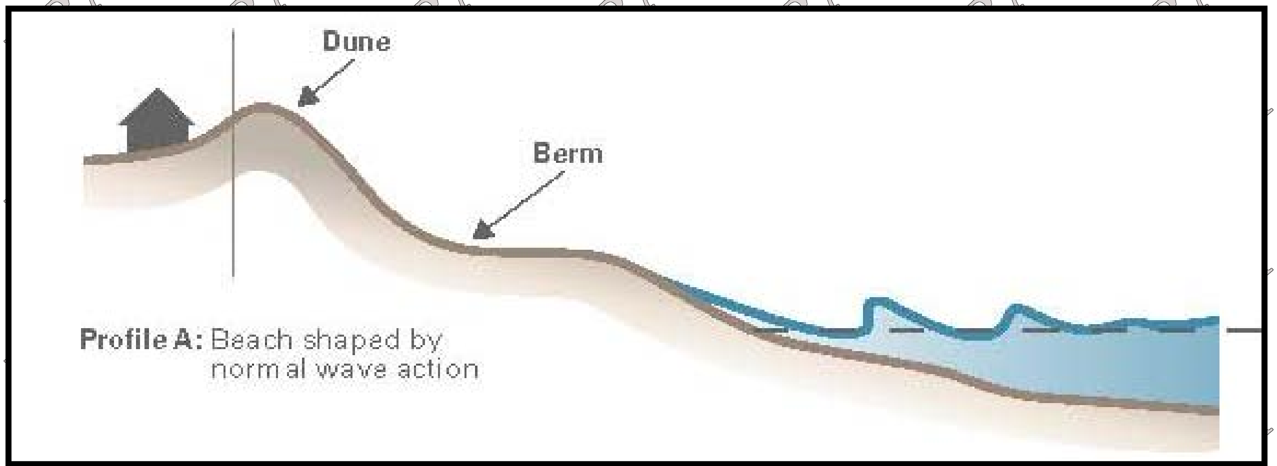

Figure 7-9. Typical beach profile and features (USACE, 2002).

Nourishment design parameters for Nantasket Beach included the following:

- *Nourishment Length:* The goal project length (extending alongshore) is 6,800 feet, spanning the entire DCR portion of Nantasket Beach.
- *Berm Width:* Berm widths of 25, 50, 75, and 100 feet were evaluated. The berm width relates directly to the increase in overall beach width. In the initial simulations, it was discovered that berm widths of 25 and 50 feet did not maintain adequate performance and were eliminated. Therefore, initial berm widths of 75-100 feet (varies alongshore) were

used. These berm widths resulted in the placement of approximately 100 cubic yards per linear foot of beach.

- *Berm Height:* Berm elevations of both 10 and 12 feet NGVD were evaluated in the alternatives assessment.

- *Offshore Slope:* For all berm templates, offshore slopes of both 1:18 and 1:25 (vertical to horizontal) were evaluated.

- *Nourishment Volume:* Nourishment volumes were determined for all scenarios based on the design beach nourishment template. In the alternatives assessment, the volume templates ranged from 610,000 to 789,000 cy of material.

- *Grain Size/Source:* Three specific grain size combinations were evaluated. These included: (1) a grain size of 0.25 mm that matches the native beach sand portion, (2) a grain size of 0.45 mm, as slightly coarser grain size than native, and (3) a mixed grain size of cobbles and sand that currently resides on Nantasket Beach.

Beach Nourishment Performance Methodology

The evaluation of proposed nourishment alternatives combines the conservation of sediment equation with the linearized transport equation. This formulation, called the Pelnard-Considére (1956) equation (Equation 7-7), is used in obtaining theoretical results to establish design and performance standards for nourishments. A more detailed description of the derivation of the equations and their applications can be found in Dean (2002).

$$M(t) = \frac{2\sqrt{Gt}}{l\sqrt{\pi}}\left(e^{-\left(\frac{l}{2\sqrt{Gt}}\right)^2} - 1\right) + erf\left(\frac{l}{2\sqrt{Gt}}\right) \qquad (7\text{-}7)$$

where *M(t)* is the proportion of sand remaining in the placed location, *G* is the alongshore diffusivity parameter, *t* is time, and *l* is the project (nourishment) length. The alongshore diffusivity is presented by Pelnard-Considére (1956) as:

$$G = \frac{KH_b^{5/2}\sqrt{\frac{g}{\kappa}}}{8(s-1)(1-p)(h_* + B)} \qquad (7\text{-}8)$$

where K is the sediment transport coefficient (a function of sediment size), B is the berm elevation, H_b is the breaking wave height, h_* is the depth of closure, p is the *in-situ* sediment porosity (approximately 0.35 to 0.40), s is the sediment specific gravity (approximately 2.65), and κ is the ratio of wave height to water depth within the surf zone (approximately 0.78).

The Pelnard-Considére equation can be applied to determine the performance of a beach nourishment project. For example, Figure 7-10 presents the spreading of an idealized, rectangular nourishment. Although simplified, this example illustrates the planform view of nourishment dispersion. Figure 7-10 contains a series of lines depicting the temporal planform evolution of a rectangular nourishment. The resulting planform is symmetrical about the centerline of the nourishment. Therefore, only one-half of the resulting planform is shown in Figure 7-10. The solid black line indicates the initial fill template, and subsequent lines indicate the temporal progression of the nourishment. The vertical axis indicates the nourishment width (or distance seaward from the original shoreline), while the horizontal axis indicates the alongshore distance from the center of the nourishment. Within 1-year of placement of the nourishment, the shoreline excursion at the center of the project has already retreated over 100 ft, as sand has been transported in both directions due to the perturbation that is created on the shoreline. However, as shown by the lines corresponding to temporal changes in fill, the material diffuses onto the adjacent properties and is not lost from the local system immediately.

The Pelnard-Considére equation can be applied to many different scenarios by adjusting the boundary conditions. Dean (2002) has adapted the equations to evaluate sand movement in regions with inlets and/or structural influences. In addition, since the wave environment at Nantasket Beach can be complex, calculation of the alongshore diffusivity was completed based on the wave distribution for each average annual directional approach bin, as described in Chapter 4. Values of alongshore diffusivity were then computed for each directional bin and used in the modeling of beach nourishment performance.

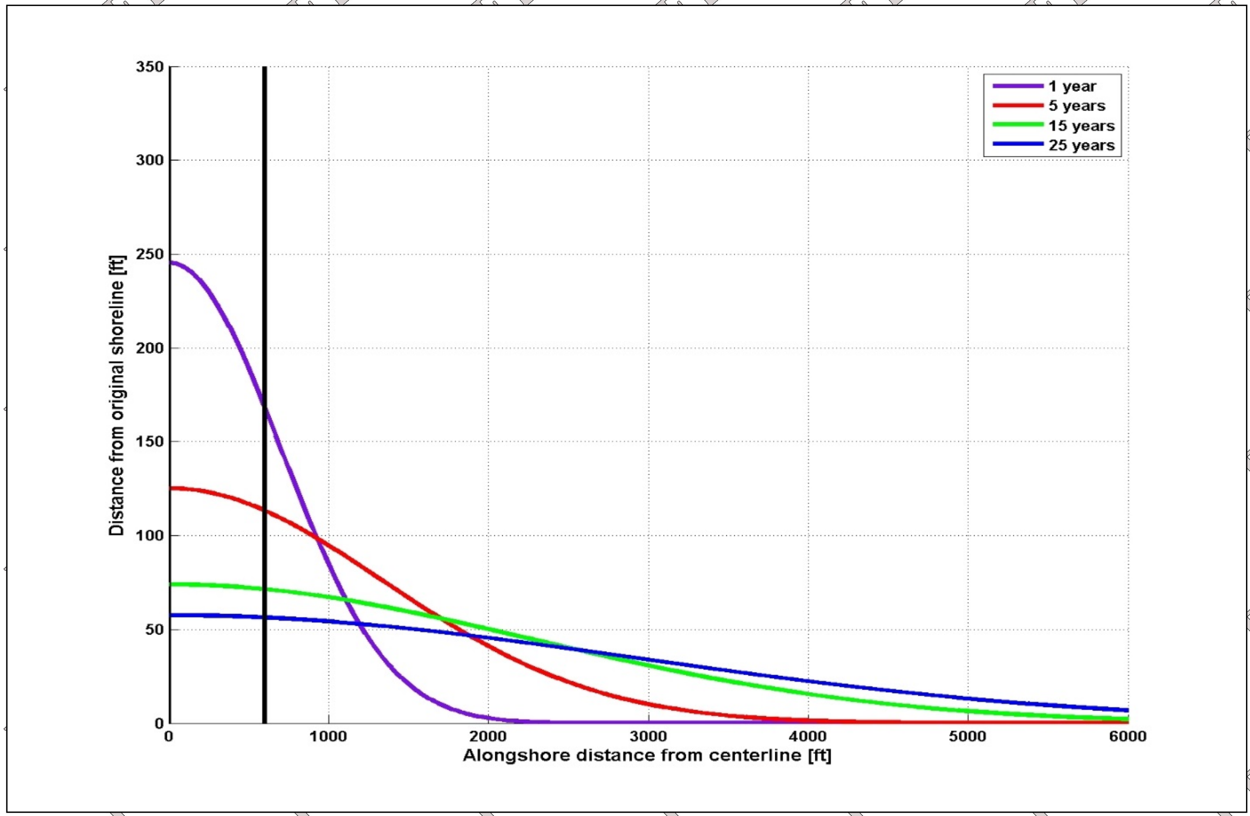

Figure 7-10. Temporal evolution of an example nourishment. Since the nourishment spreading is symmetrical in this simple case, only half the fill distance is presented.

Beach Nourishment Performance

Beach Longevity

Since the material diffuses (spreads) over time, it is possible to evaluate the longevity of the nourishment by looking at the amount of material (by percent) left in the project area. Subsequently, alternatives can be compared to one another based on their ability to maintain a beach. The service life of the beach nourishment is based upon the percent of the initial beach nourishment left within the boundary of the initial fill. The percentage remaining will decrease with time, but that material is not necessarily lost from the system, it has just spread to regions outside of the original nourishment template. For example, sediment may have been transported offshore or along the beach. Therefore, although the sediment no longer falls within the initial nourishment template, it has not disappeared from the system as a whole. The lifetime is calculated using the wave model results and the sediment transport results for average annual conditions. This includes typical storm events that occur over the course of an average year; however, this does not include larger storm events that may disperse a significant amount of material during a single event. Since the infrequent, larger storms are unpredictable, they are not directly included in the analysis. Therefore, the performance evaluation provides a reasonable estimate of the lifetime of the beach for each alternative given typical conditions that can be expected. If an infrequent, larger storm does occur during the project lifetime, the expected longevity would be reduced.

Figure 7-11 presents the performance of the range of beach nourishment scenarios (between the upper and lower solid lines) at Nantasket Beach. The black line represents the best performing beach nourishment scenario, while the blue line represents the lowest recommended performance beach nourishment scenario. The performance is expressed in terms of amount of material remaining in the initial template region, as a function of time. All results include a background erosion rate corresponding to 1.0 ft/yr. That is, in addition to the dispersion that is occurring, an additional 1.0 ft/yr is eroded due to the natural erosion of the beach (the highest average rate of erosion from the historical shoreline change evaluation for the DCR portion of Nantasket Beach). The percent of initial material remaining is presented along the left hand axis, while the time (in years) is presented along the bottom axis. For example, after 5 years, approximately 26-40% of the initial fill volume is remaining depending on the exact amount of material, type of material, and berm width used. Additionally, Figure 7-11 shows that 50% of the nourishment remains in the initial template region after approximately 2 to 4 years. This does not indicate that 50% of the initial fill volume has disappeared, but rather is no longer in the initial template area. Curves similar to those presented in Figure 7-11 were used to determine the relative performance impacts of various berm widths and heights, offshore slopes and grain sizes. For example, Figure 7-12 shows the performance of various grain size nourishment material at Nantasket Beach. The solid black line shows the performance of a mixed sand (0.25 mm) and cobble nourishment, the red line show the performance of a 0.45 mm mean grain size sand nourishment, and the blue line shows the performance of a 0.25 mm mean grain size sand nourishment. As expected, performance is slightly increased for the larger grain size fill material. These types of performance curves can be used to select the best performing nourishment design template considering all potential variables.

In order to verify that the performance modeling for Nantasket Beach was reasonable, the performance curves were compared to the measured performance of monitored beach nourishment projects in Massachusetts, as well as some in Florida. Figure 7-13 presents a comparison of the mean modeled performance with monitored nourishment performances for Gulf Shores, Sanibel Island, and Bonita Beach, Florida, as well as Dead Neck and Long Beach, Massachusetts. The modeled nourishment performance for Nantasket Beach (red line) appears reasonable, and perhaps somewhat conservative, when compared to actual nourishment performance. The range of modeled performance curves for Nantasket Beach compare well to those nourishments in the northeast, where a similar wave climate would be expected.

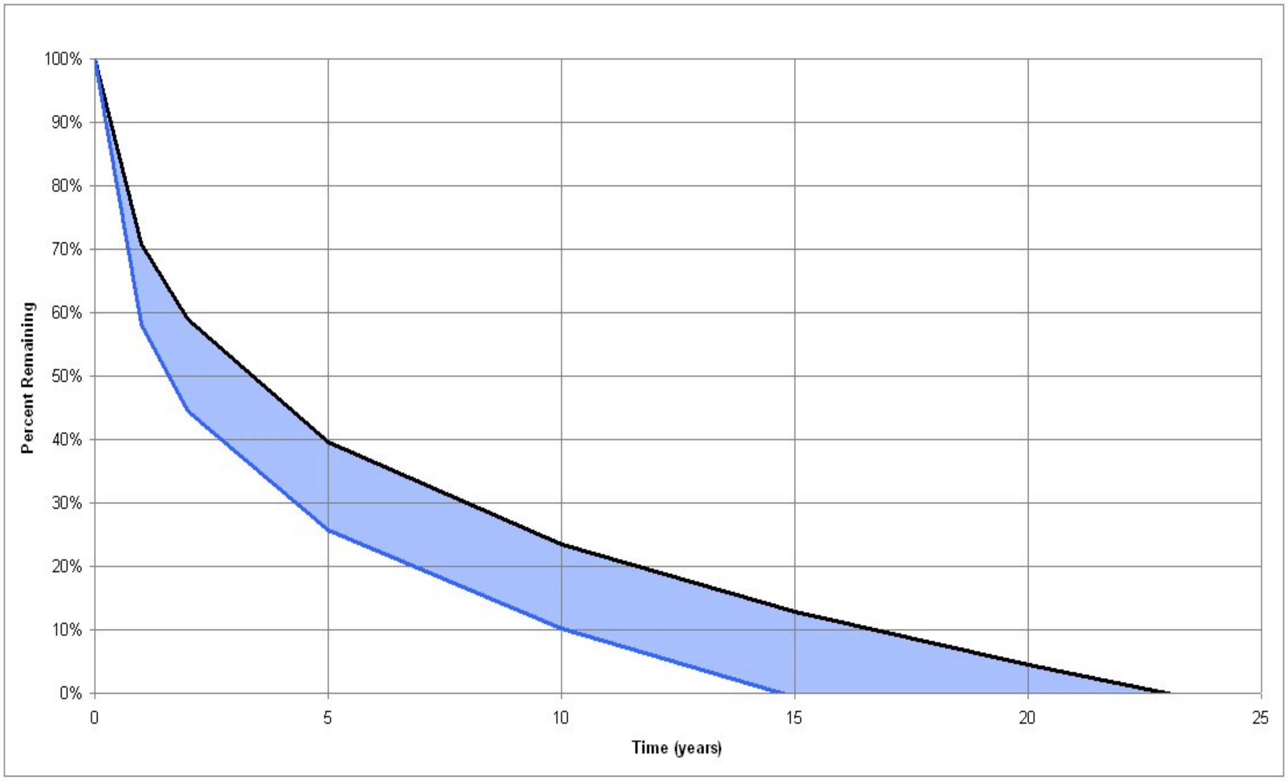

Figure 7-11. Beach nourishment performance for nourishment scenarios simulated at Nantasket Beach. The vertical axis represents the percent of fill remaining in the initial template area, while the horizontal axis represents time in years.

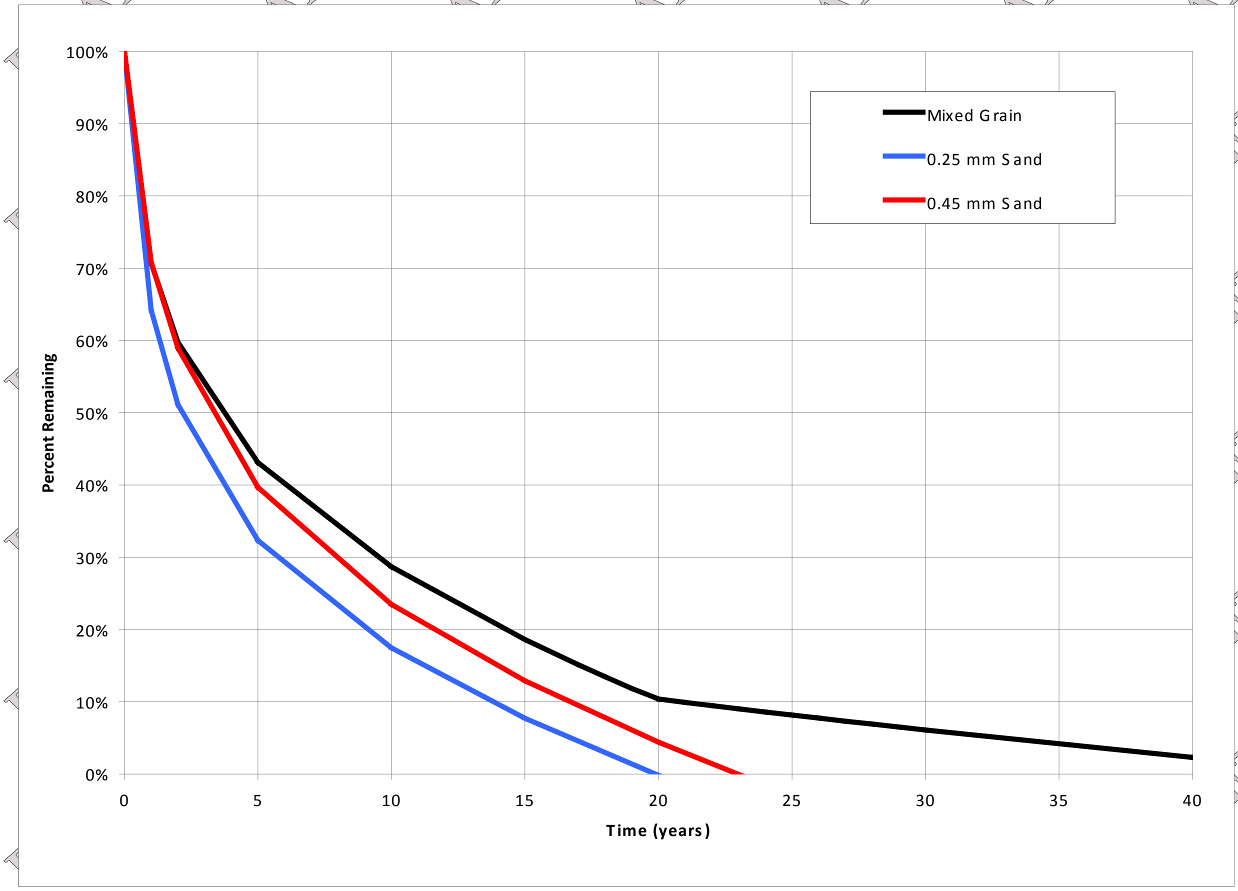

Figure 7-12. Beach nourishment performance for nourishment scenarios with a mixed cobble and sand grain nourishment (black line), a 0.25 mm sand nourishment (blue line), and a 0.45 mm sand nourishment (red line).

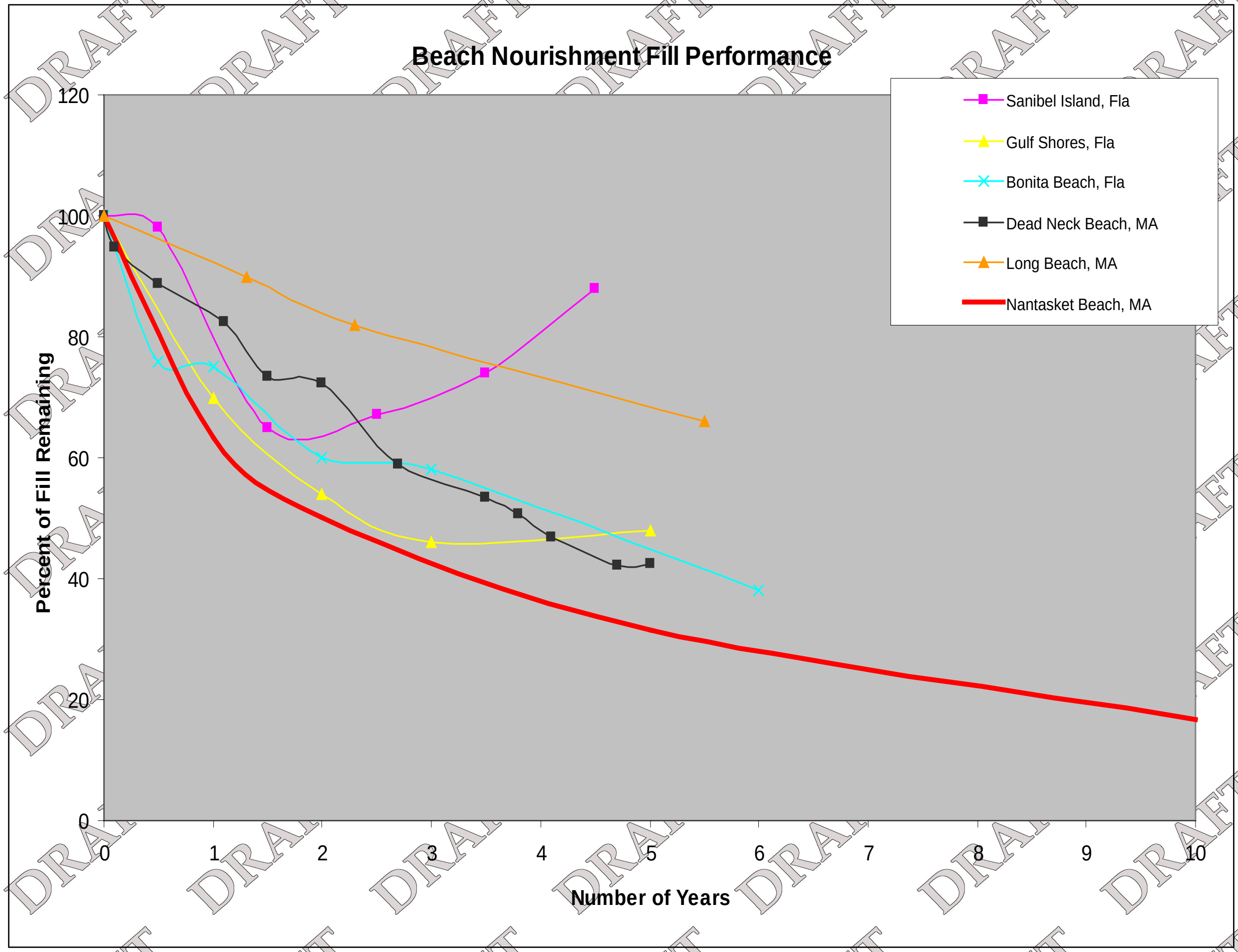

Figure 7-13. Comparison of the average projected Nantasket Beach nourishment performance to monitored beach nourishment performance.

For Alternative 7, the existing seawall would be demolished and a new seawall and fronting revetment would be constructed 30 feet landward. The fronting revetment would be similar to the toe protection that currently exists along the southern portion of the current seawall. As such, rock armor units would extend approximately 35 feet seaward from the base of the new seawall. Therefore, the actual increase in beach width would be minimal (relative to the current beach width). Subsequently, sand would be brought in to cover some of the fronting toe protection material and provide some temporary dune and beach area. This material would be much smaller in quantity and placed at a much steeper slope than the proposed beach nourishment alternatives (4, 5, 6, and 8). This dune-like feature would consist of a smaller volume of material and would not extend the beach width by more than approximately 40-45 feet from the toe of the revetment (compared to the 180-200 feet associated with the beach nourishment alternatives). This partial sand dune like feature would cover the revetment (35 feet seaward from the seawall) and extend the beach approximately 5-10 feet seaward of the toe of the revetment, and does not represent a significant gain in overall beach width. For Alternative 7, it is assumed that the gained beach width (approximately 5-10 feet from the base of the revetment) would continue to erode at the historical erosion rate of approximately 1.0 ft/yr. Although the overall gained beach width for Alternative 7 is significantly less than the gained beach for the full beach nourishment alternatives, the rate of erosion would be slower. The minimal amount of gained beach for this alternative would erode at a slower rate than sand pushed much further seaward into the active littoral zone, where dispersion of the sediment would be increased With the historic rate of erosion (1.0 ft/yr) the gained beach would erode back to the base of the revetment over approximately 5-10 years.

Critical Width

Beach nourishment projects are designed to optimize storm damage reduction benefits relative to costs. Designing a project to protect against any and all storms is not economically feasible. Extreme conditions and severe storms could exceed the capacity of a beach nourishment project to protect property. Therefore, a reasonable storm damage protection goal is typically established, defined here as the critical width. For Nantasket Beach, the critical width was defined as the minimum beach width remaining after nourishment before which a 10-year storm event would jeopardize upland infrastructure or the coastal structure (seawall, revetment). It assumes that once the beach width reaches the critical width, maintenance nourishment would be required to provide protection against a 10-year storm event, even though some amount of the existing nourishment may still be remaining. To assess critical width, a cross-shore profile adjustment model (SBEACH) was used to evaluate the storm protection provided by the design nourishment templates. Once the beach reaches this critical width, there is a reasonable chance that damage may occur during a moderate to large storm event. This signifies when a renourishment project should be planned. The critical width varies for various alternatives. For example, for the alternatives where a coastal structure (e.g., seawall, revetment) is used to provide a second line of defense for the beach nourishment, the beach could be allowed to erode back to its current condition and the coastal structure would still provide protection from a 10-year storm event (until the service life of the seawall is reached). However, for the alternative that removes the seawall, the beach nourishment could not be allowed to erode completely since some of the beach/dune system would be needed to provide protection against a 10-year return period storm. These differences in critical width define the overall system service life before maintenance would be required (Section 7.2.2).

The computer model chosen to perform the beach cross-shore evolution was SBEACH (Larson and Kraus, 1989). SBEACH is an empirically based numerical model for simulating two-dimensional cross-shore beach change. The model was initially formulated using data from prototype-scale laboratory experiments and further developed and verified based on field measurements (Larson and Kraus, 1989; Larson, Kraus, and Byrnes, 1990). The model predicts the time-dependent evolution of existing or design beach and dune profiles for specified water levels and wave conditions. In addition to the proposed nourishment template, the model requires a time-series of wave heights, wave periods and water levels as forcing inputs. The specific storm information required by SBEACH is a time history of total water level (tide plus surge) and wind wave height and period. For evaluation of the proposed beach nourishment templates, SBEACH was used to simulate erosion of the beach profile during storms of record using the wave information developed in Chapter 4.

Figure 7-14 shows the results of the cross-shore profile adjustment caused by a 10-year storm event at Nantasket Beach for Alternative 8. The initial profile (black line) shows a 15-foot beach berm at elevation 12 feet NAVD 88 and dune fronting a representative transect at the DCR portion of Nantasket Beach. The large structure behind the dune structure represents a building. The red line shows the beach profile following the 10-year storm event. The initial profile is eroded significantly and the dune has been exposed to wave action and overtopping and the start of significant flooding is expected. Therefore, once the initial nourishment has decayed to width of approximately 15 feet, a 10-year storm event could cause significant upland damage. For example, if Alternative 8 was constructed, after 9 to 17 years the beach would have a width of 15-feet (Figure 7-11) and renourishment would need to be considered.

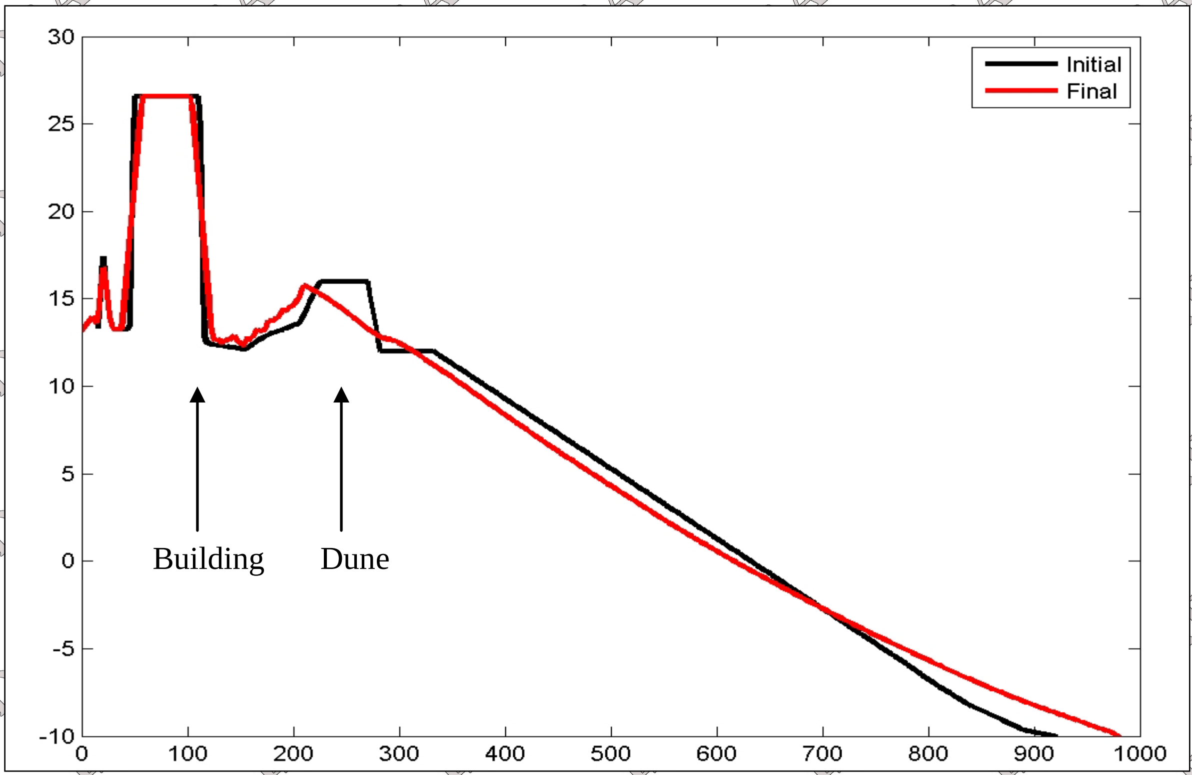

Figure 7-14. Pre and post storm profiles of a 15-foot wide beach berm at 12 feet NAVD 88 for Alternative 8. Elevation in feet NAVD 88 is presented on the vertical axis, and cross-shore distance (feet) is presented on the horizontal axis.

7.2.2 Structure Service Life and Overall System Service Life

In order to determine the overall system service life of each alternative, the service life of any proposed structures must be considered in addition to the beach lifetime. The overall service life is then the combination of the performance of the beach nourishment (if included) and the service life of the structure (if any).

- **Alternative 1:** The existing service life of the seawall structure with no protection is 0 to 6 years, as discussed above, based on beach erosion calculations and can vary depending on storm frequency and intensity.

- **Alternative 2:** Service life of the seawall is directly linked to the service life of the toe protection. The typically life of toe protection, which is sometimes considered a "temporary" measure, has an expected life span without maintenance of 15 to 25 years.

- **Alternative 3:** This alternative would construct a revetment structure in front of the existing seawall designed to be a more permanent storm damage control and scour countermeasure. The revetment is designed to have a 50 year lifespan without significant maintenance requirements.

- **Alternative 4:** This service life is based on the life span of the beach nourishment (15-23 years) plus the expected life of the wall with no protection (0-6 years). Therefore, the overall service life is 15 to 29 years.

- **Alternative 5:** Service life of the seawall is directly linked to the service life of the toe protection and beach nourishment. The typically life of toe protection, which is sometimes considered a "temporary" measure, has an expected life span with no maintenance of 15 to 25 years, beginning from a point which beach nourishment has eroded to the critical width (15 to 23 years). Therefore, the overall system service life would be approximately 30 to 48 years.

- **Alternative 6:** Service life of the seawall is directly linked to the service life of the revetment and beach nourishment. The revetment was designed to have a 50 year lifespan without significant maintenance requirements, beginning from a point which beach nourishment has eroded to the critical width (15 to 23 years). Therefore, the overall system service life would be approximately 65 to 73 years.

- **Alternative 7:** The construction of a new seawall and revetment is expected to have a design life of approximately 65 to 75 years. This alternative does not include the full beach nourishment of alternatives 4, 5, 6, and 8, and only includes a partial sand dune that is intended to cover the new revetment.

- **Alternative 8:** There is no proposed coastal structure in this alternative, and the beach will require renourishment after approximately 9 to 17 years, when the beach will reach a critical width. Although the beach itself will last 15 to 23 years, without any second line of defense, the beach would need to be renourished in order to maintain protection for upland infrastructure against a 10-year return period storm when the nourished beach width is reduced to 15 feet.

Table 7-2 presents a summary of the beach and overall system service life for each of the alternatives as detailed in this section. As discussed, the beach service life is provided as a range based on the grain size distribution, beach berm width, and berm height selected for final design. Table 7-2 also presents the increase in the high tide beach width initially after placement of the proposed alternative.

Table 7-2. Beach and overall system service life for the final alternatives.

Alternative	Initial High Tide Beach Width	Useable Beach Service Life	Overall Shore Protection System Service Life
1. No Action	Current Conditions	N/A	0-6 years
2. Toe Protection	N/A	No high tide beach	15-25 years
3. Revetment	N/A		50+ years
4. Beach Nourishment	185-200 feet	15-23 years	15-29 years
5. Toe Protection with Beach Nourishment	185-200 feet		30-48 years
6. Revetment with Beach Nourishment	185-200 feet		65-73+ years
7. Move Seawall back, revetment and dune	5-10 feet	5-10 years*	65-75+ years
8. Remove seawall and build dune	185-200 feet	15-23 years	9-17 years

* 20-30 years to reach the base of the seawall without a revetment/toe protection

7.3 Socio-Economic Impacts

The primary socio-economic considerations of any alternative consist of the following:

- Aesthetic and recreational benefits
- Economic benefits

This analysis focuses on the shoreline protection aspect of the project. Impacts from improvements of the upland portion of the Nantasket Beach Reservation are considered in the Master Plan.

7.3.1 Aesthetic and Recreational Benefits

As stated, Nantasket Beach is one of the primary recreational beaches of the area, drawing visitors from the Town of Hull and surrounding communities in the summer. Recreational activities along the beach and the seawall include the following (Figures 7-15 to 7-21):

- Sunbathing
- Swimming
- Surfing
- Kite-surfing
- Canoeing
- Socializing
- Walking along the promenade or along the beach at low tide
- Activities at the Bernie King Pavilion (such as senior citizen dances; youth events)
- Entertainment activities within the Nantasket Beach Reservation (carousel, mini-golf, arcades)
- Special events held at the Nantasket Beach Reservation (e.g., Nantasket Beach Car Show; Hull Youth Football Carnival).

Naturally, the primary season for recreation is the summer due to warm air temperatures and water temperatures that are acceptable for bathing. However, recreation occurs throughout the year at varying degrees of intensity.

Aesthetic and recreational benefits cannot easily be quantified as they are largely a personal experience. However, general assumptions can be made based on common perceptions:

- **Beach Width:** A large expanse of sand is considered preferable over a narrow strip of sand for the following reasons:
  - It allows recreation on the beach at all tidal levels (including high tide).
  - It increases the capacity of the beach for beachgoers, which means that beachgoers can spread out more unless the total number of beachgoers goes up proportionately.
  - It is visually more pleasant.
- **Grain Size:** A pure sand beach is preferable over a cobble beach, or mixed sand/cobble beach.
- **Beach Access**: Obstructed beach access (stairs, ADA accessible ramps) is not desirable (Figure 7-22).
- **Rocks:** Rocks along the seawall are not visually pleasant in combination with a narrow beach. The wider the beach, the less are rocks perceived to be a concern.

- **Seawall damage:** A seawall damaged during a storm, and resulting safety measures are not desirable.

Considering these assumptions, the following would pertain to the evaluated alternative with regards to aesthetic and recreational values (Table 7-3).

- **Alternative 1:** There would be little change under the no-action alternative. However, should the mid-section of the seawall fail during a storm, the aesthetic and recreational impacts would be considerable, as experienced during the collapse and repair period for the northern section of the seawall (Figure 7-23). The damaged section would be roped off, interrupting the walk along the promenade. Parts of the seawall may lie on the beach. Repairs would be slow given the needed design and permitting requirements. Depending on the location of the seawall failure, facilities such as the MJM bathhouse may become unavailable.

Figure 7-15. Beach in mid-section of the seawall during high tide (July 2005).

Figure 7-16. Beach in mid-section of the seawall during low tide (July 2007).

Figure 7-17. Beach in southern section of the seawall with existing toe protection during high tide (July 2005).

Figure 7-18. Beach in southern section of the seawall with existing toe protection during low tide (July 2007).

Figure 7-19. Beach promenade at MJM Bathhouse during high tide (July 2005).

Figure 7-20. Senior citizen dance at the Bernie King Pavilion (July 2005).

Figure 7-21. Socializing along the Nantasket seawall (July 2007).

Figure 7-22. Access to the beach via granite stairs constructed in 2007.

Figure 7-23. Damaged beach section along the northern section of the seawall. The seawall failed in 1991; it was repaired by 2006.

Table 7-3. Socio-economic benefits of the shore protection alternatives.

Alternative	Aesthetics and Recreational Benefits	Economic Benefits
1. No Action	No change short-term	No change short-term
2. Toe Protection	Less attractive	Minor benefit
3. Revetment		Minor benefit
4. Beach Nourishment	More attractive	Benefit
5. Toe Protection with Beach Nourishment		
6. Revetment with Beach Nourishment		
7. Move Seawall back, revetment and dune	Mixed	Minor Benefit
8. Remove seawall and build dune	Mixed	Uncertain

- **Alternatives 2 and 3:** The placement of rocks along the 2,100-foot-long mid-section of the seawall would reduce the width of the beach. The placement of toe protection (Alternative 2), similar to the toe protection along the southern part of the seawall, would typically narrow the beach over a width of approximately 20-25 feet, depending on the elevation of sand in front of the toe protection. The placement of a revetment (Alternative 3), similar to the revetment in the northern section of the seawall, would narrow the beach also by approximately 20-25 feet. Both alternatives would is essence eliminate most of the remaining high-tide beach in the mid-section of the seawall (Figure 7-15). The revetment would be more massive than the toe protection, thus would likely be perceived as a greater aesthetic impact. Either alternative would reduce the recreational benefits during high tide. On the other hand, both alternatives would prevent failure of the seawall thus avoid the resulting recreational and aesthetic impacts in the long term.

- **Alternatives 4 to 6:** Placing sand on the beach would be attractive for the aesthetic and recreational reasons outlined above. It is assumed that the wider the nourished beach, the less relevant are the aesthetic and recreational impacts of a hard structure placed in front of the seawall in addition to the beach nourishment (i.e., toe protection under Alternative 5; revetment under Alternative 6). Relative to Alternative 4 (no hard structure), a hard structure as part of Alternatives 5 and 6 would reduce the risk of seawall failure if a severe storm was to erode most of the beach nourishment.

- **Alternative 7:** Moving the seawall back by 30 feet increases the width of the high tide beach, although part of the gain would be taken up by the revetment. In addition, a partial sand dune would initially result in a widening of the beach after placement, as the sand dune would spread out. The width of the high tide beach for this alternative would depend to a large extent on the design of the partial sand dune. A wider footprint and a larger volume of sand placed into the dune would result in a wider high tide beach. The specific design of the sand dune would also have an effect on the aesthetic and recreational value. On the other hand, a landward shift of the seawall by 30 feet would have adverse impacts from the loss of the MJM Bathhouse, and the reduced functionality of the Bernie King Pavilion.

- **Alternative 8**: The aesthetic experience would be considerably different from the existing experience. In place of an easily accessible beach, there would be a sand dune and natural beach. Parking would be further offsite, as the current parking areas adjacent to the seawall would be largely taken up by the natural beach. The setting of Alternative 8 is considered aesthetically more attractive than the current seawall. Recreational impacts are mixed, however. On one hand, the experience of beachgoers would be improved due to the natural setting and wider beach. On the other hand, less people would have access to the beach. In addition, the loss of existing infrastructure such the Bernie King Pavilion, MJM Bathhouse, playground, restaurants, adjacent parking, and the Clarion Hotel are considered a considerable adverse impact. Furthermore, aesthetics and recreational benefits could be severely impacted after a storm if reservation and private buildings are damaged or destroyed.

7.3.2 Economic Benefits

Current economic activities on the reservation include the following:

- **Hotel:** The three-story Clarion Hotel is located along Hull Shore Drive, to the south of Water Street (Figure 7-24). The hotel has 105 guest rooms and is open year-round.

- **Residential properties**: There are several condominium buildings along the southern end of the beach:
  - Ocean Place Condominiums (Figure 7-25)
  - Horizons Condominium
  - Atlantic Hill Condominium (Figure 7-26)
  - Oceania Residences, constructed in 2007 on the hillside to the south of Nantasket Beach (Figure 7-26).
  - Condominiums are also planned along the northern section of the seawall on a parcel owned by the Hull Redevelopment Authority.

  Property values of these condominium buildings are expected to be affected by the recreational and aesthetic benefits of the Nantasket Beach.

- **Food establishments**: There are several restaurants, small coffee shops, ice-cream store within or just outside of the Reservation (Figures 7-27 to 7-28). Some of these establishments are open year-round, while others are only open during the summer.

- **Carousel**: Open from May through September (Figure 7-29).
- **Gift and craft shops, Arcades**: These establishments are only open during the summer.
- **Nantasket Landing Miniature Golf:** Open from early May to October, depending on the weather.
- **Bank:** The Rockland Trust Bank adjacent to the Red Parrot Restaurant is largely unaffected by beachgoers.
- **Parking:** Parking fees of the DCR lots are set by DCR. There are also some private lots, including the lot by the Hull Redevelopment Authority.
- **Summer camp along the beach:** Day camp groups for children spend the day on the beach during the summer (Figure 7-30).
- **Equipment rentals along the beach:** Currently, there are no commercial activities along Nantasket beach such as kayak or beach chair rentals.
- **Master Plan** *(in progress):* Planned improvements as part of the Master Plan, such as vendor stands along the promenade.

Figure 7-24. Clarion Hotel.

Figure 7-25. Ocean Place Condominiums.

Figure 7-26. Condominium buildings on Atlantic Hill (Oceania Residences on the right and Atlantic Hill Condominium on the left).

Figure 7-27. Restaurants along Nantasket Avenue.

Figure 7-28. Ice cream shop along Nantasket Avenue in the summer.

Figure 7-29. Friends of the Paragon Carousel.

Figure 7-30. Members of a summer day camp recreating at Nantasket Beach.

Variables related to the shore protection alternatives assessment for economic benefits include the following:

- **Number of beachgoers:** A greater number of beachgoers would result in a greater number of economic activities.
- **High tide beach conditions**: A beach that is unavailable during high tide results in people spending less time at the Reservation, resulting in less economic activity. While some beachgoers may move to the beach along the northern part of the Reservation, or go out for lunch, an increase in the length of the period during which the beach is inundated during high tide likely results in a decrease in beachgoers.
- **Seasonal vs. year-round activities**: Most economic activities at the site currently occur in the summer. A greater degree of activities during other seasons would depend on the attractiveness of the reservation as a day destination for primarily recreation, or evening destination for activities such as eating out.

Considering these factors, the following economic impacts are anticipated for the various shore protection alternatives (Table 7-3). It is noted that revenues from parking were not considered in this analysis, as parking would shift to other nearby locations, and as parking fees are currently set at a comparatively low rate.

- **Alternative 1:** There would be little change under the no-action alternative. However, should the mid-section seawall fail during a storm, the economic benefit would be reduced slightly as less people would be attracted to visit Nantasket Beach.

- **Alternatives 2 and 3:** In the short term, the placement of a rock structure (toe protection or revetment) in the mid-section of the seawall would have a minor adverse economic impact as the existing high tide beach in this section would be reduced. However, over the long term, the reduction in risk of seawall failure would result in minor economic benefits relative to current conditions.

- **Alternatives 4 to 6:** Placing sand on the beach would have economic benefits as a greater number of beachgoers would be attracted to the beach. In addition, beachgoers would stay longer, as there would be a beach during high tide. Additional benefits would occur as a result of improvements proposed as part of the Master Plan (in progress). There would also be an increase in value of private and DCR-owned properties and buildings (including condominiums).

- **Alternative 7:** Moving the seawall back by 30 feet increases the width of the high tide beach, although part of the gain would be taken up by the revetment. In addition, the partial sand dune would add additional beach width. As a result, beachgoers would stay longer on the beach, presumably frequenting businesses more often, thus resulting in a minor economic benefit.

- **Alternative 8**: The economic benefits are more speculative for this alternative. Less beachgoers would be expected on the beach due to more difficult access to the beach. On the other hand, the beach may be considered aesthetically more attractive, bringing in more visitors during other seasons or in the evening. However, an economic factor that would need to be considered as well would be the loss or damage of private and DCR-owned property during a large storm. The risk of such damage would affect property values and insurance rates. In addition, the loss of business along Hull Shore Drive (e.g., Red Parrot Restaurant, Clarion Hotel) would have adverse economic impacts. Also, there would be less space available for new amenities considered under the Master Plan.

7.4 PERMITTING AND CONSTRUCTION

7.4.1 Permitting

All of the proposed Nantasket Beach shore protection alternatives would trigger a number of state and federal regulatory programs. With the exception of Alternative 1, all the alternatives involve substantial fortification (toe protection or revetment; Alternatives 2, 3, 5, 6) of the existing seawall, or involve demolition and replacement with a new seawall (Alternative 7) or sand dunes (Alternative 8). The level of permitting complexity for the various alternatives varies (Table 7-4).

All alternatives, except Alternative 1, require the following filings:

- Massachusetts Environmental Policy Act (MEPA) Environmental Impact Report
- Massachusetts Wetlands Protection (WPA) Order of Conditions
- Section 401 Water Quality Certification
- Chapter 91 Waterways License
- Section 404 U.S. Army Corps of Engineers authorization
- Coastal Zone Management (CZM) Federal Consistency Concurrence.

Alternatives with a beach nourishment or dune construction component (Alternatives 4 to 8) introduce substantially greater permitting complexity and cost due to potential environmental impacts associated with the sediment source, transport and placement. Based upon preliminary estimates of required sand volumes, upland sources for sand and trucking to the site would be considerably more expensive than a marine source. However, recent efforts to seek regulatory approvals for offshore sediment sources for beach nourishment have stalled. Permitting with sand from an offshore sand source would be more stringent than with sand from an upland sand source and would also require approvals from the National Marine Fisheries Service (NMFS) regarding impacts to Essential Fish Habitat.

Impacts to landside infrastructure associated with Alternative 8 (and to a lesser extent with Alternative 7) add another layer of regulatory considerations with additional cost. These alternatives may require relocation of roadways and underground utilities, displacement of residents and businesses, impacts to open space protected under Article 97, impacts to historic buildings protected under Section 106, hazardous materials concerns with building demolition and FEMA approvals for alternation of flood zones.

Table 7-4. Environmental permitting and construction period estimates of the shore protection alternatives.

Alternative	Environmental Permitting: Complexity	Environmental Permitting: Permitting Period	Construction Period
1. No Action	None	n/a	n/a
2. Toe Protection	Comparatively simple *(5)*	**0.75 years**	**1 year**
3. Revetment	Standard	**1.5 years**	**1 year**
4. Beach Nourishment	Complex	**3 years (offshore source)** *(1)* **1.5 years (upland source)**	**Rock Structure (Alt. 5 & 6)** *1 year* **Beach Nourishment (Alt. 4 - 6)** *1 year - Offshore source: (1)* *9-14 years (upland source) (2)* **Totals**: Alt. 4: 1-14 years Alt. 5: 2-15 years Alt. 6: 2-15 years
5. Toe Protection with Beach Nourishment		**3 years (offshore source)** *(1)* *Rock structures:* 1.5 year *Beach Nourishment:* 3 year	
6. Revetment with Beach Nourishment		**1.5 years (upland source)** *Rock structures:* 1 year *Beach Nourishment:* 1.5 years	
7. Move Seawall back, revetment and dune	Complex	**3 years** (offshore source) *(1)* or (upland source)	**4 years (offshore source)** *(1)* *Wall / Rock structure:* 3 years *Partial sand dune:* 1 year **6+ years (upland source)** *Wall / Rock structure:* 3 years *Partial sand dune: 3+* years *(3)*
8. Remove seawall and build dune	Very complex	**3-5 years** (Offshore sand source) *(4)*	**4 years** (offshore sand source) *(4)*

(1) This assumes that an offshore sand source can be utilized which is currently not possible.

(2) Based on a nourishment rate of 75,000 and 50,000 cy/year, respectively.

(3) Rough estimate only, as the length for construction depends significantly on the specific design and volume of sand to be placed in a partial sand dune.

(4) This alternative is not considered feasible using an upland sand source.

(5) Permit applications are largely prepared as part of the former Seawall Toe Protection (STP) application in 2006.

Estimates of the permitting period are included in Table 7-4. The shortest permitting is required for Alternative 2 (i.e., nine months), for which some of the permit applications already partially exist as a result of permitting efforts in 2006 for the placement of seawall toe protection (STP) in response to an accelerated shore protection schedule proposed by then DCR Commissioner Golledge. Permitting for Alternatives 3 would require approximately 1.5 years. Permitting for the remaining alternatives would be considerably longer and are fundamentally affected by the following two factors:

- **Offshore Sand Source:** An offshore sand source is currently unavailable and will likely not be available for several years. The extent of permitting requirements, if and when an offshore source is available, is currently not known. Estimates listed in Table 7-4 are provided for the time that a source *is* available.

- **Upland Sand Source:** The Town of Hull has stated that it is concerned about the environmental impact from the required truck traffic due to noise, traffic congestions, and structural impacts to roads.

7.4.2 Construction Period

The length of construction varies considerably between different alternatives (Table 7-4):

- **Alternatives 2 and 3:** Rock structures in the mid-section of the seawall will require approximately one year to be placed.

- **Alternatives 4 to 6:** Construction of the rock structures for Alternatives 5 and 6 would require one year; these structure should be placed prior to placing beach nourishment. Beach nourishment from an offshore source (if available) can be completed within one year. Beach nourishment from an upland source would require considerably more time and can be done over several years, depending on the agreed nourishment rate using trucks. However, the rate of nourishment from upland sources needs to be greater than the rate of erosion to be effective. The recommended rate for nourishment is 50,000 to 75,000 cy/year (see Section 8).

- **Alternative 7:** Demolition of the existing seawall and construction of the new wall and affected infrastructure is estimated to require 3 years. Demolition of the old wall and construction of the new wall would need to be carried out in a manner that does not endanger coastal properties during the demolition of the existing structures. Placing the sand for the partial sand dune requires approximately one year using an offshore source (if available). As for Alternatives 4 to 6, the duration needed for placing the dune from an upland sand source is dependent on the agreed frequency of truck traffic, and thus may last several years.

- **Alternative 8:** Demolition of the existing wall and construction of the sand dune and affected infrastructure is estimated to require 4 years. Demolition of the old wall and construction of the dune would need to be carried out in a manner that does not endanger coastal properties during the demolition of the existing structures. An offshore source is more critical for this alternative for two reasons: (1) A gradual placement of the sand is not practical and would make the beach unattractive for as long as it takes to provide the needed sand for the dune, as the existing seawall would need to stay (at least partially) to provide shore protection in the interim. (2) A significant sand source should be readily available in case a major storm erodes part of the dune to a point where it no longer provides effective shore protection (assuming that the extent of the storm damage is contained and still allows for reconstruction of the dune).

7.5 COST ESTIMATES

Cost estimates were developed for the shoreline protection alternatives consisting of the following components:

- Initial capital costs
- Operation and maintenance costs
- Right-of-Way costs
- Upland damage costs

Costs do not include loss of business costs which are most relevant for Alternative 8.

7.5.1 Initial Capital Costs

Capital costs pertain to the construction of the infrastructure required for each shoreline protection alternative. These costs include the following components, as applicable:

- Final Design and Permitting
- Demolition and Removal
- Construction of rock structures, seawall, dunes, roads, utilities
- Placement of beach nourishment

Costs are based on estimated quantities and items of the conceptual design on a per-foot basis. Unit costs were obtained from a variety of standard sources including the following:

- Previous projects completed at Nantasket Beach
- Other beach restoration projects
- Other marine infrastructure projects
- Massachusetts Highway Department projects
- Other New England Department of Transportation projects
- U.S. Army Corps of Engineers cost estimates
- Engineering judgment based on complexity

7.5.2 Operation and Maintenance Costs

Operation and maintenance (O&M) consisted on the following key components:

- **Renourishment costs of the beach:** This applies to alternatives with a beach nourishment component. For Alternatives 4 to 6, the beach is estimated to require renourishment on average every 20 years. For Alternative 8, the beach is estimated to require renourishment on average every 12 years at a cost of approximately $16 million at current dollars (i.e., unadjusted for inflation).

- **Routine repairs to existing and proposed structures, and a 10-year cycle**: This would include repairs of the seawall, resetting of the revetment, adjustments to the dunes, and repairs of building from storm damage. It is assumed that the return period of a storm causing damage is 10 to 25 years.

The total operation and maintenance costs calculated for each alternative was closely linked to the service life of each respective structure.

7.5.3 Right-of-Way Costs

These costs are based on research conducted by U.S. Army Corps of Engineers (New England District) that were updated in 2007. These costs only include private parcels at this time.

7.5.4 Upland Damage Costs

Upland damage costs pertain to damage of public and private buildings and infrastructure from storms. These estimates were developed by the U.S. Army Corps of Engineers on February 8, 2006 and provided to us for this project. Baseline values for upland damage costs that were applied consist of the following:

- Alternative 1: $0.53 million/year
- Alternatives 2 and 3: $0.395 million/year
-
- Alternative 4: $0.05 million/year year (assuming the beach is maintained)
- Alternatives 5 and 6: $0.05 million/year (first 20 years), and $0.395 million/year during the last 30 years (unless beach is renourished)
- Alternative 7: $0.05 million/year for the first 30 years, and $0.395 million/year for the last 20 years (unless beach is renourished)
- Alternative 8: $0.05 million/year (assuming the beach is maintained)

7.5.5 Costs for each Alternative

Costs for the eight shoreline protection alternatives are summarized in Table 7-5 and Figure 7-31. These costs are based on current value dollars (i.e., are not adjusted for inflation).

- **Alternative 1:** Capital costs pertain largely to concrete spall and seawall joint repairs along 4,500 linear feet of the seawall (mid-section and southern section of the seawall). Q&M costs would consist of routine repairs to the seawall, resetting of the toe protection, and emergency repairs to the wall and other infrastructure after major storm events. Upland damage costs ($26.5 million) are the highest of all alternatives as a result of the risks from seawall failure during a storm. The total life cycle costs for Alternative 1 are estimated to be $42 million to $67 million. The wide spread is a function of damage from seawall failure as a result of a major storm.

- **Alternative 2:** Capital costs pertain to concrete spall and seawall joint repairs along 4,500 linear feet of the seawall (mid-section and southern section of the seawall; $0.6 million), as well as the placement of the toe protection in the mid-section of the seawall ($3.6 million). The upland damage costs are still high ($19.8 million) as risks to structures during major storms remain. Q&M costs would consist of routine repairs to the seawall and resetting of the toe protection. The total costs for Alternative 2 are estimated to be $26 million.

- **Alternative 3:** Capital costs pertain to concrete spall and seawall joint repairs along 4,500 linear feet of the seawall (mid-section and southern section of the seawall; $0.6 million), the removal of the toe protection in the southern section of the seawall ($1.4 million), as well as the placement of the revetment in the mid-section and southern section of the seawall ($11 million). Q&M costs would consist of routine repairs to the seawall and revetment. Upland damage costs are similar to the costs for the revetment using the USACE approach ($19.8 million). The total costs for Alternative 3 are estimated to be $35 million.

- **Alternative 4:** Capital costs pertain to concrete spall and seawall joint repairs along 4,500 linear feet of the seawall (mid-section and southern section of the seawall; 0.6 million), as well as placement of beach nourishment across the full length of the beach (6,000 linear feet; $16 million). Q&M costs would consist mostly of renourishment costs every 20 years, as well as repairs to the seawall which would increase within each renourishment cycle as the sand is gradually eroded. Upland damage costs are sharply reduced to $2.5 million due to the much wider beach. The total costs for Alternative 4 are estimated to be $67 million.

- **Alternatives 5 and 6:** Capital costs for these alternatives would be the sum of the capital costs for Alternatives 2 and 3, respectively, and the costs for beach nourishment. Q&M costs would consist of repairs to the seawall and rock structures. The largest O&M line item would pertain to renourishing the beach at 20 year intervals ($16 million per renourishment). Upland damage costs are lower with renourishment than without renourishment. The total costs for Alternatives 5 and 6 are estimated to range from $35 million to $78 million, depending on the chosen rock structure and on renourishment plans.

- **Alternative 7:** Capital costs pertain to the removal of the existing toe protection, seawall and parking ($8 million); MJM bathhouse modifications or removal ($2 million); construction of a new seawall ($17 million); construction of a revetment ($12 million), and placement of a partial sand dune ($9 million). O&M activities would consist of routine repairs to the seawall and revetment, and optional beach nourishment. As for Alternatives 5 and 6, upland damage costs would vary depending on renourishment plans. The total costs for Alternative 7 are estimated with $59 million or $96 million, depending on renourishment plans.

- **Alternative 8:** Capital costs pertain to the demolition of the seawall, rock structures, MJM bathhouse, Bernie King Pavilion, and Tivoli bathhouse; excavation of parking lots and roadways; and roadway and utility reconstruction. An additional $12 million would be required for Right-of-Way costs as a result of buildings that need to be taken along Hull Shore Drive along the mid-section of the seawall (i.e., buildings from the Parrot Restaurant through the Clarion Hotel); these costs do not include lost revenue by these businesses. O&M activities would consist of beach renourishment every 12 years to maintain the critical beach width ($67 million over 50 years), as well as repair or replacement of the ProTec tubes which would form the central core of the dunes ($7 million in 50 years). Upland damage costs would be low, assuming the critical beach width is maintained to be able to withstand a major storm at all times. The total costs for Alternative 8 are estimated with $133 million to $145 million; the higher value includes the Right-of-Way costs.

Table 7-5. Life cycle cost estimates of the shore protection alternatives.

Alternative	**Initial Capital Costs**	**Operation and Maintenance Costs** *50-year Horizon* (Present Value Cost)	**Upland Damage Costs** *(6)* (USACE, NAE District Estimates)	**Total Costs 50-year Horizon** (Present Value Cost)
1. No Action	$0.6 million	$15 - $40 million *(1)*	$26.5 Million	**$42 - $67 million**
2. Toe Protection	$4 million	$2.5 million *(2)*	$19.8 million	**$26 million**
3. Revetment	$13 million			**$35 million**
4. Beach Nourishment	$17 million	$47.5 million *(2,3)*	$2.5 million	**$67 million**
5. Toe Protection with Beach Nourishment	$20 million	$2 million *(2)* *(without renourishment)* $47 million *(2,4)* *(with renourishment)*	$12.9 million *(without renourishment)* $2.5 million *(with renourishment)*	**$35 million** *(without renourishment)* **$70 million** *(with renourishment)*
6. Revetment with Beach Nourishment	$29 million			**$44 million** *(without renourishment)* **$78 million** *(with renourishment)*
7. Move Seawall back, revetment and dune	$48 million	$2 million (2) *(without renourishment)* $ 46 million *(2,5)* *(with renourishment)*	$9.4 million *(without renourishment)* $ 2.5 million *(with renourishment)*	**$59 million** *(without renourishment)* **$96 million** *(with renourishment)*
8. Remove seawall and build dune	$56 million *(without Right-of-way)* $68 million *(includes Right-of-way) (6)*	$74 million *(7)*	$2.5 million	**$133 million** (without Right-of-way) **$146 million** (includes Right-of-way) *(6)*

(1) Highly variable. Possible range $3 million to $8 million every 10 years.

(2) Rock structure maintenance (reset/replace) as well as seawall maintenance every 10 years.

(3) Beach requires renourishment approximately every 20 years ($16 million).

(4) Beach can be renourished every 20 years ($16 million for Alt. 4-6; $8.8 million for Alt.7), but not required.

(5) Beach can be renourished after 10-15 years, but not required.

(6) Capital costs do not include the value of long-term, or shorter-term, revenues lost by businesses.

(7) Beach/dune requires renourishment approximately every 12 years ($16 million), as it must be maintained once the beach reaches critical width (10-15 feet). Also, replacement of ProTec tubes after significant storm events.

Figure 7-31. Estimates of Total Costs (based on 50-Year Horizon in Present Value Dollars).

8.0 SAND SOURCE INVESTIGATION

Since beach nourishment may likely be a key component of the preferred alternative, borrow sediment would be required to supply beach nourishment material to Nantasket Beach. A key component of a nourishment project is identifying a suitable sand source(s) that meet the engineering design criteria, is affordable, and is acceptable from an environmental standpoint. A sufficient quantity and quality of sand must be identified, preferably from a location in close proximity to the beach, and from a location where removal of sand will not result in undesirable environmental impacts.

Although identification and assessment of a specific source of sediment to nourish Nantasket Beach was not included as part of the current scope of the study, an initial investigation was conducted to identify potential feasible source options for beach nourishment alternatives. This investigation represents a preliminary evaluation on potential upland and offshore sources, including a feasibility assessment of using upland material in the construction of a large nourishment project. Upland sources may be significantly more expensive due to transportation costs. Locating a new offshore borrow site can be challenging since locations need to have a significant quantity of compatible material and limit environmental impacts to the dredge location. Additional studies, field data collection, environmental assessments, compatibility evaluation, and permitting is required prior to final selection, approval, and utilization of a borrow location.

Sand grain size is typically a governing design factor. The ideal sand source provides a grain size that is at least as coarse as the native beach material. Sand that is finer than the native beach sand often is eroded more rapidly from the beach by waves and currents. The result of using sand that is finer than the native beach sand is added expense, reduced storm protection, and reduced beach nourishment design life. Consequently, adequate testing of the native beach and the alternative sand source(s) is crucial to ensure the sand source provides clean, beach-compatible material that satisfies the engineering design criteria.

As part of this study, both upland and offshore sources were considered as to their potential for beach nourishment operations at Nantasket Beach, at a preliminary level. The location of the sand source dictates the method(s) by which the sand can be transferred to the beach, and the cost of construction. Sand from upland sources is typically trucked to the beach, which can be expensive depending upon the proximity of the source to the beach and the prevailing cost of trucking and fuel. Trucking operations also limit the volume of sand that can be delivered to the beach, and can cause traffic and community conflicts. For large nourishment projects like Nantasket Beach, use of upland sand sources would require the nourishment to take place over multiple years in order to get the total amount of sand required to the beach. A closer look at upland and offshore sand sources, as they pertain to Nantasket Beach, is included in the subsections to follow.

8.1 UPLAND SAND SOURCES

Based on the current regulatory climate and recent history in permitting offshore sand sources for beach nourishment in Massachusetts, an upland-based source may be the most feasible option for Nantasket Beach from a regulatory standpoint, at least for the foreseeable future. If another offshore sand source is considered in the future, it will likely not be available for mining for 3 to 5 years, at a minimum. Therefore, an assessment of the feasibility, logistics, and performance of using a land-based sand source for beach nourishment was conducted. Specifically, the potential feasibility of using an upland-based sand source to nourish Nantasket Beach, requiring construction over multiple seasons to complete the full nourishment project was evaluated in this section.

8.1.1 Potential Upland Sources and Vendors

Although a number of vendors were contacted for information regarding their sand resources and availability to provide material for this project, only vendors that stated they could provide the entire targeted nourishment volume of at least 25,000 cubic yards (cy) per year are presented in this report. All sand supply contractors have stated that the information (e.g., sand unit prices, grain sizes, and source locations) provided to the Woods Hole Group for this report is not guaranteed and is subject to change. The costs presented in this section are based on cost in 2008, and do not include potential impacts of economic fluctuations or inflation. Competitive bidding at the time of construction will determine the actual costs.

- *Kingstown Corporation, Plymouth, MA:* The Kingstown Corporation of Plymouth, MA has stated that it can supply up to 700,000 cy of beach compatible sand over the duration of the project. The unit cost for the sand is $16.50/cy, which includes delivery from the Plymouth quarry to Hull. The grain size D_{50} of the material is 0.38 mm. Kingstown has stated that it can deliver approximately 2,000 cy/day using dump trailers with a capacity of 34 tons, or roughly 26 cy.

- *P.A. Landers, Plymouth, MA:* The P.A. Landers, Inc. company of Plymouth, MA stated that it could supply up to 700,000 cy of beach compatible sand over the duration of the project. The unit cost for the sand was not provided at this time, but the cost would include delivery from their multiple quarry locations in Plymouth to Hull. A grain size was not provided for the material, although it was assured that the material would have a D_{50} of approximately 0.3 to 0.6 mm. P.A. Landers has a large fleet of trucks with 26 cy capacity trailers and has the ability to deliver up to 3,000 cy per day to the project site.

- *Cape Cod Aggregates, Bourne, MA:* The Cape Cod Aggregates company of Hyannis, MA stated that it could supply up to 700,000 cy of beach compatible sand over the duration of the project. The unit cost for the sand was $20.50 – $22.50/cy, which includes delivery from either of their source quarries in Bourne or Sandwich, to Hull. The distance from Bourne to Nantasket is 47 miles one way, and 52 miles from Sandwich to Nantasket. The grain size D_{50} of the Bourne and Sandwich material is 0.41 mm and 0.53 mm, respectively. Cape Cod Aggregates stated that it could deliver approximately 30 to 40 truck loads, or 800 to 1,100 cy/day using dump trailers with a capacity of roughly 26 cy.

- *G. Lopes Construction, Taunton, MA:* The G. Lopes Construction company of Taunton, MA stated that it could supply up to 700,000 cy of beach compatible sand over the duration of the project. As of late August 2008, G. Lopes had over 100,000 cy available for immediate delivery. The unit cost for the sand was $19.25/cy, which includes delivery from their source quarry, 46 miles to Hull. The grain size D_{50} of the material is approximately 0.3 to 0.45 mm. G. Lopes stated that it could deliver approximately 2,240 to 2,800 cy/day using dump trailers with a capacity of roughly 28 cy.

- *Plympton Sand and Gravel, Plympton, MA:* The Plympton Sand and Gravel Company of Plympton, MA stated that it could supply up to 60,000 cy/year of beach compatible sand over the duration of the project. The unit cost for the washed sand was $23.75/cy, which includes delivery from their Plympton, MA source quarry to Hull. The washed sand product was proposed by Plympton S&G because it contains only trace amounts of fine grained sediments. The grain size D_{50} of the material is 0.65 mm. The company has stated that it could deliver approximately 2,000 to 3,000 cy/day using dump trailers with a capacity of roughly 26 cy.

- *A.A Will Materials Corporation, Stoughton, MA:* The A.A. Will Materials Corporation of Stoughton, MA stated that it could supply up to 700,000 cy of beach compatible sand over the duration of the project. The unit cost for the sand was $28.50/cy, which includes delivery from their Sandwich, MA source quarry to Hull. The grain size D_{50} of the material is 0.36 mm. A.A. Will stated that it could deliver approximately 230 to 310 cy/day using dump trailers with a capacity of roughly 26 cy.

- *A.D. Makepeace, Wareham, MA:* The A.D. Makepeace Company of Wareham, MA stated that it could supply up to 700,000 cy of beach compatible sand over the duration of the project. The unit cost for the sand was $20.00/cy, which includes delivery from their Wareham and Carver, MA source locations to Hull. The grain size D_{50} of the material is 0.61 mm. A.D. Makepeace stated that it could deliver approximately 2,000 to 3,000 cy/day using dump trailers with a capacity of roughly 26 cy.

8.1.2 Compatibility Comparison of Sources

A compatibility comparison is presented in this section for each of the identified upland sources and suppliers. This comparison is intended to assist in a potential decision of which upland source may be most appropriate for use as nourishment material of Nantasket Beach. The comparison is based on the physical properties of the sand, delivery logistics, and cost.

The options for a Nantasket Beach nourishment source require careful consideration in order to choose the most appropriate and efficient means to complete the project and minimize impact to the environment and community. Consideration of the upland sources and vendors described in the previous section was performed by evaluating certain common parameters in a comparative cost-benefit analysis. These parameters assess beach compatibility and rate and cost of delivery. Table 8-1 tabulates the parameters evaluated in this analysis: material grain size, delivery method, delivery distance, rate of delivery, and unit cost. It is important to note that the information contained in Table 8-1 was provided by the sand supply contractors for feasibility guidance only, and that information is subject to change based upon source availability, source location, and fuel costs at the time of the nourishment construction.

Although the evaluation parameters may be self-explanatory in nature, they are nonetheless defined here to ensure the relevance to the compatibility comparison and Table 8-1.

- *Material Quantity:* Defines the volume of sediment available for nourishment usage for each year. For example, A.D. Makepeace Company of Wareham, MA stated that it could supply up to 700,000 cy/year, while the Plympton Sand and Gravel Company of Plympton, MA stated that it could supply up to 60,000 cy/year. However, the amount of sediment supplied each season is limited by the available days for transport and number of trucks available. Therefore, the value presented in the table presents the maximum amount of material available for each nourishment season. This value can be compared to the scenarios presented in the technical analysis section (8.1.4).

- *Material Grain Size:* Defined as the median grain size (D_{50}) of a source sample. This was the primary parameter used to evaluate the compatibility of the upland source material with the native Nantasket Beach material, and quantify the resistance of the nourishment material to erosional forces. In addition, other physical parameters (such as source sorting and color) were also considered when speaking with the vendors and reviewing the grain size distributions. However, the exact grain size, sorting, color and/or upland source location is not selected as part of the current analysis. The focus of this analysis is solely the technical feasibility of using an upland source for a nourishment project of this scale.

- *Delivery Method:* Describes the process and equipment used to transport nourishment material to Nantasket Beach.

- *Delivery Distance:* Quantifies the road distance in miles that a truck must travel to transport the nourishment material from the source to the project site.

- *Rate of Delivery:* Defines the rate at which a volume (cy) of material can be transported to Nantasket Beach in a single workday.

- *Unit Cost:* Monetary value ($) associated with a volume (cy) of nourishment material. This includes all costs (mobilization/demobilization, transport, fuel, etc.) unless specifically indicated.

Table 8-1. Nantasket Beach Nourishment: Matrix of Upland Sources.

Vendor	Source Location	Material Quantity (cy/year)	Material Grain Size (D_{50} mm)	Delivery Method	Delivery Distance (miles)	Rate of Delivery (cy/ workday)+	Unit Cost ($/cy)	Notes
Kingstown Corporation	Plymouth, MA	100,000	0.38	26 cy Dump Trailer	30	2,000 – 3,000	$16.50	
P.A. Landers, Inc.	Plymouth, MA	100,000	0.3 – 0.6	26 cy Dump Trailer	30	3,000	TBD*	
Cape Cod Aggregates	Bourne and Sandwich, MA	100,000	0.41 – 0.53	26 cy Dump Trailer	47 – 52	800 – 1,100	$22.50	
G. Lopes Construction	Taunton, MA	100,000	0.3 – 0.45	28 cy Dump Trailer	46	2,100 – 2,600	$19.25	100,000 cy avail. as of 8/29/08
Plympton Sand and Gravel	Plympton, MA	60,000	0.65	26 cy Dump Trailer	35	2,000 – 3,000	$23.75	Washed Sand, Limit of 60,000 cy/year
A.A. Will Materials Corporation	Sandwich, MA	100,000	0.36	26 cy Dump Trailer	50	~300	$28.50	Masonry Sand, Truck Limited
A.D. Makepeace	Wareham and Carver, MA	100,000	0.61	26 cy Dump Trailer	45	2,100	$20.00	

* PA Landers did not provide a cost/cubic yard of material.
+ Assumes an 8 hour workday

For this analysis, all sources will be transported to Hull from RT 3 via RT 228, Summer St. (or RT 3A), Rockland St., and George Washington Blvd. This transportation route was referenced in USACE (2004b) as an approved trucking route. This route minimizes the distance from the sources to the project site and minimizes the noise and environmental impact of the trucks on the residential community and roads.

8.1.3 Nourishment Delivery Scenarios

In order to evaluate the performance and efficiency of beach nourishment supplied solely from upland sand sources, four specific beach nourishment scenarios were identified based upon the information received from the upland sand source vendors, the technical feasibility of transportation of the material and impacts to the roadways, and review of previously Nantasket Beach nourishment investigations (USACE, 2004b). These four scenarios are designed to represent the potential range in delivery rates during the nourishment construction. Table 8-2 tabulates the characteristics and working statistics of the four scenarios. When developing each of the nourishment scenarios, transportation logistics, community impacts, and environmental impacts were accounted for to ensure that each scenario was designed using realistic assumptions. In each incremental scenario the total volume of sand delivered to the project site per season is increased.

Table 8-2. Nantasket Beach nourishment scenarios used in performance evaluations.

Scenario	Total Volume per Season (cy)	Individual Load Volume (cy)	Loads per Day	Truck Passage Frequency (min.)	Project Time (Seasons)
1	25,000	12 cy	16	14	28
2	50,000	26 cy	16	15	14
3	75,000	26 cy	30	8	9.3
4	100,000	26 cy	60	4	7

One assumption that was kept constant in each of the four scenarios was the amount of workdays available to transport and spread sand on Nantasket Beach in one complete nourishment season. Environmental regulations and recreational usage requirements limit the period of beach nourishment construction to the 7-month-long off-season, lasting approximately from October through April. Based on this work period it was assumed that 120 workdays would be available to perform the nourishment each season. This is a conservative estimate that takes into account a 5-day work week over 28 weeks, subtracting 6 days for inclement weather (4% contingency), and 14 days of holiday time. This conservative estimate also allows for the possibility that the construction period could reach up to 133 workdays with satisfactory working weather and the minimum amount of holidays (7 days). The 120 days represents an aggressive, yet feasible number of working days through the environmental time window. All of the scenarios represent a significant community impact during each nourishment season. Truck passage frequency will be high in all scenarios, and will also be occurring consistently throughout the entire nourishment season (October through April) over a number of years.

Scenario 1

Scenario 1 was designed to represent the lowest quantity of material that may be delivered from upland sources per nourishment season (Table 4-1). Over a single nourishment season Scenario 1 calls for 25,000 cy of sand to be delivered to Nantasket Beach. In this scenario, only a limited volume of sand will be delivered to the project site in dump trucks with a 12 cy capacity. The reasoning behind this scenario is that cost, environmental, roadway, and community requirements and regulations limit the delivery method to the smaller volume truck and less trips to the site per day. For example, during the construction of the revetment work on Nantasket Beach, approximately 40,000 to 60,000 cy of material and debris were transported over the existing roadways with little overall impact to the road conditions. Therefore, this may be a realistic scenario in that the 12 cy dump trucks have a lower impact on noise pollution, air quality, roadway and bridge wear, and potentially financial cost, when compared to the larger 26 cy capacity dump trailer. In reducing the impact of these concerns, Scenario 1 keeps the truck passage frequency down; however, this drastically reduces the total volume of material that can be delivered to the beach per nourishment season, regardless of financial cost. The project-wide impact of Scenario 1 to the nourishment is that the project time for the placement of 700,000 cy is 28 years. This is an unrealistic timeline considering that annual losses due to natural processes will require the placement of additional material. For example, the USACE (2004b) estimated that 18,000 cy of material would be lost each season, requiring an additional 504,000 cy of sand to be placed on the beach to meet the nourishment template. The rate of construction in Scenario 1 is inefficient in time, materials usage, and financially, thus preventing the successful completion of the nourishment template. Nonetheless, WHG completed a performance evaluation and modeling of the Scenario 1 nourishment to determine if it was infeasible.

Scenario 2

Scenario 2 calls for a total nourishment volume of 50,000 cy of sand per work season (Table 8-2). The material will be transported to the project site in 26 cy capacity dump trailers, which amounts to 16 loads per workday over the course of the nourishment season. The delivery rate for this scenario equates to a truck passage frequency of 15 minutes along the delivery route. Under Scenario 2, it will require 14 seasons to deliver the total nourishment project volume of 700,000 cy, not including overfill for lost (eroded) material. Scenario 2 was designed to increase the total volume of nourishment material delivered each season without increasing the truck passage frequency or significantly impacting the condition of the existing roads. Scenario 2 is clearly a more efficient and economical choice than Scenario 1. The increase in total volume of Scenario 2, provided by using trucks hauling larger loads, is desirable because it accelerates the rate of project construction without a drastic environmental and community impact when compared with Scenario 1.

Scenario 3

Scenario 3 calls for a total nourishment volume of 75,000 cy of sand per work season (Table 8-2). As in Scenario 2, the material will be transported to the project site in 26 cy capacity dump trailers, requiring approximately 30 loads per workday over the course of the nourishment season. The delivery rate for this scenario equates to a truck passage frequency of 8 minutes along the delivery route. Scenario 3 will require 9.3 seasons to deliver the total nourishment project volume of 700,000 cy, not including overfill for lost material. As the successful and efficient completion of this upland nourishment project is limited by the delivery rate of sand, this scenario was developed as a compromise between construction interests and potential environmental and community interests. The scenario requires a total volume of 75,000 cy per nourishment season, which is a logistically attainable value for this construction methodology. The compromise to increasing construction efficiency is to increase the negative impact of the construction to the environment and community adjacent to the material transportation route.

Scenario 4

Scenario 4 calls for the greatest volume of nourishment material of the four scenarios presented in this investigation. The total nourishment volume of Scenario 4 is 100,000 cy of sand per season (Table 8-2). The material will be transported to the project site in 26 cy capacity dump trailers, requiring approximately 60 loads per workday. The delivery rate for this scenario equates to a truck passage frequency of 4 minutes along the delivery route. Scenario 4 will require 7 seasons to transport the total nourishment project volume of 700,000 cy to Nantasket Beach. However this estimate does not include overfill for lost material. Based upon communications with upland sand supply contractors, it is logistically possible to deliver 100,000 cy of sand to Nantasket Beach each season, and it is preferable from a project efficiency standpoint. However, due to the constraints of the work period and workday, the rate of delivery required to meet the total nourishment volume of Scenario 4 is very high, and may be prohibitive to the project because: (1) construction rates for template spreading at the project site may be outpaced by delivery leaving no place to dump materials, and (2) the truck passage rate of 4 minutes may cause significant annoyance to residents along the truck route by increasing noise levels, dust/debris levels, traffic, and excessively deteriorate road conditions. Scenario 4 represents the most aggressive upland-based source nourishment approach, and is likely at the upper limit of what is logistically feasible.

8.1.4 Evaluation of Nourishment Scenario Performance

Using the modeling results completed as a component of the alternatives analysis (Chapters 4, 5, and 7), each of the four upland-based scenarios was evaluated for feasibility and performance at Nantasket Beach. The design assumptions were the same as those used in the alternatives analysis, including:

- *Nourishment Length:* The goal project length (extending alongshore) is 6,800 feet, spanning the entire DCR portion of Nantasket Beach. This corresponds to the preferred nourishment length evaluated in the alternatives analysis. However, since the upland-based nourishment approach requires the nourishment effort span multiple seasons, the length of each yearly nourishment varies. This length variation is described in detail under the placement methodology described below.

- *Berm Width:* Berm widths of 25, 50, 75, and 100 feet were evaluated in the original alternatives analysis. In that assessment, berm widths of 25 and 50 feet did not maintain adequate performance and were eliminated. In the upland-based source analysis presented herein, initial berm widths of 75-100 feet (varies alongshore) were used. These berm widths resulted in the placement of approximately 100 cy per linear foot of beach.

- *Berm Height:* An initial berm elevation of 12 feet NGVD was used for all nourishment scenarios in the current evaluation. Berm heights of both 10 and 12 feet were evaluated in the alternatives assessment.

- *Offshore Slope:* For all berm templates and length scenarios, an offshore slope of 1V:25H was incorporated.

- *Nourishment Volume:* Nourishment volumes were determined for all scenarios based on the design beach nourishment template. In the alternatives assessment, the preferred volume templates ranged from 610,000 to 789,000 cy of material. Therefore, for this feasibility analysis, a total nourishment volume of 700,000 cy was assumed to be reasonable to assess the feasibility of a multi-year nourishment approach.

- *Grain Size/Source:* In the alternatives assessment, three specific grain size combinations were evaluated. These included: (1) a grain size of 0.25 mm that matches the native beach sand, (2) a grain size of 0.45 mm, as slightly coarser grain size than native, and (3) a mixed grain size of cobbles and sand that currently resides on Nantasket Beach. In order to assess the feasibility of an upland-based source, a grain size of 0.25 was used. This represents the most conservative performance evaluation since this material would have the fastest erosion rate.

Placement Methodology

Using the parameters listed above, material was placed on Nantasket Beach for each of the four delivery scenarios. The length of each nourishment episode varied based on the volume of sand delivered. For example, if 25,000 cy of material was delivered during the nourishment season, then the length of the nourishment spanned approximately 250 feet alongshore. The placement sequencing and location also changed for both the initial and subsequent nourishments. As such, the performance modeling evaluates the most effective construction sequencing and methodology. Three specific construction sequence approaches were evaluated as listed below. This produced 12 specific nourishment performance evaluations (4 delivery scenarios with 3 construction sequences).

- **Construction Sequence A:** Initial placement in the center of the DCR portion of Nantasket Beach, with subsequent annual placements also in the center of the DCR portion of Nantasket Beach. The initial placement would include a berm width of approximately 100 feet, and subsequent nourishments would intend to return the berm width to the initial 100 foot width. For this construction approach, each subsequent nourishment would (1) extend in length and (2) naturally spread across the 6,800 foot total nourishment area.

- **Construction Sequence B:** Initial placement in the center of the DCR portion of Nantasket Beach, and subsequent annual placements on alternating, adjacent sides (north and south) of the initial placement. For this construction approach, subsequent nourishments would extend in length due to the presence of material from the proceeding nourishments.

- **Construction Sequence C:** Initial placement in the southern corner of the DCR portion of Nantasket Beach, and subsequent placements advancing northward. For this construction approach, a performance gain is expected due to the natural headland boundary that exists to the south.

Beach Nourishment Performance Results

For this performance analysis, where nourishment is provided in an incremental fashion from upland-based sand sources, sediment will only be considered to be "eroded" once the sediment leaves the full project area (the 6,800 feet of DCR beach). Therefore, although sediment may be lost from the area where it was initially placed, it is not considered a loss from the larger project area. For example, incremental nourishment may only span 500 feet of shoreline, and although sediment may leave this incremental nourishment region, it may not be lost from the 6,800 feet comprising the larger project area. For example, a significant portion of the material will naturally spread alongshore, remaining within the 6,800 feet of the larger project area.

Figure 8-1 presents the beach performance results for all four scenarios using construction sequence A, as well as the performance of a single initial nourishment of 700,000 cy (as presented in Chapter 7). The horizontal axis shows time in years, while the vertical axis shows the percentage of sediment that remains (or is maintained) in the entire project area (6,800 feet of the DCR portion of Nantasket Beach). This percentage is normalized by the total design nourishment volume (700,000 cy). Each scenario is simulated until a total volumetric amount of 700,000 cy is placed. For example, Scenario 2 includes the addition of 50,000 cy each year for 14 years to reach the total design volume of 700,000 cy. Scenario 1 does not produce an increase in beach width to any significant degree, and therefore is not recommended.

Upland-based source Scenarios 2 to 4 show a general increase in volume through time as additional material is continually supplied into the nourishment area. Eventually, the amount of material in the nourishment area will surpass the amount of material remaining from a single initial nourishment of 700,000 cy. For example, after 6 years of delivery and grading of 75,000 cy of sediment, Scenario 3 has the same amount of material in the template region as the initial single nourishment.

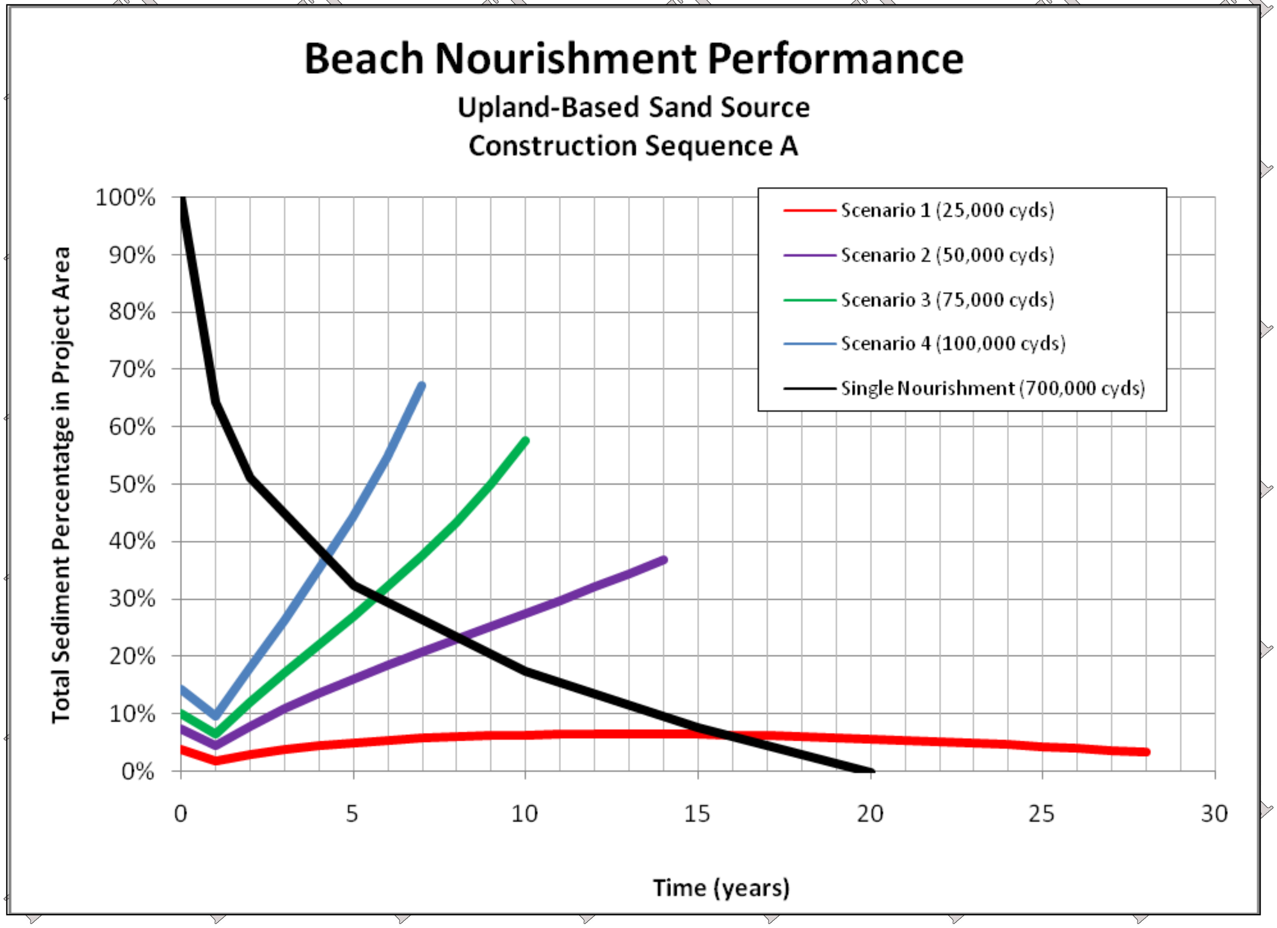

Figure 8-1. Beach nourishment performance for all multi-year upland-based scenarios using Construction Sequence A. Results are compared to a single nourishment from a potential offshore source (black line).

With the exception of scenario 1, all the multi-year nourishment scenarios perform reasonably well. However, there are some technical limitations. The upland-based source scenarios would require additional years of nourishment (overfill) to reach the initial design template. This also means that the designed beach width would never be attained without total nourishment volumes exceeding 700,000 cy. Additionally, the beach/seawall would be vulnerable to damage from a single storm event for a number of years. Until the nourishment percentage reaches approximately 30%, a single storm event would be capable of eroding all of the nourishment volume that had been placed in the previous seasons. For example, for scenario 2, the entire nourishment could be eroded in a single storm event until 11 years of nourishment episodes are complete. This storm erosion results in potential serious consequences for the structural stability of the seawall; however, this does not mean that sand is completely removed from the system. A portion of the sand may likely return to the project region after the storm event as seasonal waves transport the material back onshore.

Figures 8-2 and 8-3 present similar beach performance results for Construction Sequences B and C. The figures show similar performance to Sequence A; however, construction sequence B does show reduced performance compared to Sequences A and C. Therefore, continuous nourishment episodes placed at the center of the DCR portion of Nantasket Beach, or nourishment placement starting at the southern end of the DCR portion of Nantasket Beach, is preferred over staggered nourishments throughout the proposed beach nourishment template. Essentially, each subsequent nourishment increment should build on the previous nourishment to increase the overall performance.

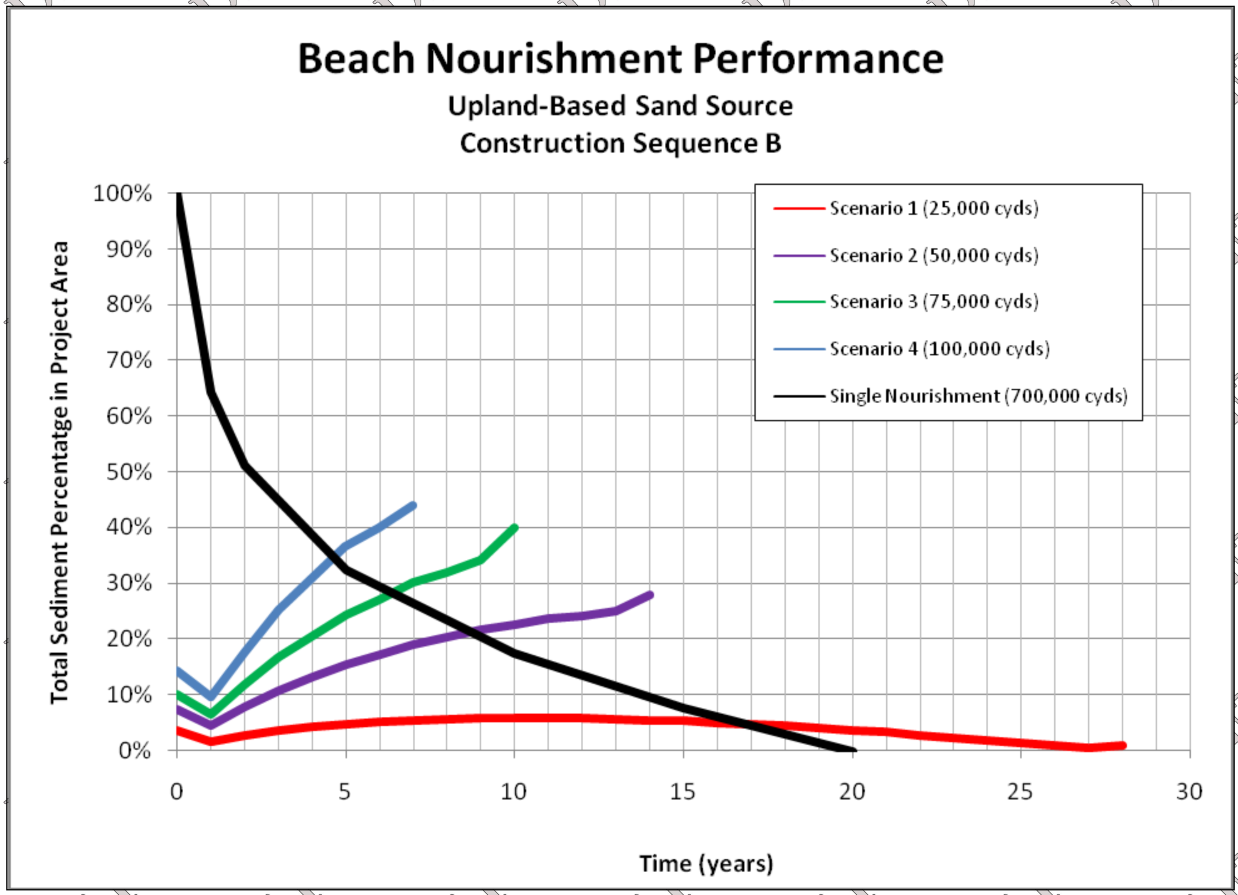

Figure 8-2. Beach nourishment performance for all multi-year upland-based scenarios using Construction Sequence B. Results are compared to a single nourishment from a potential offshore source (black line).

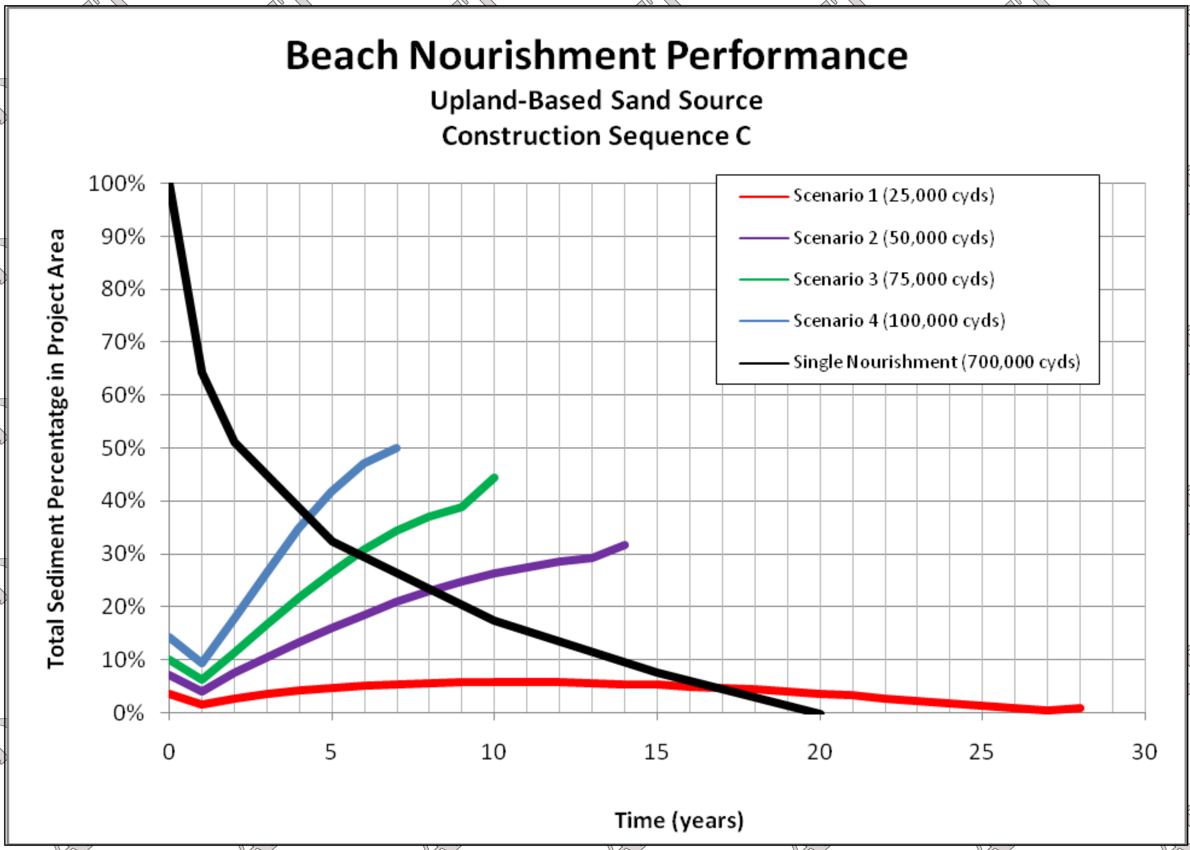

Figure 8-3. Beach nourishment performance for all multi-year upland-based scenarios using Construction Sequence C. Results are compared to a single nourishment from a potential offshore source (black line).

To further illustrate the variations in construction sequencing, Figure 8-4 shows the beach nourishment performance of Scenario 3 for all 3 construction sequence options. The horizontal axis presents the time in years, while the vertical axis presents increased beach width. The solid lines for each construction sequence represent the increase in beach width at the center of the nourishment, while the dashed lines represent the increase in beach width at a distance approximately 3,000 feet north and south (near the ends of the DCR portion of Nantasket Beach). Therefore, throughout the nourishment timeframe, the increased width of the beach should lie in-between the solid and dashed lines. This illustrates the relative improved performance of Construction Sequences A and C.

The technical assessment and modeling indicate that an upland-based sediment source does appear technically feasible for nourishing Nantasket Beach. However, there are some limitations using a multi-year nourishment approach as well. Specifically, the following limitations should be considered:

- In order to achieve the full design template and beach width, an increased amount of additional material (overfill) will be required. Ultimately, the amount of material needed will extend the number of years that nourishment will be required and increase the volumetric requirements and cost.

- If multi-year upland nourishment is selected, Nantasket Beach and its seawall would be vulnerable to potential damage from a single large storm event for a number of years. Until the nourishment percentage reaches approximately 30%. Until the 30% amount is achieved, a single storm event would be capable of eroding all of the nourishment volume that had been placed in the previous seasons. This leaves the beach and seawall vulnerable over these initial seasons. For example, for Scenario 2, the entire nourishment could be eroded in a single storm event until 11 years of nourishment episodes are complete. This storm erosion results in potential serious consequences for the structural stability of the seawall; however, this does not mean that sand is completely removed from the system. A portion of the sand may likely return to the project region after the storm event as seasonal waves transport the material back onshore.

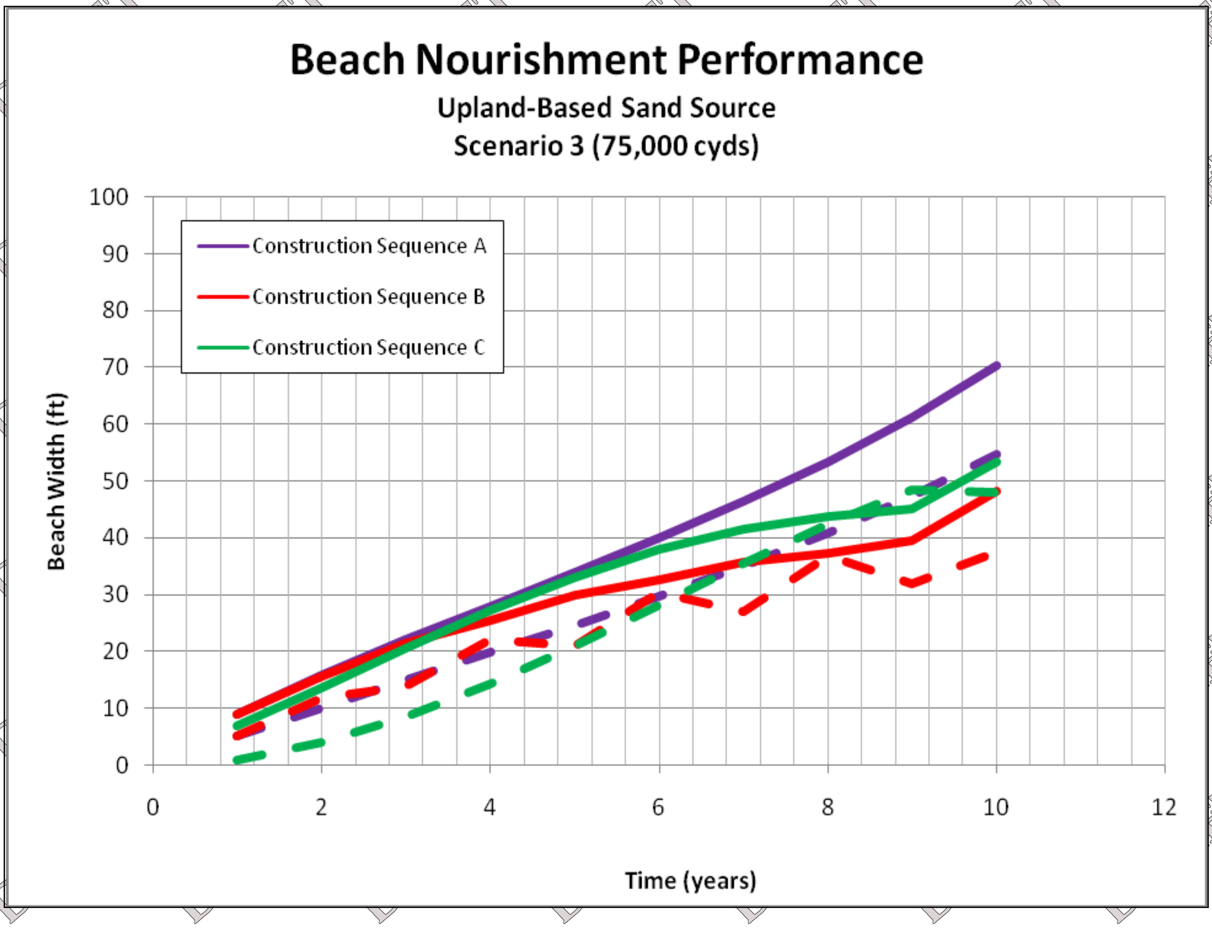

Figure 8-4. Beach nourishment performance for scenario 3 comparing Construction Sequencing A, B, and C. The solid lines show the beach width at the center of the nourishment template, while the dashed lines show the beach width at the edges of the nourishment template (approximately 3,000 feet to the north and south).

8.1.5 Costs Associated With Upland Sources

The cost for a multi-year upland-based source nourishment is expensive, especially when the nourishment extends through multiple nourishment seasons. Simply applying 2008 rates, upland based nourishment of 700,000 cy is approximately $16 million; whereas an offshore borrow location would cost between $7 million and $10 million (see Section 8.2). Additional costs can be expected due to future inflation rates. For example, if only 50,000 cy is brought to the beach each year (Scenario 2), then it will take over 14 years to get the full nourishment completed. Therefore, increased costs can be expected for mobilization, transportation, and grading in each future year. It is also likely that additional sediment will be required (in addition to the 700,000 cy) to complete the desired design template, adding further costs. Prior to final selection of an upland-based sediment source, a financial assessment accounting for future costs should be conducted. Additionally, more detailed comparisons to potential offshore source options should be evaluated. Based on similar projects in the New England region, identification and permitting of a compatible offshore source may take in excess of 10 years and $1 million for field observations, study, and permitting costs. Therefore, a benefit to using upland-based sources is that they can more quickly be permitted and placed on the beach.

8.2 OFFSHORE SAND SOURCES

Utilizing an offshore subaqueous sediment source or material from a navigational channel that requires dredging are alternatives to the use of upland sand sources for the proposed nourishment at Nantasket Beach. Beneficial reuse of sand dredged from navigation channels is desirable, provided the sand is clean and beach-compatible, since costs of nourishment can be shared with the navigation interests, and the environmental impacts can be minimized (i.e., eliminate or reduce needs for additional impacts associated with offshore dredging). Considering the quantity of material that is required to nourish Nantasket Beach, as well as the limited navigational channels that lie within a reasonable distance to Nantasket Beach, the feasibility of beneficially reusing sediment from dredge navigation projects is minimal. As such, the use of an offshore borrow source is likely the most cost-effective alternative capable of providing the quantity and quality of beach compatible material.

Currently, there are no approved offshore borrow sites in the waters of the Commonwealth of Massachusetts, nor has there been any studies undertaken to identify a specific offshore borrow site for Nantasket Beach due to the inability to obtain permits for offshore sand mining. However, use of a nearby offshore sand source for a nourishment project could provide substantial benefits in reducing the project costs and timeline, as well as reducing impacts on the local communities, when compared to land-based sources. However, there are additional environmental impacts to be considered when evaluating an offshore borrow site for nourishment purposes. Numerous studies have been conducted in the past to investigate sand resources immediately offshore Nantasket Beach. One study estimated that there were 13 million cubic yards of sediment available for mining within 1.5 miles of the shore (Smith, 1993). More recent investigations have adjusted that figure to less than 1 million cubic yards (Byrnes et al., 2000); however, this would still be more than an adequate amount for nourishing Nantasket Beach. Geological and geophysical studies of the seafloor material offshore Nantasket Beach indicate that the sediment is compatible to the native beach material and characterized the material as well-sorted, fine-grained sand (Ackerman et al., 2006). The results of these preliminary investigations, as well as a more recent study performed in 2005, indicate that there is a significant volume of beach compatible sand available for nourishment in the waters off Nantasket Beach (USACE, 2006). A more comprehensive and updated investigation would be required to ascertain any changes to the seabed morphology and fully assess potential offshore sand sources, as well as determine potential environmental impacts associated with a nearshore borrow site.

Sand from offshore sources is most often delivered to the beach via a dredging operation. Sand obtained close to shore can typically be pumped directly to the beach via a hydraulic dredge. Sand obtained further offshore, or in locations/times of year when conditions preclude establishment of a fixed hydraulic dredge, can be dredged and pumped onto a hopper barge, which can then transport onshore and pump the sand onto the beach. Hopper dredge operations are also used to transfer sand from regional navigation dredging projects to a beach in need of sand for nourishment.

The overall cost of a utilizing an offshore sand source for beach nourishment is highly variable and is dependent upon a variety of factors. Construction methodology affects the price substantially, as does the volatility in the dredging market (e.g., equipment availability, cost of fuel, time of year, project location, etc.), the quantity of sand to be moved, and other factors. Generally, the cost of a beach nourishment operation increases with the number of times the material needs to be handled. For instance barging of upland sand to a remote beach tends to be the most expensive, since the sand needs to be handled at a quarry or pit, trucked to a barge site, loaded on the barge, barged to the beach, pumped to the beach, and graded on the beach. Costs of upland sand delivery by barge have exceeded $40/cy in some instances. By comparison, the per price of a direct hydraulic dredging operation tends to be the least expensive (typically $5 to $8/cy) once the equipment is onsite. However, equipment mobilization costs can be prohibitive for individual projects (can exceed $1 million) unless the project is very large or if the mobilization fee can be shared with a nearby project. Hopper dredge costs also are quite variable (typically $8 to $16 per cubic yard), depending upon the availability of equipment, location, and time of year.

For example, a large national dredging and marine construction contractor was recently quoted to provide an estimate for a large-scale hydraulic dredging and beach nourishment operation at Nantasket Beach. The estimate was provided for an approximately 700,000 cy nourishment project, mined by a hydraulic hopper dredge from an offshore borrow site located within 5 miles of the nourishment site. The hopper dredge would pump the sand onto the beach via pipeline with booster pumps (Figure 8-5). The cost associated with the mobilizing the construction equipment for the project was on the order of $1 million, with an additional construction cost of $12/cy, or $8.4 million. The production rate to dredge and deliver the material to the nourishment site was estimated at 15,000 cy/day. Dredging operations are ideally scheduled for the fall season, before the unpredictable winter/spring weather window, which can cause substantial weather stand-by charges to be incurred by a project. The overall construction cost and timeline, without any contingency plans or sand movement limitations on the beach, was estimated to be $9.4 million and 47 work days.

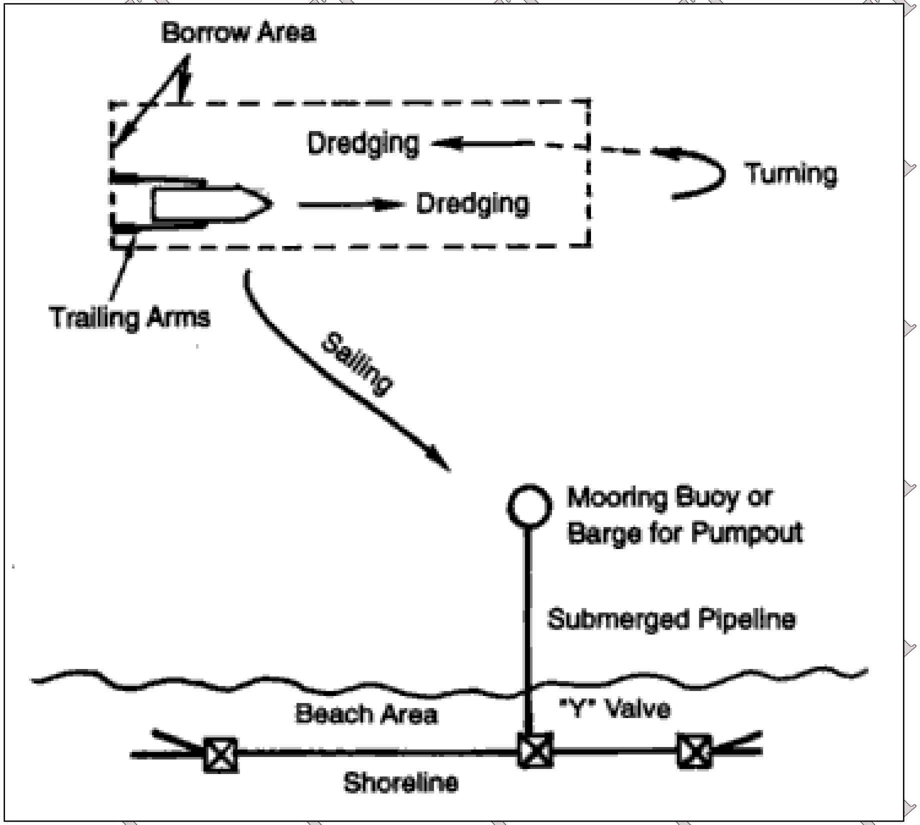

Figure 8-5. Schematic of the hydraulic hopper dredge and pipeline operation for beach nourishment (Figure from Nourishment and Protection, National Research Council, 1995).

When compared to upland sources, the use of an offshore borrow site can reduce the overall cost of a nourishment project by 50-70%. In addition, the project schedule for completing the transport of fill is drastically decreased (months versus a decade) when utilizing an offshore sand source. The marine construction production rate enables the project to be completed within a *single season*, rather than a multi-year (7-28 year) effort with trucking of upland sand. Furthermore, implementation of an offshore source will not impact the communities, environment, and roadway traffic and infrastructure along the trucking routes proposed for upland source delivery. However, there are also well-identifiable negative impacts in utilizing an offshore sand source. These include environmental impacts to the benthic habitat on the seafloor, the potential for changing offshore wave characteristics by altering existing bathymetry, as well as water quality and aesthetic impacts, to name a few. The ability to use an offshore borrow site as a Nantasket Beach nourishment source is subject to DCR obtaining permits from Federal and State regulatory agencies. These permits require comprehensive assessment of the borrow site and surrounding areas, in order to evaluate the potential for environmental harm. The costs associated with permitting and environmental studies associated with these permits can be high (although still less that the construction costs associated with trucking upland sand), and can be a lengthy process requiring data collection, analysis, reporting, and review. As such, it is expected that identifying, permitting, and approving a compatible offshore borrow source would take a minimum of 5 years.

Despite the campaigns, quality, and quantity of research that has been performed to support the use of offshore nourishment sources in Massachusetts, these permits could not be obtained. An example where this has occurred in recent years was at Winthrop Beach, MA. The Massachusetts Department of Conservation and Recreation (DCR) had plans for a nourishment project at Winthrop Beach that proposed mining an offshore sand source for approximately 500,000 cy of sand. As such, the DCR performed a comprehensive evaluation of potential site-specific impacts associated with the mining of the offshore source. Although this investigation concluded that environmental impacts to the site were nominal, and the coast at Winthrop Beach continued to degrade, the USACE denied the permit due to concerns over Essential Fish Habitat (EFH) of the bottom by the National Marine Fisheries Service (NMFS) at that location (Conti, 2008). In some ways, the situation at Winthrop Beach is similar to that at Nantasket Beach, and although it may seem logically sound to use an offshore nourishment source, the Winthrop case should pose caution in approaching the expensive investigations and permitting of an offshore source for Nantasket Beach and no guarantees.

9.0 SUMMARY AND CONCLUSIONS

9.1 EXISTING CONDITIONS

The region of Nantasket Beach represents a complex coastal setting. The following key findings were determined in the existing conditions analysis as presented in Chapters 1 through 5.

- The wave modeling results show areas of increased wave energy ("hot spots") caused by wave refraction and diffraction. Wave refraction and diffraction result in an uneven distribution of wave energy along the coast that affects sediment transport in the region. Wave modeling results provided information on wave propagation across the continental shelf and to the shoreline, revealing areas of increased erosion or areas of increased energy. The refraction and diffraction mechanisms also result in changes in the offshore wave direction that may significantly influence the rate and direction of sand movement along Nantasket Beach for specific wave conditions. On an annual basis, increased wave energy is shown along the DCR portion of Nantasket Beach, with a specific hot spot located at the northern portion of their section of coastline (the location of the previous seawall failure). As such, the DCR portion of Nantasket Beach may not behave in a similar manner to other portions along the Nantasket shoreline.

- Areas of accretion and erosion develop along Nantasket Beach due to the irregular offshore bathymetry and thus, the uneven distribution of wave energy. Sediment flux results show relatively small rates of sediment transport. There are regions along Nantasket Beach where the net sediment transport is to the south, and others where the net sediment transport is to the north. In either case, the rates are relatively small. The sediment transport model was validated through comparison to rates of shoreline change and reasonably predicted these changes.

- Net sediment transport in the DCR portion of Nantasket Beach is from south to north with the average rate of transport of approximately 4,000 to 5,000 cy/yr, and maximums varying between approximately 13,000 and 50,000 cy/yr. During certain wave conditions, sand will also move from north to south, but over an average year the sand will move from south to north.

- The cobble portion of the sediment mixture at Nantasket Beach has a net sediment transport rate that is from north to south in the DCR portion of Nantasket Beach. Cobbles are only transported during the stronger northern and north-eastern approach waves, which have enough energy to mobilize the cobble component of the Nantasket shoreline. The more commonly occurring, but lower energy, eastern and southern waves cannot mobilize the cobble. Therefore, the net transport of cobble is from north to south, while the net transport of sand (which is mobilized for all wave approach directions) is from south to north.

- There is a lack of sediment supply for the DCR portion of Nantasket Beach. The combination of the net northward sediment movement and the limited sediment supplied by regions to the south (due to the Atlantic Hill headland) results in a lack of available sediment for the DCR portion of Nantasket Beach. Therefore, on an average annual basis, the DCR portion of the beach is erosional.

9.2 RECOMMENDED ALTERNATIVE

The recommended alternative was selected based on five key points:

1. The Nantasket Beach Seawall is Necessary and Beneficial

Although seawalls are not always the most ideal coastal protection method, in heavily developed areas, seawalls are very effective. For example, the value of a sound seawall was demonstrated in Galveston, Texas, during the passage of Hurricane Ike on September 14, 2008. The portions of Galveston located landward of the seawall experienced minimal damage, while areas without seawall protection or other coastal protection measures were significantly damaged and/or destroyed. The Nantasket Beach seawall has been in place since approximately 1915, and has been an effective protection measure throughout the years. The protective values alone provided by the seawall justify its presence in a highly developed and urban setting like Nantasket.

Additionally, leaving the seawall in place is the most cost-effective solution for satisfying the need for protection of the Nantasket Beach Reservation and upland resources owned by DCR, the Town of Hull, and private owners. The existing seawall is structurally sound, but has been compromised by the continued erosion of the beach, which has rendered the initially designed support inadequate. Specifically, the seawall no longer extends far enough into the subsurface to remain stable. Therefore, the existing seawall needs additional support through beach nourishment, toe stabilization, or both (see Point 4 below). Utilizing the current location of the seawall, coupled with a nourishment project, maintains upland area for community Master Plan improvements and layouts. Therefore, it is recommended that the existing seawall be a component of the solution at its current location.

2. Beach Nourishment is a Key Component

Nantasket Beach is a valuable, convenient recreational resource in the area and is one of the few large urban beaches in the Boston area. Nantasket Beach is very accessible, in part due to its available parking facilities. The popularity of the beach may increase with potential accessibility options such as better public bus connections, potential ferry connection, etc. Due to its open-ocean setting with an absence of rivers and major stormwater outfalls entering the beach, the beach has consistently good water quality even immediately after large storm events. However, currently because of the limited beach berm, beach visitors need to leave the beach during high tide. Therefore, beach nourishment is an important component for shoreline protection. Beach nourishment will significantly improve its recreational value, increase the storm damage protection, and provide increased economic return. Ultimately, Nantasket Beach should remain a viable recreational beach, which means that a useable, sandy beach environment needs to be provided to service a variety of beachgoers (e.g., surfers, sunbathers, families, swimmers, etc.) It is recommended that the preferred alternative should include a beach nourishment component.

3. Sediment Source for Nourishment

All feasible and preferred alternatives include beach nourishment. Therefore, important consideration needs to be given to potential sediment sources. Basically, sediment can be obtained from either an offshore borrow source, dredging of a navigational channel, and/or an upland source. A subaqueous borrow source is typically the most cost-effective option and provides a good source of beach compatible material once a suitable site is identified. However, recent experience has shown that obtaining permits to mine offshore material is a lengthy, costly process and may ultimately be unsuccessful. For example, DCR has recently tried to obtain permits to mine an offshore borrow site for nourishing Winthrop Beach, MA. The permitting process has taken over 10 years and has currently been unsuccessful. Considering that the offshore sand source was recently denied for the nourishment of Winthrop Beach, an upland-based source may be a feasible option for Nantasket Beach, at least for the foreseeable future. An offshore borrow site for Nantasket could be a difficult pursuit, at minimum resulting in a significant time commitment and delaying possible nourishment of Nantasket beach for at least 5 years.

Although significantly more expensive, based on the results of the technical assessment and modeling performed, an upland-based sediment source does appear technically feasible for nourishing Nantasket Beach. However, there are some limitations using a multi-year nourishment approach as well. If multi-year upland nourishment is selected, Nantasket Beach and the current seawall would be vulnerable to potential damage from a single storm event for a number of years. Until enough sediment (approximately 30%) is supplied to the beach, Nantasket and the seawall would remain vulnerable over these initial seasons (approximately 5 to 6 years for a reasonable upland sourced construction rate).

Therefore, it appears any sand source will leave the seawall and Nantasket exposed for the next few years. The offshore source will likely take years to permit and get approval, while upland sources will take numerous years to construct, while being exposed to storm events. Without some sort of seawall fortification, the seawall will remain at risk for the next 5 to 6 years if sand nourishment alone is the solution. Therefore, it is recommended that beach nourishment be coupled with some seawall fortification measure, with the intent that the fortification method provides insurance against storm events and does not take the place of beach nourishment. This is discussed further in Point 4 below.

4. Strengthen Seawall with Toe Protection and Start Nourishment from Upland Source(s)

At present the seawall is at risk of failure in the mid-section during a large storm. The USACE (2006) determined that the elevations in front of the seawall shall not be less than the following in order to provide adequate support:

- No-storm condition: 7 feet
- 100-year storm conditions: 9 feet

At times, elevations in front of the unprotected mid-section of the wall have decreased to an elevation below 7 feet, such as during the October 18, 2006 survey. In addition, undercutting by waves during the December 1992 storm resulted in the collapse of a section of the seawall. This stretch of the beach was closed off for many years until the wall was recently repaired.

Nourishing the beach with sand from an ocean-source can be done rapidly over one season, thus limiting the exposure of the seawall to the risk of collapse during a severe storm. However, as discussed, the potential availability of an ocean-based sand source may take numerous years to permit, leaving the seawall and the Nantasket Beach Reservation vulnerable during this time. Additionally, nourishing the beach from upland sources, although feasible, would also leave the seawall and Nantasket vulnerable for a number of years. For example, based on an assessment of feasible scenarios, nourishing the beach with 700,000 cy of sand will require approximately nine to ten years (at 75,000 cy/year) and the added sand will not provide adequate protection for the seawall for the first 5 years, until sufficient sand has been added to the beach.

It is recommended that seawall fortification (specifically toe protection) be included in the preferred solution. Once adequate volumes of sand are placed on the beach, rocks would be covered by sand. Thus, the beach would be similar in appearance as nourishment without added toe protection in the mid-section of the seawall. Additionally, the toe protection would provide a second line of defense during major storms.

The added protection of is also recommended given the changes in global climate over the last decades. Specifically, while official NOAA rates for annual sea level increases have been incorporated in our analyses, other predictions indicate that even greater increases may be possible over the next century.

5. Pursue an Offshore Sediment Source for Long-term Nourishment

A commitment by DCR to nourish the beach implies that the beach will require renourishment in the future, as the sand will erode over time. Using upland sources for sand is significantly more expensive than using ocean sources. Therefore, we consider it important, and fiscally wise, to pursue an appropriate sand borrow site for beach nourishment. An approved offshore borrow site would also allow for cost-effective and rapid future nourishments for Nantasket Beach.

Affected communities and organizations such as the CAC can assist in furthering the goal of having an appropriate offshore site authorized. It is likely that using offshore sand sources will have lower overall environmental impacts and a lower carbon-footprint than using land sources, considering issues such as air quality, noise, traffic, etc.

Further, identifying and permitting an appropriate offshore borrow site will not just be important for Nantasket Beach but also for other beaches and its surrounding communities in the Commonwealth.

Conclusion

The technical team recommends Alternative 5 for the preferred Alternative at Nantasket Beach. Alternative 5 (toe protection and nourishment) should be coupled with short-term nourishment from an upland source and long-term offshore nourishment. This solution provides immediate protection for the seawall and upland infrastructure, as well as a second line of defense when needed. An offshore sand source should be pursued vigorously as it will also be needed by other coastal communities in the Commonwealth in the future.

Shore protection with beach nourishment, coupled with planned improvements of the upland portion of the Nantasket Beach Reservation, will considerably enhance the value of this important recreational asset in the Commonwealth. Despite its urban setting, the beach has excellent water quality, and should continue to be enjoyed by the greater community, as it has been over its long and storied past.

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APPENDIX A

Numerical Wave Transformation Results

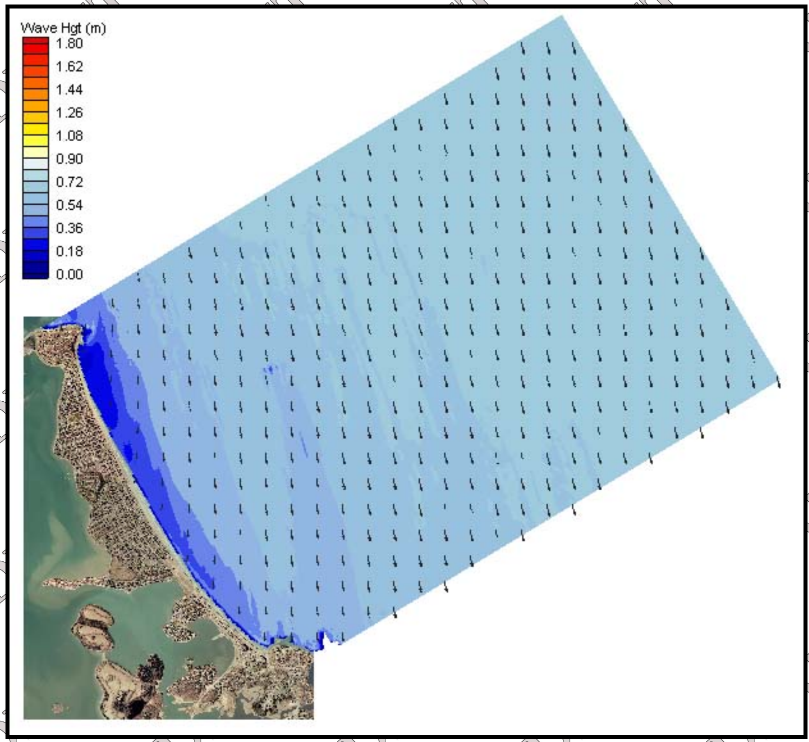

Figure A-1. Spectral wave modeling results for a north-northwest approach direction (329-351.5 degree bin) in the Nantasket Beach region.

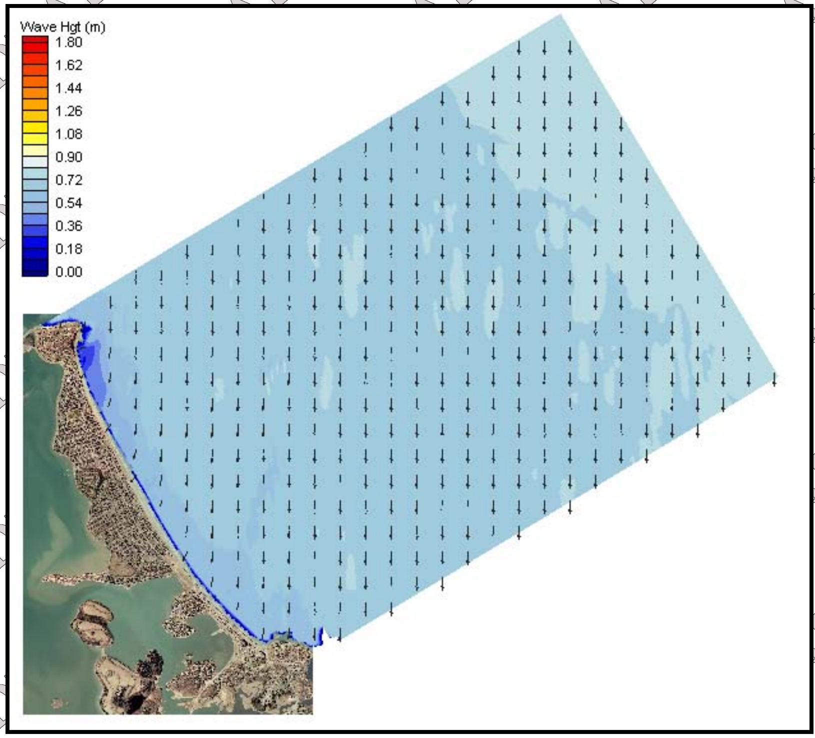

Figure A-2. Spectral wave modeling results for a north approach direction (351.5-14 degree bin) in the Nantasket Beach region.

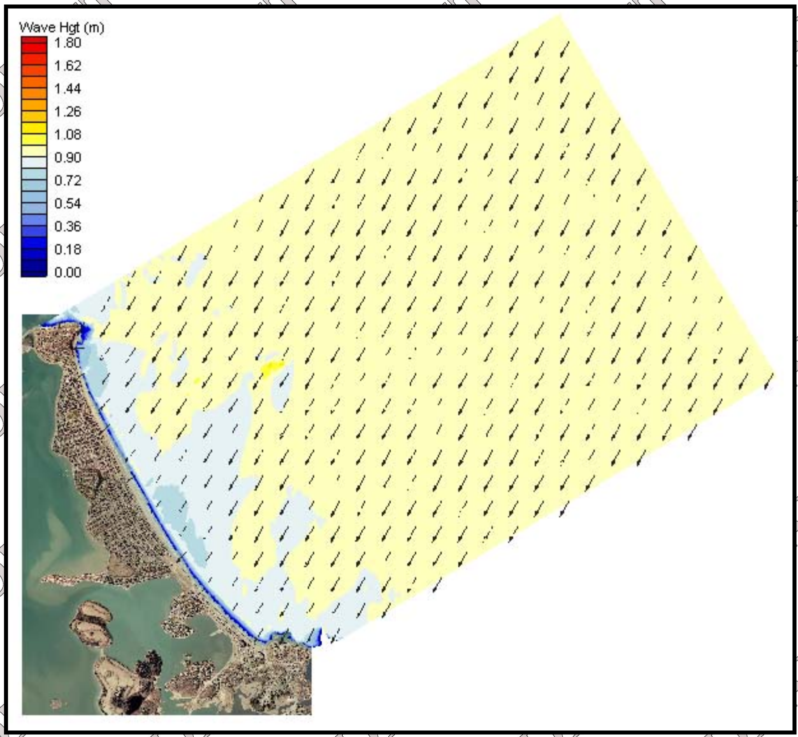

Figure A-3. Spectral wave modeling results for a north-northeast approach direction (14-36.5 degree bin) in the Nantasket Beach region.

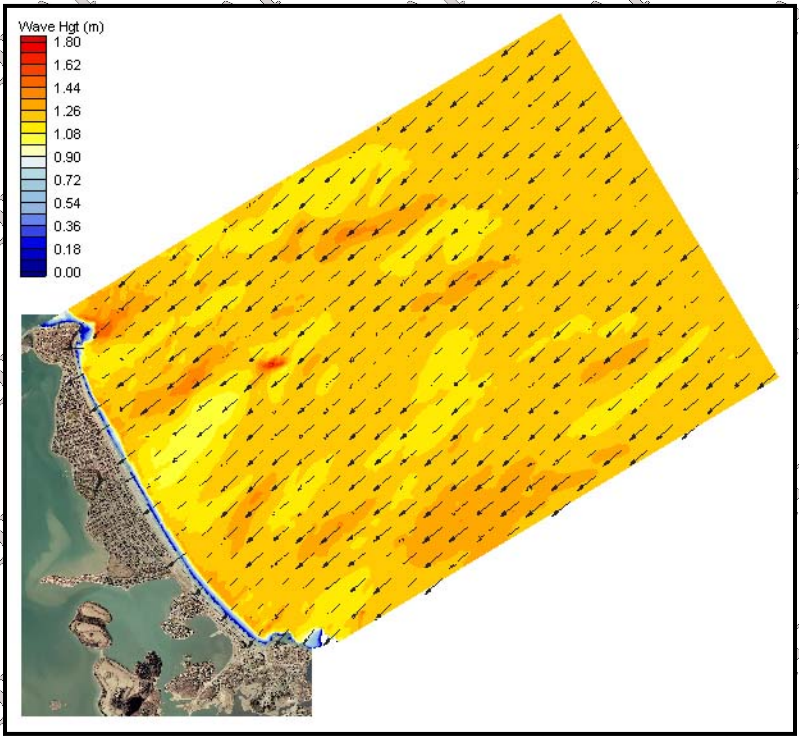

Figure A-4. Spectral wave modeling results for a northeast approach direction (36.5-59 degree bin) in the Nantasket Beach region.

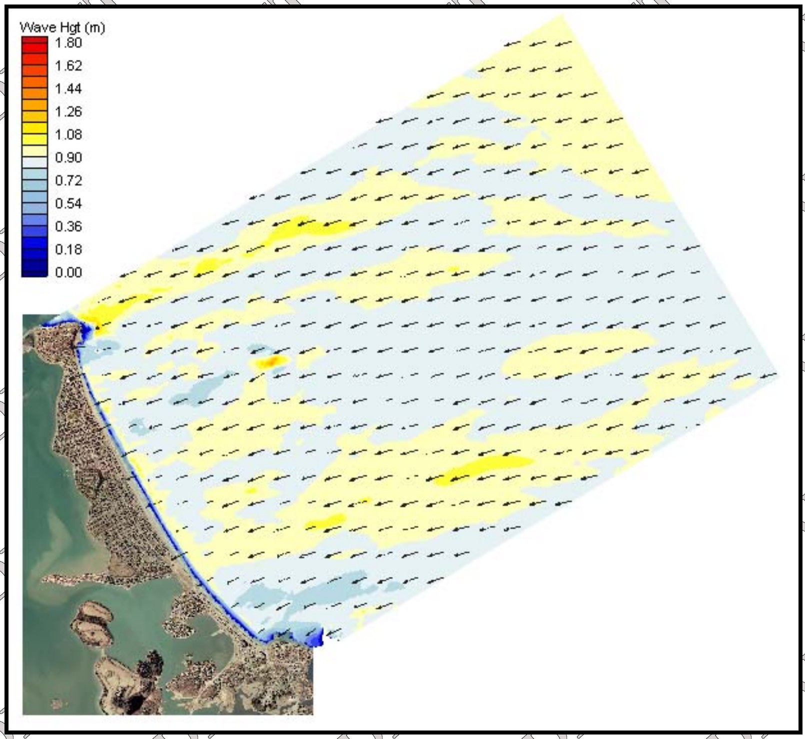

Figure A-5. Spectral wave modeling results for an east-northeast approach direction (59-81.5 degree bin) in the Nantasket Beach region.

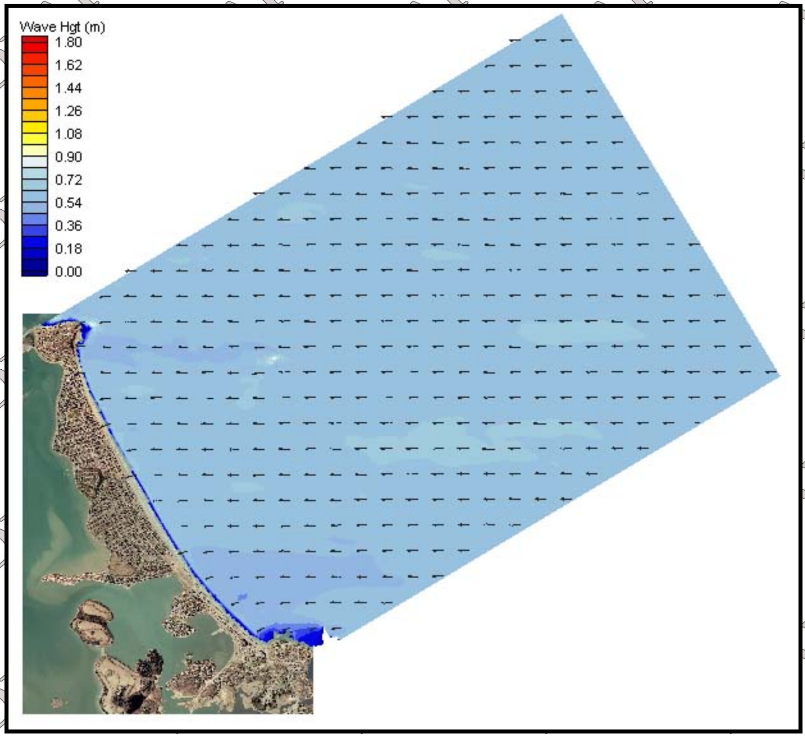

Figure A-6. Spectral wave modeling results for an east approach direction (81.5-104 degree bin) in the Nantasket Beach region.

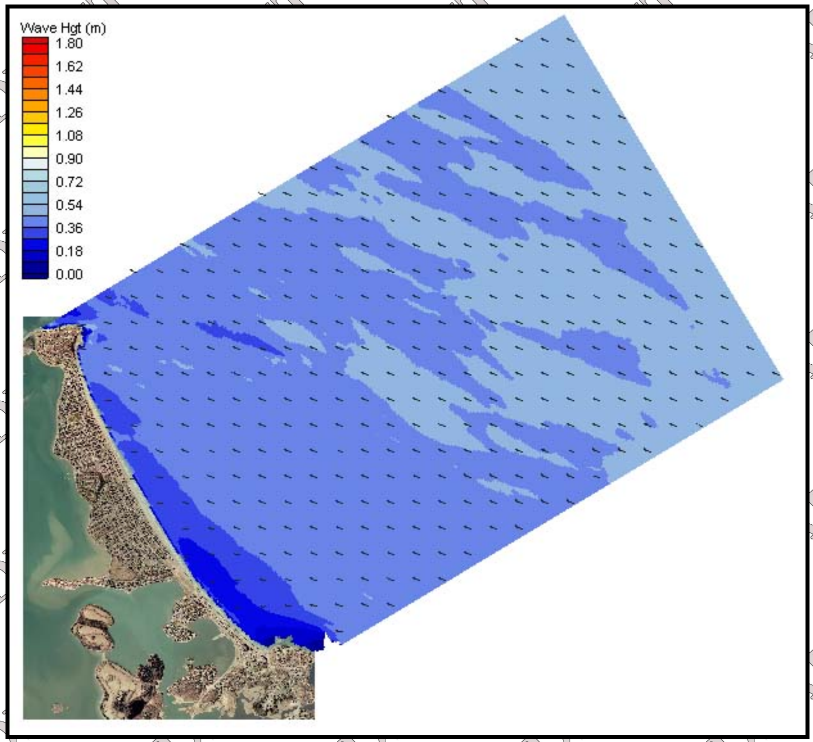

Figure A-7. Spectral wave modeling results for an east-southeast approach direction (104-126.5 degree bin) in the Nantasket Beach region.

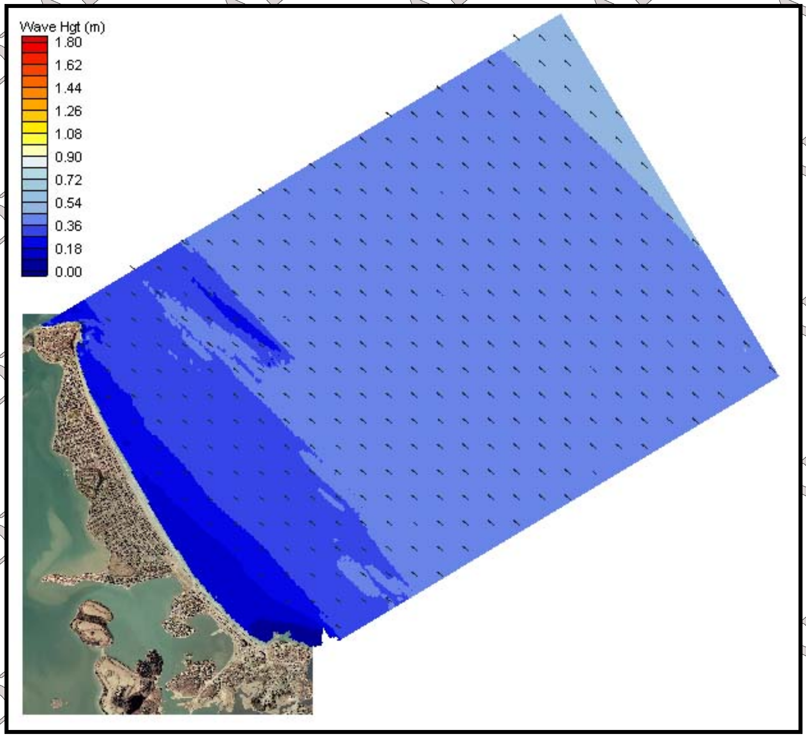

Figure A-8. Spectral wave modeling results for a southeast approach direction (126.5-149 degree bin) in the Nantasket Beach region.