EVOLUTION OF THE MORPHOLOGY SURROUNDING DETERIORATING SHORE-PARALLEL PROTECTION STRUCTURES ON SANDY ESTUARINE BEACHES

by

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ABSTRACT OF THE DISSERTATION

EVOLUTION OF THE MORPHOLOGY SURROUNDING DETERIORATING SHORE-PARALLEL PROTECTION STRUCTURES ON SANDY ESTUARINE BEACHES

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Coastal armoring has historically been the preferred method for the protection of coastal infrastructure threatened by inundation. With sea level expected to accelerate in the future, the use of shore protection structures is anticipated to increase along with the likelihood that pre-existing structures will be at risk for overtopping and deterioration. While pre-existing structures may be upgraded, maintained, or removed, abandonment and deterioration is the most likely scenario for structures not protecting important cultural, historical, or recreational resources due to the lack of cost and effort involved. This study aims to understand and characterize the morphological changes that take place surrounding shore-parallel structures on sandy estuarine beaches as they deteriorate and remain within the landscape past their useful lifetime. Four sites containing wood sheet pile bulkheads, four sites containing stone riprap revetments, and one natural site in Gateway National Recreation Area were evaluated based on topography and landcover as case studies, in conjunction with comprehensive shore protection structure inventories.

Results reveal that changes in the landscape over the course of a structure's lifetime are predictable and can be described by four distinct morphological stages, where *stage* is a period in the lifetime of a structure characterized by the effectiveness of the protection structure and manifest in indicative features in the surrounding landscape. As the condition or effectiveness of a structure decreases over time and stage increases, the amount of open water or bare sand landward of the structure increases along with sediment mobility. Shoreline irregularity peaks during the deterioration process, before it returns to a more natural, linear state. Successful renovations or improvements on existing structures should consider the pattern of deterioration during the planning process, and weigh the benefits of protection provided by the structure versus increased ecosystem resiliency of a natural beach. A protection structure life stage model is presented as a tool to aid in the decision-making process. The most critical stage to make a decision regarding the improvement, repair, removal, or abandonment of a structure is Stage 2, which can be determined by managers via site visits or remote imagery using the key features described in this study.

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Introduction

1.1 The issue of shore protection

An increase in global temperatures is currently occurring and is predicted to continue (IPCC 2007). Coupled with increasing temperatures, global sea level rise is expected to accelerate (Meehl et al. 2007; Parry et al. 2007) and the number of large storms to increase (Webster et al. 2005). Increased sea surface temperatures may also allow for higher magnitude tropical storms (Emanuel 2005; Webster et al. 2005). The effects of increased sea level and storm surge on coastal areas, the most densely populated areas on the globe, will be significant but will vary by location (Gornitz 1991). Currently about 10% of the global population resides at elevations below 10 m above sea level (McGranahan et al. 2007), and 60% of the United States population lives within 60 km of a coastline (Griggs 1999). Within these areas of dense population, human infrastructure is widespread and threatened by rising water levels (Wu et al. 2009; Neumann et al 2010).

On time scales of hundreds to thousands of years, beaches and barrier island systems respond to increased water levels by migrating landward (Orford and Pethick 2006; FitzGerald et al. 2008). Habitats within these environments may also migrate landward while maintaining their ecosystem services, including beaches, dunes, and maritime forests (Leatherman 1979; FitzGerald et al. 2008; Nordstrom and Jackson 2013) and salt marshes (Redfield 1965; Donnelly and Bertness 2001). Oftentimes however, on shorter time scales on the order of decades, coastal environments are not able to migrate landward due to constrictions caused by man-made infrastructure and beaches will instead be inundated or erode in place (Doody 2004; Orford and Pethick 2006; Dugan et al. 2011; Nordstrom and Jackson 2013). Coastal managers are faced with the task of deciding if and how to protect infrastructure as it is threatened by this increasing sea level, and this task will continue to become increasingly difficult as water levels and coastal populations increase (Nordstrom and Jackson 2013). There are three broad areas of response types for coastal management: retreat (abandon vulnerable areas and retreat from the coast), accommodation (continue occupancy and adjust to the hazard), and protection (defend vulnerable areas) (Dronkers et al. 1990; National Research Council 2014).

Relocating human development away from the shore is often advocated but is usually resisted by the public and rarely implemented (Abel et al. 2011; Roca and Villares 2012; Niven and Bardsley 2013; Kousky 2014), leading to demands for protecting buildings and infrastructure in place through shore protection programs. Shore protection structures currently in place along the shoreline will experience decreasing structural integrity due to aging and rising sea level as the area of focused wave energy on the structures increases in elevation. Even if structures retain their integrity, they may be too low to retain their design function with rising water levels. Landowners and policy makers are thus faced with a decision to rebuild, improve, or abandon existing coastal protection structures. There are currently few studies to inform managers of the consequences of abandoning structures, or of ways the deteriorating structures will affect the surrounding environment in the future. This critical research need is a focus of this dissertation.

1.2 Shore Protection Structures

Several options are available to managers and landowners to protect assets along a coastline, including structural and non-structural methods. These methods may be employed for one or a combination of: reducing storm damage, mitigating coastal erosion, and restoring ecosystem function (Pope 1997; Basco 2008). Non-structural methods to mitigate erosion and coastal inundation of infrastructure include planting vegetation, altering groundwater drainage, beach nourishment, sand bypassing, and retreat. Beach nourishment is currently the preferred method of shore protection in the United States primarily due to its ability to preserve the aesthetic and recreational characteristics of a natural beach at relatively low cost. Historically, structural methods of shore protection (also known as armoring) have been preferred over non-structural methods (Rupp-Armstrong and Nicholls 2007). Armoring is the attempt to stabilize the shoreline and protect landward infrastructure using engineered structures. These structures range from temporary, such as sandbags and geotubes (Hornsey et al. 2011), to large concrete and rock seawalls (Griggs 2005).

Permanent structures have been the most common solution for shore protection, as they restrict the dynamism of the coastline surrounding infrastructure. Shore protection structures continue to be constructed, despite increased implementation of beach nourishment and living shoreline strategies (Kana 1991; Basco 2008; Kittinger and Ayers 2010), as engineering focus shifted from pure stabilization and protection to considerations of environmental value and maintaining natural ecosystem functions (Nordstrom 2000). Reliance on hard protection structures is being questioned as long-term side effects of their employment are realized and newer threats like sea level rise and climate change need to be considered (Rupp-Armstrong and Nicholls 2007; Cooper and McKenna 2008). In many cases living shorelines and softer coastal defenses may be the preferred method of shore protection (Nicholls and Klein 2005; Campbell and Benedet 2006), but the use of structures is expected to increase in the future due to a combination of population growth, sea level rise, and erosion which will result in an increase in the number of all types of shore protection projects (Dugan et al. 2008; Walker et al. 2008; Bulleri and Chapman 2010; Nordstrom 2014). Pre-existing shore protection structures will also remain in the landscape through their useful lifetime and often for much longer.

Shore protection structures can disrupt natural coastal processes (van der Nat et al. 2016) by interfering with sediment transport and supply and morphology of the shoreline and acting as barriers to the migration of coastal environments (Pilkey and Wright 1988; Hall and Pilkey 1991; Dugan et al. 2011). These effects are dependent on the environmental setting and the design and construction of the structure, making it difficult to make broad statements applicable to all types of structures. Biological effects from structures may include modification of biodiversity, productivity, and coastal ecosystem function, value, and resilience (Bulleri and Chapman 2010; Kittinger and Ayers 2010; Shipman et al. 2010; Chapman and Underwood 2011; Dugan et al. 2011). Effects on the environment are not necessarily limited to the area of intended protection and may extend much farther (Dronkers et al. 1990). Many of the collateral effects of structures remain unknown (Nordstrom 2014) while the need to understand interactions between geomorphic, ecological, and human processes in the beach environment remains (Jackson et al. 2013).

With more focus on strategies to adapt to sea level rise associated with climate change, there is increased importance in understanding the long-term ability of structures to protect against erosion and flooding and assess their effects on coastal evolution and environmental change through time. Although hard engineering structures are called static (van der Nat et al. 2016), this is not necessarily the case. Structures are designed with a specific useful lifetime and naturally degrade (Basco 2008, CERC 1984). Structure lifetimes are dependent on installation methods, design, material, and external factors. Protection structures are also designed to withstand a specific maximum water level and wave energy (Housley and Thompson 2008, CERC 1984). Structures that experience damage or degrade naturally may benefit from maintenance and reconstruction to retain maximum effectiveness, but reconstruction is generally limited by cost and space. Maintenance inertia may play a role in the public opinion and decision-making process as well, even if the protective measures previously used were not effective (Brunsden and Moore 1999).

1.3 Rationale and Objectives

As structures degrade, a decision must be made to either restore or rebuild to meet new standards, provide sediment to the system via beach nourishment, allow the structure to continue to degrade, or remove the structure entirely (Bocamazo 1991; Jackson and Nordstrom 1994; Nordstrom et al. 2007; Nordstrom and Jackson 2013). The effects of deteriorating structures cannot be accurately depicted using existing engineering models or lab studies that concern only intact shore protection structures. Deteriorating structures are especially prevalent in urbanized estuaries where there is little demand for developing shorefront property when the initial use is abandoned (Nordstrom 2014), and includes both structures that were not well designed initially or have passed their useful lifetime (Jackson et al. 2006).

As shore protection structures are subjected to changes in sea level and physical degradation, they may mimic the attributes of a different type of structure. For example, as shoreline retreat occurs and a deteriorating bulkhead is left stranded offshore, it may function as a breakwater or sill. Similarly, a portion of a shore-parallel structure left remaining as the adjacent shoreline migrates landward may exhibit a groin effect by trapping sand moving alongshore and restrict delivery to downdrift beaches. Functionality of structures is subject to change when the structure is left in a dynamic coastal environment. This includes a decrease in freeboard and a decrease in maximum allowable deep-water wave height with rising sea level (Sekimoto et al. 2013).

The effects and feasibility of removing structures has been of increasing interest to coastal managers and geomorphologists (e.g. Nordstrom and Jackson 2013; Nordstrom et al. 2016). Removing structures may result in beneficial changes, such as allowing for the landscape to return to a more natural state with increased exchange of sediment and biota, but may also result in negative changes such as increased sedimentation in navigable waterways or adverse effects on biota that have adjusted to the structure. Where complete removal of the structure is not feasible due to cost or mechanics, structures may be abandoned and allowed to deteriorate within the landscape (Nordstrom et al. 2016). Abandonment can actually be a proactive approach to accommodating sea level rise by allowing the shoreline to erode and deliver sediment needed for restoration of beaches and wetlands (Nordstrom et al. 2016).

Deterioration is the most likely scenario for many structures that are not directly protecting important historic, cultural, or recreational resources, as maintenance of these structures is not likely to be funded. One example that would lead to this occurring is land that was owned or managed by one party for a particular purpose before ownership was transferred and management goals were shifted to a different purpose (Nordstrom et al. 2016). This transfer is common on estuarine beaches originally modified to accommodate industrial, transportation, and military uses that were considered more important than maintenance of natural environments. Transfers on ocean beaches are usually related to recreation, with goals remaining unchanged.

The objectives of this study are to: 1) produce a conceptual model depicting predictable life stages through which a structure will progress over time as the structure deteriorates; 2) determine how shore-parallel protection structures with different levels of deterioration on an estuarine shore affect the surrounding morphology; and 3) differentiate patterns of deterioration and associated changes in the surrounding morphology between wood bulkheads and riprap revetments.

1.4 Hypothesis

The hypothesis is that shorelines with degraded shore-parallel protection structures pass through a series of predictable stages, with beach slopes and widths, environmental types, and shoreline orientations changing from a protected stage to a natural stage. The change to successive stages should differ temporally due to structure design, construction materials, maintenance frequency, change in water level, and wave regime. It is crucial to clearly define the difference between and separate the terms *condition* and *stage*. *Condition* refers only to the physical integrity of the structure, without regard to the surrounding environment or nearby infrastructure. *Stage* refers to a period in the lifetime of a structure, characterized by the effectiveness of the protection structure and manifest in indicative features in the surrounding landscape. The hypothesis assumes that the condition of the structure and the characteristics of the surrounding landscape are directly correlated and that the pattern of changes in the landscape should be predictable based on the condition of the structure in a sandy estuarine beach environment.

1.5 Proposed Life Stage Model

Geomorphological models are useful tools to explain, predict, and simplify complex changes that may occur in an environment over time and have been used in many types of morphology studies (e.g. Keller 1972; Penland et al. 1988; Simon and Hupp 1992; Kana et al. 1999). Models help scientists understand and categorize a process and are a useful tool for environmental managers and policy makers who may not be experts. A conceptual four-stage dynamic model describing the complete lifetime of shore protection structures was proposed prior to executing this study as a guideline to aid in understanding the changes in the position of the shoreline and shape of the coast that may occur as a beach transitions from containing a new, fully functioning structure to a more natural state where structures do not exist. Present conditions of existing structures were identified and their characteristics were classified along with descriptions of the surrounding morphology. Once a present condition was assigned to each structure, analysis of beach parameters and features surrounding each structure provided a more precise framework for characterizing life stages without regard to the age of the structure. The four stages of the initially proposed model are described in detail below.

1.5.1 Stage 1

The structure is intact with no structural damage; it conforms completely to engineering specifications. There is no apparent erosion, scour, or deposition landward of the structure, or standing water. Regular maintenance or upgrading of the structure to offset deterioration and increased sea level may extend Stage 1. Original justification for the structure is still applicable (Figure 1).

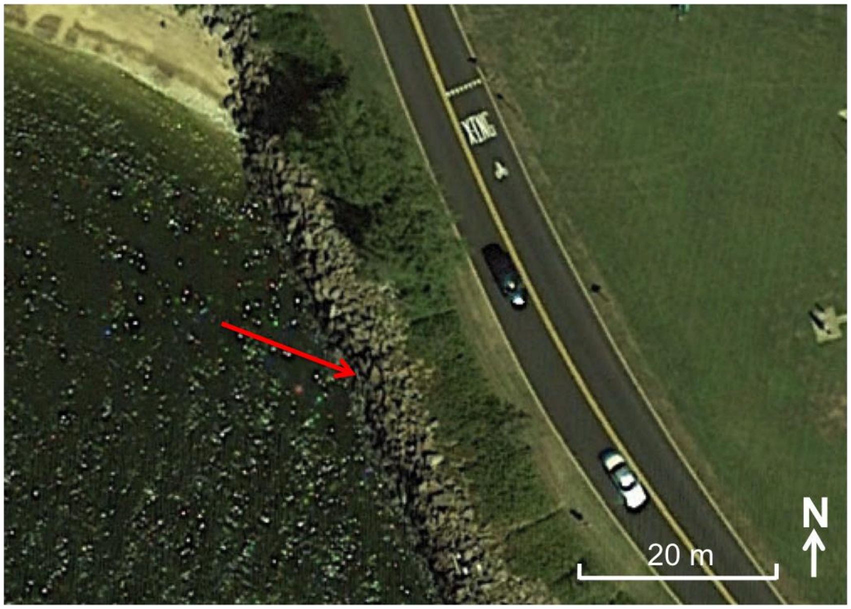

Figure 1. Satellite imagery from Google Earth depicting an example of Stage 1 of the initially proposed shore protection structure life stage model (Sandy Hook, NJ). The structure is intact and there is no evidence of erosion or the regular presence of water landward of the structure.

1.5.2 Stage 2

The structure is mostly intact, but time has elapsed since the most recent maintenance. There may be surface damage and minor structural damage. The structure remains as one cohesive unit and can still be generally described by the original engineering specifications. Sediment stability, entrainment, or transport occur as anticipated by the design. There is some erosion landward or adjacent to the structure. Original justification for the structure is still applicable, although changes in sea level or storm intensity or frequency may limit its ability to prevent overtopping (Figure 2).

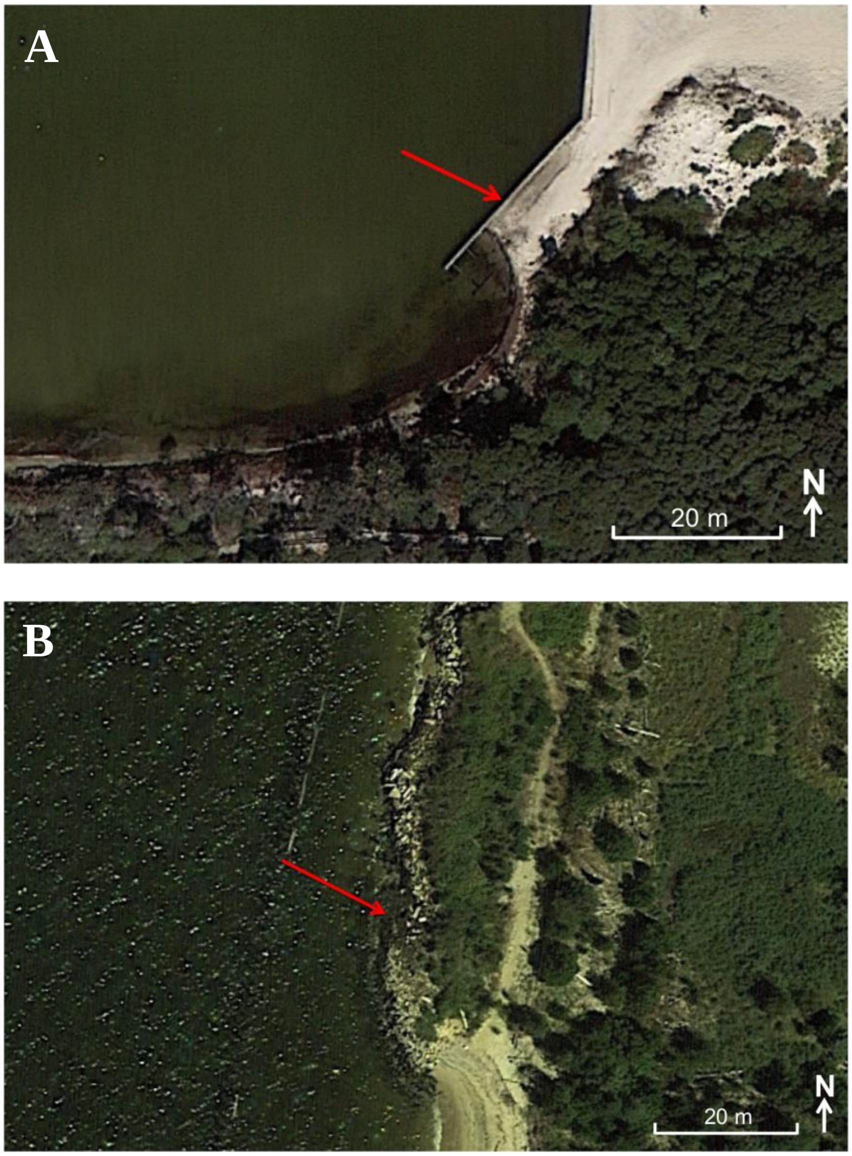

Figure 2. Satellite imagery from Google Earth depicting two examples of Stage 2 of the initially proposed shore protection structure life stage model (A: Fire Island, NY; B: Sandy Hook, NJ). Overtopping or breaching of the structures is occurring.

1.5.3 Stage 3

Regular maintenance of the structure has stopped and is not expected to resume. Noticeable surface and structural damage is present. The use of the infrastructure or land requiring protection when the structure was first built no longer justifies the cost and effort of maintaining or rebuilding the structure. Natural shoreline processes have begun to manifest themselves. Erosion is now occurring landward as well as adjacent to the structure. Water is present landward of the structure during high tidal stages. Infrastructure landward of the structure may be at risk (Figure 3).

Figure 3. Satellite imagery from Google Earth depicting an example of Stage 3 of the initially proposed shore protection structure life stage model (Brooklyn, NY). The high water line is located landward of the structure. Erosion is evident and natural shoreline processes have resumed.

1.5.4 Stage 4

Significant deterioration of the structure or change in water level due to sea level rise has taken place, and the beach system has returned to a more natural state. Few remnants of the structure remain, but their effects on the shoreline and sediment transport are reflected in the morphology. The low water line is located landward of the structure (Figure 4).

Figure 4. Satellite imagery from Google Earth depicting an example of Stage 4 of the initially proposed shore protection structure life stage model (Sandy Hook, NJ). The structure is in poor condition and the low water line is landward of the structure.

1.5.5 Remarks on the Proposed Model

With no interference, shore protection structures were expected to follow this generalized conceptual life stage model, beginning with Stage 1. However, with modifications, upgrades, or maintenance, a structure has the potential to move an earlier stage. For example, if a structure in Stage 3 was restored to include backfill or restoration of the area landward, it could return to Stage 2. Damage due to catastrophic events such as hurricanes could also cause a structure to skip stages and advance to later ones. The amount of time that a structure remains within each stage was unknown at the beginning of this study and was investigated during this research.

Stage 2 was hypothesized to be an especially critical point for managers to make a decision regarding the future of a structure. It represents a threshold beyond which a structure may be destined to degrade. Repeatedly modifying the original structure to maintain effectiveness could keep a structure in Stage 2. If a decision was made to no longer protect a resource and abandon the structure, there was a lack of a decision, or there was a lack of funds, the shore structure could be permitted to deteriorate and continue toward Stages 3 and 4. Refining this model and recognizing when a structure is within the critical stage for decision-makers and what follows may help managers better prepare to make decisions regarding the future of shore protection structures.

Beaches that are neither natural nor contain fully functional shore protection structures are described by Stages 3 and 4. While a structure is in one of these stages, it can no longer be accurately represented by design studies or planned outcomes. These stages may constitute a larger percentage of a structure's complete lifetime than Stages 1 and 2, and may be on the order of decades.

Beach morphology is an important diagnostic in the decision-making process. Managers can use this information to better determine the outcome of allowing a structure to deteriorate versus maintaining or removing it. Nine sites within the boundaries of Gateway National Recreation Area (GATE), managed by the US National Park Service, were chosen as case studies to refine and further define the stages of the shore protection structure life stage model. GATE was chosen for this study because of the juxtaposition of shore protection structures in various states of deterioration. The sites represent a broad range of structure conditions and distinguishing landscape features landward of the structures.

The following chapter provides an overview of types, materials, and designs of shore-parallel protection structures, with an emphasis on wood bulkheads and riprap revetments, which are the most common protection structures on estuarine shores (Nordstrom 1992; Nordstrom et al. 2016) and are found in abundance in GATE. Chapter 3 details the methods employed for this research. A comprehensive inventory of shore-parallel protection structures on estuarine shorelines in Gateway National Recreation Area follows in Chapter 4 to provide a larger dataset of structures that are characterized by condition, age, and stage to investigate relationships among these traits. Chapters 5 and 6 include a series of wood bulkhead and riprap revetment case studies that aim to describe the full spectrum of conditions and stages of protection structures. Chapter 7 and Chapter 8 contain a discussion of the results and conclusions of this study respectively.

Chapter 2

Form and Function of Intact Shore Protection Structures

2.1 Types of Structures and Their Functions

This section describes the original function and characteristics of traditional shore protection structures. Shore protection structures can generally be categorized by their orientation relative to the shoreline. Shore-normal structures primarily act as barriers to longshore sediment transport. Shore-parallel structures are more varied in physical characteristics and composition, and can be grouped into onshore and offshore structures, although structures that are built onshore can become offshore structures over time given a sufficient amount of beach retreat. Special attention is given to shore-parallel bulkheads and riprap revetments, which are the focus of this study.

2.1.1 Onshore Shore-parallel Structures

The purpose of onshore shore-parallel structures (bulkheads, seawalls, and revetments) is to provide direct protection for landward infrastructure because the natural protection of the beach has been reduced past the point of being effective (Nordstrom 2014). Shore-parallel structures built landward of the active beach have less impact on beach processes than either shore-parallel or shore-normal structures that extend into the active beach (Nordstrom 2014). Shore-parallel structures are often used because they are relatively easy to build (Paskoff 1992).

Bulkheads are vertical walls with a flexible, multi-jointed sheet construction whose primary purpose is to retain land or prevent slope failure (Morang and Szuwalski 2003; Department of Defense 2006). The secondary purpose is to protect against flooding and low energy waves and swash. Bulkheads are not substantial enough to withstand direct wave attack on open coastlines (Department of Defense 2006) and are typically built landward of ocean beaches, although they can provide primary protection on estuarine or protected coasts (Nordstrom 2014). Bulkheads are commonly made out of wood or steel and are found in abundance on estuarine coasts due to their affordability, small footprint, and resistance to low energy waves (Nordstrom 1992, Macdonald et al. 1994). Seawalls are built to prevent erosion, provide direct protection against wave action, and reduce the risk of flooding (Morang and Szuwalski 2003) in areas of higher wave energy. They are typically constructed of concrete or stone, and are more substantial than bulkheads (Department of Defense 2006).

Revetments protect the shoreline from erosion by providing a sloping, often textured surface, that helps dissipate wave and swash runup (Morang and Szuwalski 2003). Revetments traditionally have a gentler slope (e.g. 1:2 or 1:4) and are made of less massive material than seawalls. Revetments can be made of many materials, most commonly stone or concrete. Riprap is the term used to describe randomly placed (not fitted), well-graded stone used to form a protective layer.

2.1.2 Offshore Shore-parallel Structures

Breakwaters are built offshore to reduce the intensity of wave action in the lee of the structure to reduce erosion of the beach. They are also built to provide calmer waters for a marina or anchorage (Morang and Szuwalski 2003). There are many different designs for breakwaters (e.g. emergent, submerged or reef, floating), and they can be built as an individual structure or as a series of structures along the shore. Breakwaters are most commonly composed of stone riprap, but can be constructed using a variety of materials including repurposed materials such as car tires.

Submerged sills prevent beach erosion by retarding the offshore movement of sediment (Burcharth and Hughes 2011). They may be used in conjunction with beach nourishment to create a perched beach where the sand is retained landward of a structure placed on the foreshore or in the nearshore. Submerged sills are typically constructed of stone or concrete, but geotextiles are becoming increasingly used (Hornsey et al. 2011).

Storm surge barriers are designed to protect estuaries against high water levels by separating the sea from the estuary with large movable barriers or gates at the mouth of the estuary. During periods of normal water levels, storm surge barriers remain open to allow for tidal exchange and continued use of the waterway. These structures are expensive and presently uncommon, although they are the subject of increasing attention given expected increases in sea level (Aerts et al. 2014).

2.1.3 Shore-normal Structures

Groins may be the oldest and most widely used type of shore protection structure (Galgano 2004). They are built to aid in widening or reducing the loss of a beach by trapping sand being transported alongshore (Kraus et al. 1994). Sand is trapped on the updrift side of the structure, causing erosion on the downdrift side. They are typically made of stone, but are also traditionally made of concrete, steel, or wood (CERC 1984).

Structures that are constructed parallel to the beach can function as shore-normal structures at times. Termini of shore-parallel structures often extend from the active beach to the upland with a shore-oblique or -normal orientation. The portion of the structure on the beach receives the direct impact of waves often causing it to deteriorate faster than the termini, which may continue to trap sediment transported alongshore.

Additionally, some structure designs may contain both shore-parallel and –normal components as part of an armoring strategy (e.g. a revetment with attached groins).

2.2 Construction Materials

Structural and nonstructural physical properties, availability, cost, and ease of maintenance are of paramount importance when choosing the most appropriate material for protection structures. The planned design and life of the structure and the physical environment in which the structure will be placed guide this decision (Moffatt and Nichol Engineers 1983). Wood and stone are further discussed in detail as the two types of construction material that are the focus of the study.

2.2.1 Wood

Wood is widely used in the coastal zone as a construction material. Wood structures have historically been one of the most economical and viable options for shore protection structures. Wood is strong, resilient, able to absorb energy, easy to install, reasonably priced, and available nearly everywhere. The primary disadvantage is that it is prone to biological attack by fungi, bacteria, insects, which are more active in high moisture conditions, and marine organisms (Lopez-Anido et al. 2004). To protect wood from damage due to these sources and extend its life, it must be properly treated either by complete impregnation of the cells of the wood with chemicals or the application of a surface coating. While untreated wood will resist attack for no more than several years, effective preservative treatments may extend the useful life by about four to five times (Moffatt and Nichol Engineers 1983).

Physical and chemical damage are also considerations when a structure is made of wood. Boards or piles may be broken or damaged due to debris or by the force of storm waves or ice. Fastenings that connect the individual pieces of wood are almost always made out of metal, which are prone to corrosion due to saltwater exposure. Both undermine the integrity of the structure and contribute to an expected useful lifetime of years to decades (Moffatt and Nichol Engineers 1983).

2.2.2 Stone

Stone that is chosen as a construction material for coastal structures should be sound, durable, and hard, with a high specific gravity. The exact type and characteristics of the stone used for a structure will depend primarily on availability and cost. In general, a decision must be made to either use a local stone that may be of lower quality or to use a better quality stone from a greater distance. The principal benefit of using stone is its durability because the material is not affected by low wave energy, salt water, or biological organisms. Damage to the structure is more likely caused by dislodging or removal of stones from wave action than by breaking or physical erosion of stones, which may take centuries to occur. Secondly, the integrity of a stone structure is more easily maintained because movement or settling of individual stones does not usually compromise the structure as a whole (Moffatt and Nichol Engineers 1983).

2.3 Structure Design

Guidelines for the construction of protection structures provide insight to the potential for and pattern of their deterioration. There is a wide range of designs for protection structures, but most share basic components and characteristics. The designs discussed below most closely resemble the structures studied in this research.

A design procedure checklist for bulkheads and revetments is provided in Table 1. The most critical design elements are the crest elevation, support, and armor. As a general rule, structures must at least be able to "withstand conditions that have a 50 percent probability of being exceeded during the project's economic life" (USACE 1995). To accomplish this, the maximum water level and maximum breaking wave height are needed first to determine the appropriate elevation of the structure. This assumes water level, storm surge, and wave data for a given location exist and are readily available to engineers. In many cases, data are not available from a proximal site and extrapolations are made to estimate water levels at the structure site, which introduces uncertainty in the applicability of the data. A second issue is that this assumes historical data are an accurate representation of the present and future water levels, including potential storm surges. With accelerating sea level rise (IPCC 2007), this assumption is increasingly less accurate.

Table 1. Design procedure checklist for bulkheads and revetments from USACE (1995). It is imperative that structures are designed for the appropriate water level and wave conditions to prevent overtopping. Termini, backfill, and toe of the structure should be sufficiently reinforced or protected to prolong the effective life of the structure.

Design Procedure Checklist for Bulkheads and Revetments
1. Determine the water level range for the site.
2. Determine the wave heights.
3. Bulkheads only: Select suitable bulkhead configurations and design pile foundations.
4. Select a suitable armor unit type and size.
5. Determine the potential runup to set the crest elevation.
6. Determine the amount of overtopping expected for low structures.
7. Design underdrainage features if they are required.
8. Provide for local surface runoff and overtopping and runoff, and make any required provisions for other drainage facilities such as culverts and ditches.
9. Consider end conditions to avoid failure due to flanking.
10. Design the toe protection.
11. Design the filter and underlayers.
12. Provide for firm compaction of all fill and backfill materials.
13. Develop cost estimate for each alternative.

2.3.1 Wood Bulkheads

Sheet pile bulkheads are the most common wood bulkhead design along estuarine coasts in the northeastern United States. The sheet piles have a supporting framework of wales and structural piles (Figure 5) (USACE 1981). Horizontal wales are used to distribute lateral loads on the structure (USACE 1995). The primary design consideration for bulkheads is the pressure of the fill material landward of the bulkhead on the structure. The fill provides added resistance to wave forces. If the fill behind the bulkhead erodes, the bulkhead loses its support and may fail due to wave action (USACE 1981). This can occur due to failure of a component of the bulkhead, overtopping, seepage, or flanking, which is the process by which erosion of the beach adjacent to the bulkhead advances into the retained fill landward of the bulkhead.

Bulkheads constructed of wood sheet pile can be either cantilevered or anchored, referring to the mechanism that provides stability to the structure. Cantilevered bulkheads are stabilized solely by the penetration of the sheet pile into the ground and are generally only employed when the exposed wall height is low. Erosion at the base of the structure greatly threatens the stability of the bulkhead, and the depth of the buried portion of the sheet pile must be sufficient to prevent overturning (USACE 1995). An increase in the ground water level of the fill (e.g. storm surges, overtopping) increases the hydrostatic forces on the bulkhead and may contribute to scour at the toe due to water seepage under the bulkhead (USACE 1981). Anchored bulkheads, which are more common and can support greater structure heights, are additionally stabilized by deadmen landward of the sheet piles and connected by tie rods to the piles (Figure 5) (USACE 1981; Moffatt and Nichol Engineers 1983; Department of Defense 2006). Anchored bulkheads can withstand more toe scour and resist lateral earth pressures better than cantilevered bulkheads (USACE 1981). However, failure of components of the anchor system and structure failure due to displacement of the toes of the sheet piles are not uncommon (Department of Defense 2006). Wales are generally set at mean low water to minimize the moment in the sheet piling as much as possible at an acceptable cost. This also places the tie rods in permanently saturated ground, which reduces the rate of their corrosion (Department of Defense 2006).

A bulkhead's ability to retain fill landward of it is the most critical aspect of its design for it to maintain effectiveness, because that is what provides the strength of the structure to resist wave attack. If a bulkhead is not able to retain fill and the fill is compromised, whether due to leakage through the structure, overtopping of the structure, or seepage under it, the strength of the bulkhead becomes more reliant on the pilings which are not designed to withstand wave forces unsupported. As a result, pilings are often the first component of the structure to fail.

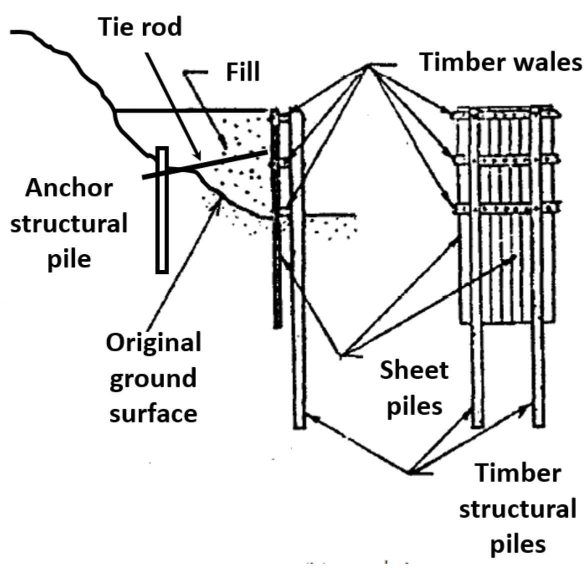

Figure 5. Design components of an anchored wood sheet pile bulkhead, derived from USACE (1981).

2.3.2 Stone Revetments

Stone revetments, including those composed of riprap (gradation of stone sizes) or quarrystone (nearly uniform stone sizes), are widely employed and are found in almost all coastal locations in the United States (USACE 1995). In both cases, the stones are placed without the use of a mortar. Riprap revetments are less stable than quarrystone revetments and are only suitable for low energy shorelines (USACE 1995). Structure stability is also proportional to the density and mass of the stones (Moffatt and Nichol Engineers 1983).

There are three major components to a revetment: the armor layer, filter layer, and toe (Figure 6). The armor layer provides the primary protection against wave action. Upland armor landward of the revetment can be used to help prevent erosion due to overtopping. The filter layer supports the armor layer and prevents sediment landward of the structure from being removed while allowing water to pass through. The toe helps to prevent undermining of the revetment and displacement of its seaward edge (USACE 1995; Department of Defense 2006).

Stone revetments can accommodate some settlement, but with significant movement or removal of armor stones, leakage of stone from the filter layer can occur. Raveling is the term used to define the disaggregation of stones in a structure. Riprap revetments that are dumped in place are likely to fail early in comparison to revetments whose stones are strategically placed.

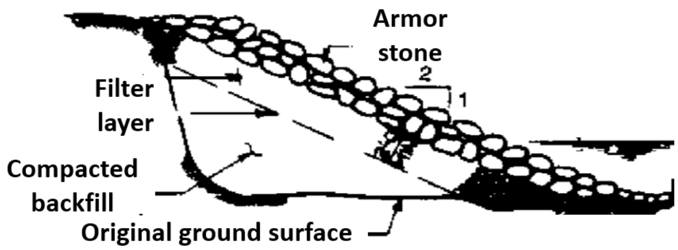

Figure 6. Cross-sectional construction details of a stone revetment, derived from Department of Defense (2006).

Other than ensuring the stone size and density is adequate for the wave environment, elevation and porosity of a revetment are deemed the two most critical aspects in the design. These aspects determine the amount of water that is able to pass through or over the structure causing erosion of the sediment underlying the stones, undermining the integrity of the structure.

Chapter 3

Methods

A two-pronged approach including remote methods and fieldwork was taken to study the structures in Gateway National Recreation Area (GATE). Remote methods included analyzing satellite imagery and maps, and reviewing published reports to compile an inventory of structures within park boundaries. Once inventories were completed, wood bulkhead and riprap revetment case study sites were chosen to characterize the morphology of the landscape surrounding structures of different conditions. Field methods for case studies included visits to structure sites to conduct topographic surveys and observations of surrounding landcover and geomorphic features. Topographic data were supplemented with a publicly available elevation dataset and historical imagery, which allowed characterization of sites using readily available data without visiting each structure.

Condition of a vertical structure with limited cross-shore width is more accurately assessed from ground level, though an indication of the condition may be gathered via imagery. Stage of a structure can be determined through fieldwork, but is limited to sites that are accessible in the field. Imagery is better suited to determine the stage of inaccessible structures. Both methods are used here.

3.1 Study Area

GATE is located in one of the most densely populated areas of the country, in close proximity to New York City (Figure 7). This area is experiencing coastal population growth at a rate of approximately 17% and relative sea level rise between 2.20 and 3.85 mm/yr (Gornitz et al. 2002). GATE is comprised of three management units, two in New York state (Jamaica Bay and Staten Island), and one in New Jersey (Sandy Hook). GATE covers more than 26,000 acres and has approximately 10 million visitors per year (NPS 2015). The majority of the coastline is estuarine with low wave energies and narrow sandy beaches. The limited amount of sediment in the estuarine beaches results in relatively high erosion rates (Nordstrom and Jackson 2016).

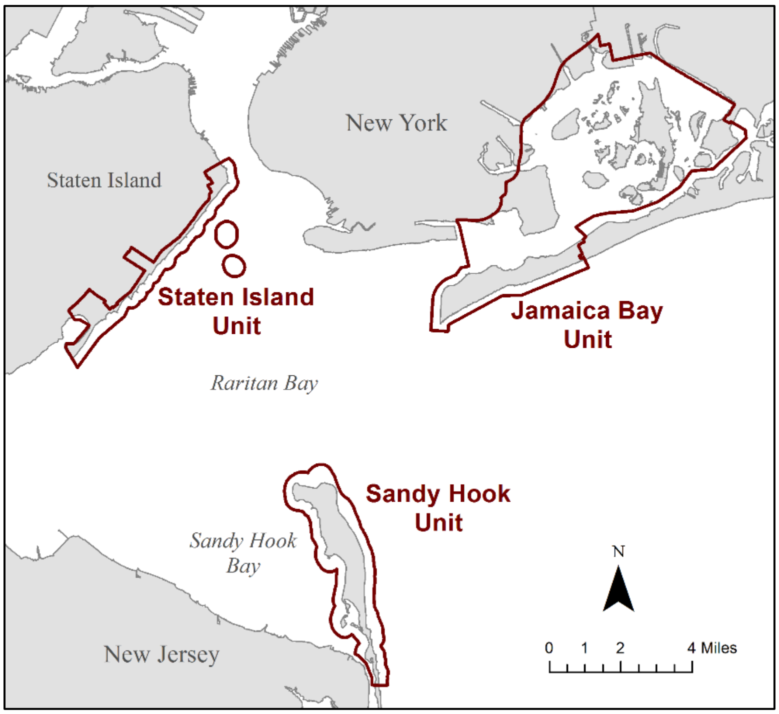

Figure 7. Gateway National Recreation Area Units include Staten Island and Jamaica Bay in New York, and Sandy Hook in New Jersey.

The ownership of the Sandy Hook Unit of GATE was transferred to the federal government by 1817. In 1895, the US Army began construction of Fort Hancock, which served as an active military fort until 1974, when it was decommissioned (NPS 2018). At its peak during World War II, Fort Hancock contained several hundred structures and housed 7,000 to 12,000 personnel (NPS, no date). GATE was added to the National Park System in 1972 (NPS 2015). Many of the shore protection structures within the park were built by the Army to protect the military facilities and artificially filled land

(Nordstrom and Jackson 2016). Dredge and fill projects have altered the shorelines within GATE since the late 19th century (Nordstrom and Jackson 2016).

A large percentage of the shore protection structures within GATE are periodically maintained where the structures protect access or maintenance roads, visitor centers, ranger headquarters, or other facilities. Structures that no longer serve a purpose for the park mission have been abandoned and begun to deteriorate.

A history of human alteration and sediment supply and transport, coupled with being one of the few locations in the area where development has not completely impeded natural processes, has made GATE the subject of interest for numerous studies that have documented sediment transport rates, erosion rates, beach form changes, and human-altered aspects of the coastline (e.g. Nordstrom 1980; Phillips 1985; Psuty and Pace 2009; Psuty et al. 2010; Nordstrom and Jackson 2013). Dallas et al. (2013) produced an inventory of coastal engineering projects within GATE, which provided historical data for structures in this study. The inventory of Dallas et al. (2013) focused on available engineering statistics and historical information of structures and nourishment projects. The focus of my research is on the impacts that the shore protection structures have on the shoreline and nearby morphology as they degrade, and how the patterns of these changes may be of use in decisions to rebuild the structures or allow them to deteriorate in place.

The nine sites chosen for the case studies discussed in Chapters 5 and 6 include four containing wood bulkheads, four containing riprap revetments, and one natural site with no history of protection structures. Eight of the sites were in the Sandy Hook Unit and one was in the Staten Island Unit of GATE. It was not possible to have all sites within the same unit because there were no intact wooden bulkheads present in Sandy Hook.

3.2 Methods for Inventories of Protection Structures

All shore-parallel, estuarine shore protection structures within the boundaries of the three units of GATE (Figure 7) were identified and compiled into inventories, which were cross-referenced with data in Dallas et al. (2013). Variables used to describe structures in the inventory include (1) type of structure; (2) construction material; (3) length of structure; (4) dates of construction and maintenance, if available; (5) effective age; (6) landform characteristics; (7) structure condition; and (9) stage. The sources used to compile the data within the inventories are discussed below.

3.2.1 Imagery

Evaluations were conducted remotely using the most recent public satellite imagery available at that time (from 2016). Scale, resolution, and exposure of imagery varied considerably, causing some features to be more easily identified in some images than others. Height of the tide at the time of image collection contributed to the ability to accurately identify structures. To reduce differences while still allowing for data redundancy, imagery was limited to Google Earth and Bing Maps. Structures were delineated using Esri ArcMap 10.3.1, which provided an overall length for the structures. Color and texture were used to identify construction material. Familiarity with local geology and management practices, information in Dallas et al. (2013), and site visits assisted in final determination of construction material.

Conditions of the shore protection structures were identified remotely as good, fair, or poor. Good is defined as the structure appearing intact; no major gaps or holes exist; and riprap is consolidated with no stray boulders. Fair is defined as the structure being mostly intact but with some structural flaws; small gaps or holes may occur in sheet pile structures or there may be stray boulders surrounding a structure composed of riprap. Poor is defined as the structure appearing in disrepair; little is left of the original structure or many gaps and holes occur; or riprap is no longer consolidated and appears as individual boulders.

A description of the land surface surrounding the structures including broad vegetation category, bare sand, open water, buildings, and other infrastructure was primarily conducted via imagery analysis, but was supplemented with geospatial datasets from the National Park Service that included inventories of infrastructure and landcover. The imagery, in conjunction with site visits and the definitions developed to characterize distinct stages identified in Chapter 1, allowed a stage to be assigned to each wood bulkhead and riprap revetment. Stage was not assigned to one riprap revetment in the Jamaica Bay Unit (Revetment 38) due to a paved area landward that did not allow for assessment of erosion or undermining of the asphalt via satellite imagery.

Identifying and describing structures through imagery was not without difficulty, and presented some issues similar to those experienced in the field. Only portions of structures that were above the water surface and not covered by vegetation or sediment were visible. Data are only representative of the elevation and morphology of the study area at the time the data were collected and do not capture dynamic changes that occur over short time periods. Quantitative measurements or changes in beach width over time for any given point along a structure could not be determined from imagery because images were captured at various points in the tidal cycle. Strategies that aided in determining the presence of a structure included the overall shape (e.g. linear), color (as distinct from sand or vegetation), and location of a feature relative to the backshore-upland contact. Site visits and conversations with park employees assisted in removing uncertainty in the information gained from imagery.

3.2.2 Published Inventory Reports

The National Park Service (NPS) published a series of Coastal Engineering Project reports for various units in the country, including GATE. The Inventory for GATE (Dallas et al. 2013) was used primarily to collect information on dates of construction and maintenance of the structures, although it also provided verification of structures that were identified via imagery.

Age was calculated using the construction and maintenance dates provided in Dallas et al. (2013) where possible, with effective age defined as the time since the most recent structural upgrade. Age was not available for all structures, and some dates provided were only an approximation or a limit (i.e. "built before" or "built after"). In some cases, initial construction was identified, but information regarding maintenance was lacking, or vice versa. Therefore, comparisons involving ages of structures contain some uncertainty. A lack in consistent record-keeping is one of the major difficulties in studying historical coastal protection structures and understanding how they affect the landscape over time.

Nordstrom and Jackson (2016) focused on 12 national parks in the northeastern United States and evaluated the potential to remove shore protection structures or allow them to deteriorate, in order to facilitate sediment exchange and improve ecosystem function. That study was useful in verifying presence, type, material, and length of structures, as well as descriptions of surrounding landform characteristics. Discussions of morphological processes within their case studies assisted in the qualitative analysis of the life stages of wood bulkheads and riprap revetments evaluated in this study.

The objectives of my study differed from the primary goals in Dallas et al. (2013) and Nordstrom and Jackson (2016), although similar methods are employed and structure inventories are described in each. Dallas et al. (2013) cataloged and mapped all coastal engineering projects to include protection structures, dredging, and beach fill projects, with the goal of developing a greater understanding of the extent of human modifications within the National Park System. Nordstrom and Jackson (2016) focused on the opportunity for removing protection structures. My research similarly used structure inventories as a base, but paired this information with field methods to describe the morphology and distinguishing features of the landscape surrounding structures of different conditions to describe how these features change over time when a structure is not regularly maintained.

3.2.3 Maps

Historical topographic maps were used to provide information on the location and orientation of the shoreline in the past. In some instances, structures were denoted on the maps, but this was the exception. It is not standard practice to include shore protection structures on topographic maps, but historical topographic maps provide an overview of the larger-scale and longer-term changes that have taken place, especially when looked at in sequence.

Historical maps used for this study are primarily from USGS and available through the Rutgers University *Maps of New Jersey* portal and Cartography Lab website (http://mapmaker.rutgers.edu/MAPS.html). USGS 1:24,000 scale base topographic maps were available for the entirety of GATE for 1947 to 2016. Historical coastal maps of New Jersey from 1878 (New Jersey Coast: First Atlas) were obtained from the Princeton University library. Small-scale maps for Fort Hancock (on Sandy Hook) were obtained from the National Park Service website.

3.3 Methods for Case Studies

Using the compiled structure inventories, structures were chosen for site visits and further narrowed down for case studies of wood bulkheads and riprap revetments. Topographic data were collected at case study sites and were supplemented with historical satellite imagery covering 1991 to 2016, and a modern digital elevation dataset.

3.3.1 Visual Observations

Site visits provided qualitative information about accessible shore-parallel, estuarine shore protection structures. Observing shore protection structures and their surrounding environment at the ground level provided a more thorough understanding and accurate assessment of condition, structural integrity, physical processes at work, and the effects of the structures on the surrounding morphology that is unattainable via remote methods.

Site visits aided in the decision of which structures were to be the focus of data gathering, and which structures were to be used for collection of qualitative information. The structures chosen for case study sites met the following criteria: the overall structure length was greater than 400 m; the structure had been in place for a minimum of 25 years; and the structure was surrounded by land that had the ability to be mobilized by natural forces (i.e. not completely hardened due to development). Locations and names of these case study sites are illustrated in Figure 8 and Figure 9.

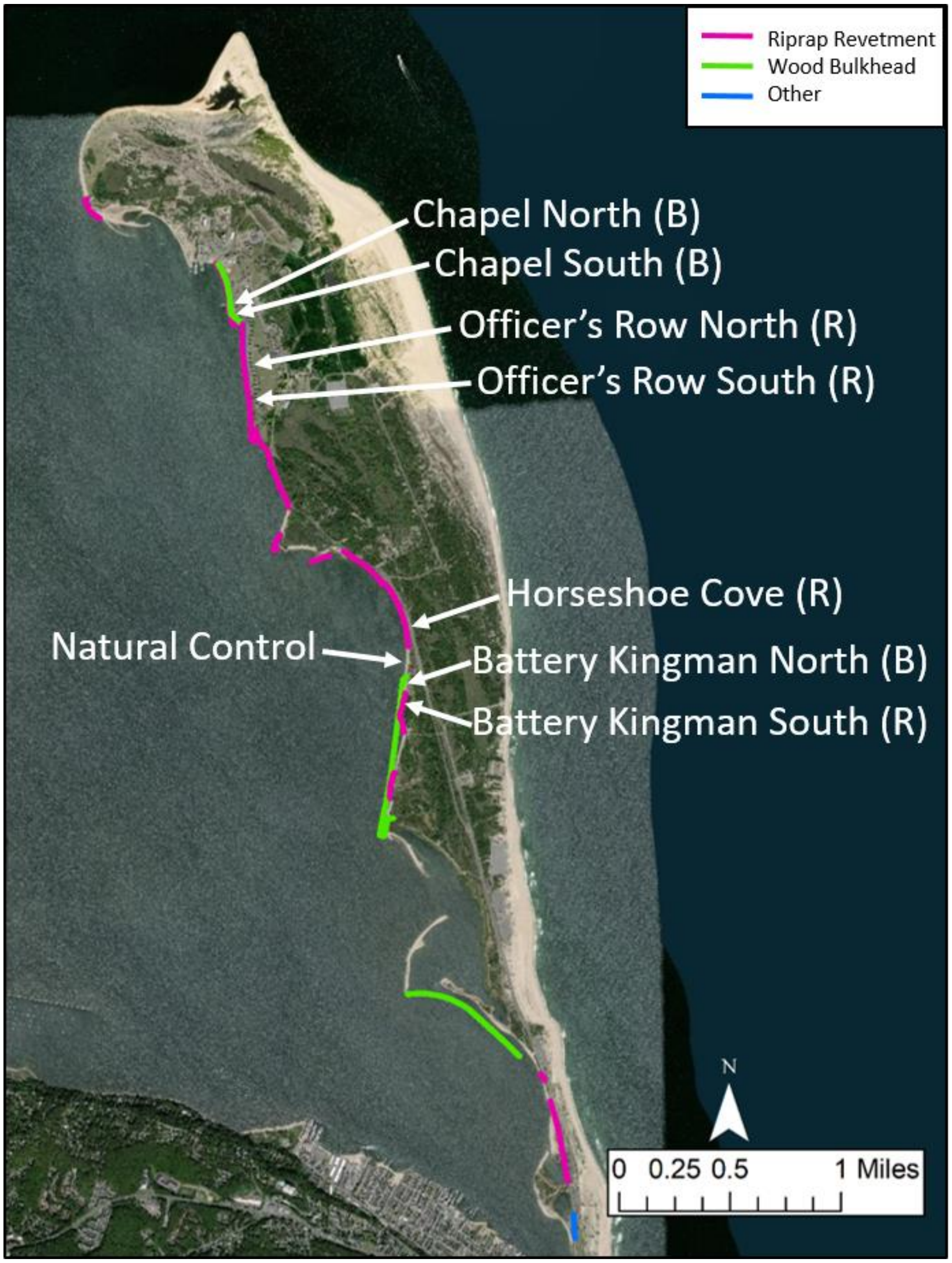

Figure 8. Shore-parallel protection structures on estuarine beaches in the Sandy Hook Unit of Gateway National Recreation Area. Case study sites are labeled "B" indicating a wood bulkhead or "R" indicating a riprap revetment. Base imagery source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

Figure 9. Shore-parallel protection structures on estuarine beaches in the Staten Island Unit of Gateway National Recreation Area. Bulkhead case study site at Great Kills is labeled. Base imagery source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

3.3.2 GPS Elevation

Topographic surveys of the sites were conducted using a Leica Geosystems real-time kinematic (RTK) global positioning system (GPS) rover. Three shore-normal profile transects were taken at each site. These profiles were spaced approximately 10 m apart and extended from the upland area or dune (if present) to the seaward extent of the structure, and further if possible. Alongshore transects extended for approximately 30 m and were taken along significant features on the beach profile (i.e. dune crest, berm crest, runnel). The number of alongshore transects that were taken varied by site but care was taken to ensure sufficient coverage to capture features between the low tide terrace and vegetated dune or upland area. Surveys were conducted as close as possible to low tide when most structures and the land directly seaward were exposed. Maximum exposure allowed for the best overall view of the site for determining small-scale geomorphology on the beach and best placement of the RTK GPS rover for data collection. Specific locations of GPS data collection are depicted in Figure 10 through Figure 15. Bulkhead sites within the Sandy Hook (SAHO) Unit of GATE were surveyed November 5-7, 2015. Revetment sites within SAHO were surveyed March 2-3, 2017.

Topographic data gathered via RTK GPS at the Chapel North Site (Figure 10) did not run parallel or normal to the bulkhead, as at all other sites. Data were collected along the contours of the beach to reflect the size and crescentic shape of the reentrant behind the gaps in the bulkhead. For consistency of presentation of data among sites, and the ability to compare NED to RTK GPS data, transects plotted represent lines parallel and normal to the bulkhead.

Elevation data were exported from the RTK GPS rover using Leica software. The data were then processed and edited using Esri ArcMap 10.3.1. Duplicate data points and points with unacceptable geospatial error were discarded. The maximum acceptable value used for 3DQ error was 0.060 m. All geospatial analyses to include distance calculations and relationships between structures and the surrounding environments were performed using Esri ArcMap 10.3.1.

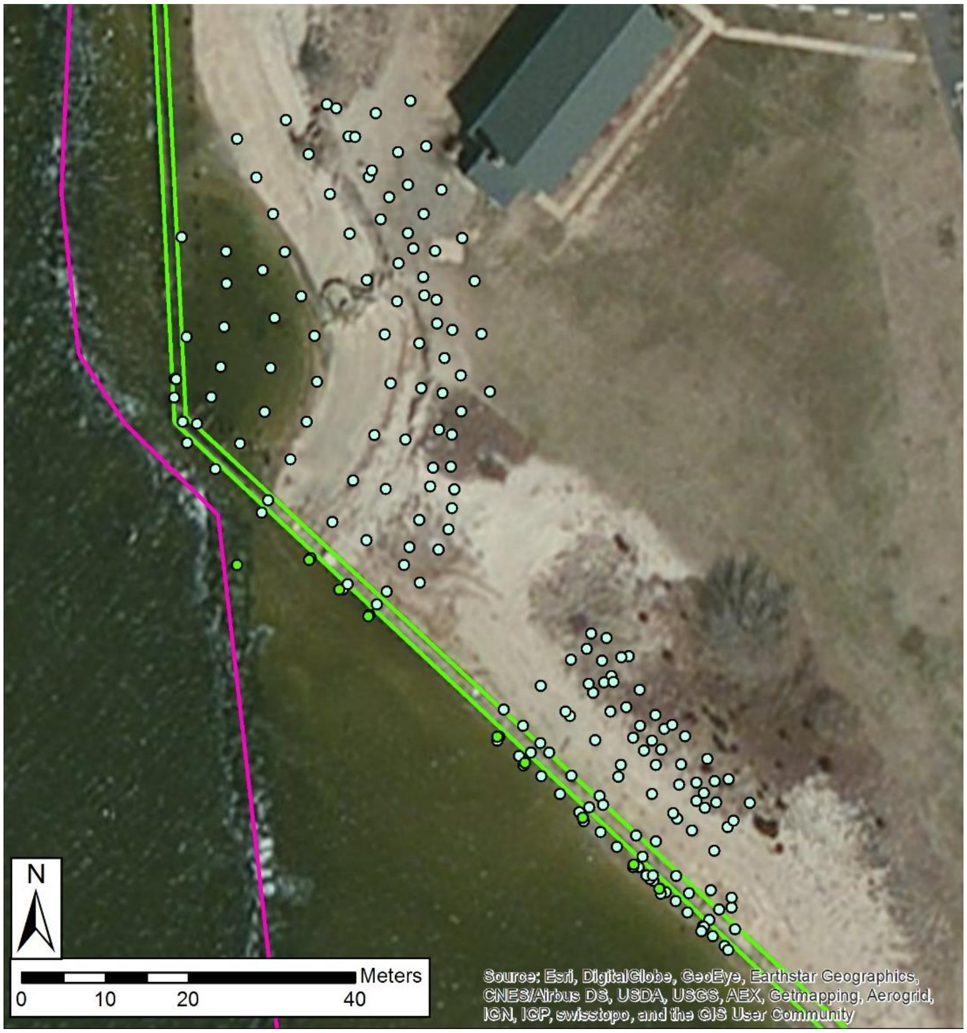

Figure 10. Chapel North and Chapel South sites RTK GPS data collection points and structures. Data collection points on the structure are depicted in green. Points on the ground surface are depicted in light blue. Lines represent shore protection structures (pink = revetment; green = bulkhead). Base imagery source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

Figure 11. Officer's Row North and Officer's Row South sites RTK GPS data collection points and revetment (line). Data collection points on the structure are depicted in pink; points on the ground surface are depicted in light blue. Base imagery source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

Figure 12. Horseshoe Cove site RTK GPS data collection points and revetment (line). Data collection points on the structure are depicted in pink; points on the ground surface are depicted in light blue. Base imagery source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

Figure 13. Natural site RTK GPS data collection points on the ground surface, depicted in light blue. Base imagery source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

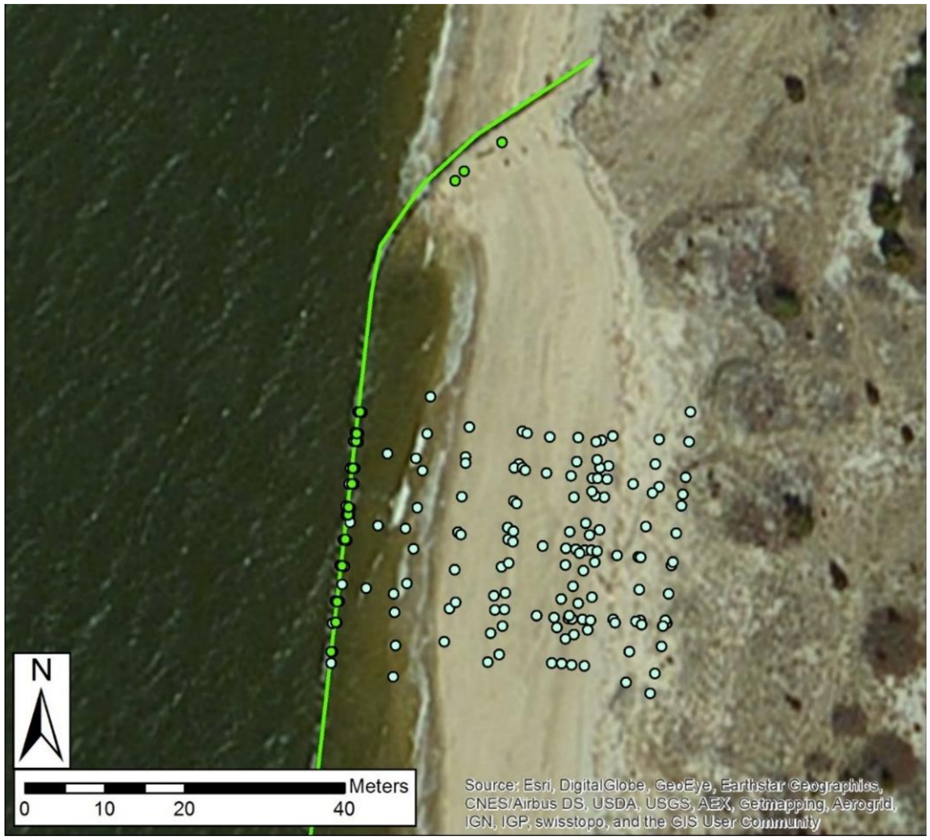

Figure 14. Battery Kingman North site RTK GPS data collection points and bulkhead (line). Data collection points on the structure are depicted in green; points on the ground surface are depicted in light blue. Base imagery source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

Figure 15. Battery Kingman North site RTK GPS data collection points and structures. Data collection points on the revetment are depicted in pink. Points on the ground surface are depicted in light blue. Lines represent shore protection structures (pink = revetment; green = bulkhead). Base imagery source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

3.3.3 National Elevation Dataset

The National Elevation Dataset (NED), a digital terrain model (DTM), was used to supplement topographic data gathered via GPS and also evaluated as an alternative to GPS if field surveys cannot be done. There are numerous advantages to using a DTM, which have increased the ability of earth scientists to analyze and model small- to large-scale features and processes (Tarolli 2009). DTMs are readily available and require fewer person-hours to incorporate into research than data collected in the field. They also provide data for areas that are not easily accessed. In addition, using a public data source with national coverage promotes multidisciplinary studies, where researchers or managers can use the same topographic data for such applications as hydrologic modeling, coastal flood zone mapping, resource monitoring, and urban planning. The NED in a seamless raster format and can be imported, analyzed, and manipulated using geographical information systems (GIS) software. The dataset has coverage across the United States with consistent projection and elevation units, and is updated continually as new data become available.

The DTM used for this study is a tiled collection of the NED and was published by the United States Geological Survey on April 30, 2015, through their National Map Data Viewer (https://viewer.nationalmap.gov/basic/). The data, which were gathered in 2014, have a one-meter resolution and represent a bare ground elevation (i.e. not the top of infrastructure or vegetation) and provide coverage over the entirety of GATE, including areas where ground surveys are not feasible or easily conducted. The terrain model is derived from diverse source data that are processed to a common coordinate system and unit of vertical measure, where only source data of one-meter resolution or finer are used. The spatial reference used for the data is Universal Transverse Mercator (UTM) in units of meters, and in conformance with the North American Datum of 1983 (NAD83). All bare earth elevation values were in meters and were referenced to the North American Vertical Datum of 1988 (NAVD88). The tiles that cover the focus sites in both the SAHO and Staten Island (STIS) units were downloaded and imported into Esri ArcGIS 10.3.1 for analysis.

Beach profiles were generated from the NED using the Interpolate Line tool in ArcGIS 10.3.1, which digitizes a 3D line from a surface. These profiles were generated both shore-normal and shore-parallel at case study sites, and extended seaward of the structures to the upland areas of the sites. The NED surface does not contain true values for submerged ground surfaces. The default elevation value for submerged ground is approximately -1.7 m. Because the NED is a raster dataset and there are no holes in the surface, slopes can be unrealistically steep between subaerial ground true elevation values and those submerged areas where data is not available (e.g. Figure 42). Both field and remote methods were used to produce the beach profiles analyzed in Chapters 5 and 6.

3.3.4 Historical Imagery

Past imagery was collected to monitor changes in the structures and landscapes that occurred over the previous three decades. Imagery prior to 1990 is not readily available or of a sufficient resolution for this study. Data collection was conducted via Google Earth using the Historical Imagery slider within the application, which is a consolidation of cloud-free imagery from multiple databases, including high-resolution satellite and aerial imagery. This tool allowed for observation of changes in structure condition, vegetation cover, shoreline orientation, and interpretation of the patterns of erosion and deposition and the timescale on which they are acting.

The maximum imagery date range available from Google Earth for the study sites within GATE was 1991 to 2016. Dates of imagery are listed in Table 2. The periodicity of images has increased over time, with clusters of images in short periods of time occurring after major events (e.g. Hurricane Sandy). The quality (i.e. resolution) of images has generally increased over time, as expected, due to the improvement of imaging technology. Small-scale features in older images are difficult and sometimes impossible to detect due to the low resolution, and are not reliable for quantitative measurements. Color images allowed for better detection of features on the beach and upland.

Imagery in Google Earth is collected from various platforms and providers to include private and government organizations and compiled into one mosaic. The scale was adjusted to an eye altitude of approximately 217 m to allow for a single source for each image, eliminating the issue of dealing with mosaic images from various sources and dates. Images from 2014 were poorer in quality than others and were excluded.

Table 2. Dates of historical imagery available via Google Earth by site.

Chapel North	Chapel South	Officer's Row North	Officer's Row South	Horseshoe Cove	Natural	Battery Kingman North	Battery Kingman South	Great Kills
Mar 1991	Mar 1991	Mar 1991	Mar 1991	Mar 1995	Mar 1995	Mar 1995	Mar 1995	Mar 1995
Mar 1995	Mar 1995	Mar 1995	Mar 1995	Dec 2001	Dec 2001	Dec 2001	Dec 2001	Dec 2003
Dec 2001	Dec 2001	Dec 2001	Dec 2001	Jul 2006	Jul 2006	Jul 2006	Jul 2006	Jul 2006
Jul 2006	Jul 2006	Jul 2006	Jul 2006	Jul 2007	Jul 2007	Jul 2007	Jul 2007	Jul 2007
Jul 2007	Jul 2007	Jul 2007	Jul 2007	May 2008	May 2008	May 2008	May 2008	Mar 2008
May 2008	May 2008	May 2008	May 2008	Dec 2009	Dec 2009	Dec 2009	Dec 2009	May 2009
Dec 2009	Dec 2009	Dec 2009	Dec 2009	Sep 2010	Sep 2010	Sep 2010	Sep 2010	Jun 2010
Sep 2010	Sep 2010	Sep 2010	Sep 2010	Nov 2012	Nov 2012	Nov 2012	Nov 2012	May 2011
Jul 2011	Jul 2011	Jul 2011	Jul 2011	Sep 2013	Sep 2013	Sep 2013	Sep 2013	Nov 2012
Nov 2012	Nov 2012	Nov 2012	Nov 2012	Apr 2016	Apr 2016	Apr 2016	Apr 2016	Oct 2014
Sep 2013	Sep 2013	Sep 2013	Sep 2013					Apr 2016
Apr 2016	Apr 2016	Apr 2016	Apr 2016					

Chapter 4

Shore Protection Structure Inventories

Sixty-four shore-parallel structures on estuarine beaches that lie within GATE boundaries were identified. Remnants of buildings currently functioning as protection structures were excluded because they are not likely to provide insight into decisions about building or rebuilding protection structures.

4.1 Sandy Hook Unit

Shore-parallel structures within the Sandy Hook Unit (SAHO) are identified in Figure 8 and their characteristics are compiled in Table 3. The eighteen structures include six bulkheads, one seawall and eleven revetments. Most structures (10) are rock; five are wood, two are primarily concrete, and one is steel. All wooden structures are bulkheads. Ten of the eleven revetments are riprap. Revetment 2 is the only structure that is fronted by groins, spaced at approximately 150 m intervals.

The ages of the structures vary greatly. The oldest existing structure (Bulkhead 5) was built before 1870 and the most recent (Revetment 8) was built between 1995 and 2002. Many structures were built to protect military infrastructure and roads prior to the creation of GATE by the US Congress in 1972. Many structures are deteriorated and are in fair or poor condition, as their original purpose is no longer applicable due to changes in land and building use. The majority of wooden bulkheads on the bay shore have deteriorated to the extent that beaches or scarps in uplands have formed landward of them (Nordstrom and Jackson 2013). The structures that remain in the best condition are those that protect access paths and roads that are still in use. Quarry stone structures such as those described in detail in Chapter 6 are also predominantly in good condition, though settling has resulted in a decrease in elevation at some locations (Nordstrom and Jackson 2016).

The protection structures in Sandy Hook represent all stages of the structure life stage model. Three structures are in Stage 1, three in Stage 2, and four in Stage 4. The largest number of structures (five) are in Stage 3, where beaches have begun to evolve landward and open water is present. Most case study sites were selected from this unit because it encompasses readily accessible examples of each stage for both wood bulkheads and riprap revetments. The only case not represented in SAHO is a wood bulkhead site in Stage 1, which is present in the Staten Island Unit.

Table 3. Inventory of shore parallel protection structures on estuarine beaches in the Sandy Hook Unit of Gateway

Structure ID	Material	Length (m)	Year constructed/ maintained[1]	Effective Age (yrs)[1]	Landward habitat/infrastructure	Condition	Stage
Bulkhead 1	Wood	490	1878	140	USCG buildings behind northern portion. Parking area and chapel behind bulkheads and seawall on NPS land.	Poor	3
Revetment 1	Riprap	490	Before 1943	>75	USCG buildings behind northern portion. Parking area and chapel behind bulkheads and seawall on NPS land.	Poor	4
Bulkhead 2	Wood	210	1897 / 1898, 1899, 1900, 1901, 1904, 1965	53	USCG buildings behind northern portion. Parking area and chapel behind bulkheads and seawall on NPS land.	Poor	2
Bulkhead 3	Concrete	360	1897 / 1965	53	Developed grassy area; bike path; road; numerous historic former officer quarters.	Fair	N/A
Revetment 2	Riprap	860	1899 / 1901	117	Developed grassy area; bike path; road; numerous historic former officer quarters.	Good	3
Revetment 3	Riprap	630	Before 1991	>27	Developed area; successional maritime forest.	Good	1
Revetment 4	Riprap	150	No dates available.	Unknown	Battery Arrowsmith; maritime beach; shrubland.	Fair	3
Bulkhead 4	Wood	50	No dates available.	Unknown	Maritime beach; shrubland.	Poor	4
Revetment 5	Gabions	140	Before 2002	>16	Unpaved path; salt marsh.	Good	N/A
Revetment 6	Riprap	370	1954 / 1988	30	Paved road; successional maritime forest; maritime red cedar forest; sand path; maritime holly forest; maritime dunes.	Good	1
Revetment 7	Riprap	510	1988	30	Paved road; successional maritime forest; maritime red cedar forest; sand path; maritime holly forest; maritime dunes.	Fair	3
Bulkhead 5	Wood	1400	1961	57	Maritime beach; maritime dunes; maritime holly forest; unpaved road/path; successional southern hardwoods; Battery Kingman and Battery Mills.	Poor	4
Revetment 8	Riprap	290	Between 1995 and 2002	16-23	Unpaved road; successional southern hardwoods; Battery Kingman; brackish meadow.	Good	1
Revetment 9	Riprap	190	Before 1995	>23	Brackish meadow; unpaved road/path; low walt marsh; salt shrub.	Poor	2
Bulkhead 6	Wood	1230	Before 1870	>148	Bay.	Poor	4
Revetment 10	Riprap	50	1988	30	Maritime dunes; paved road; salt shrub.	Good	3
Revetment 11	Riprap	570	Before 1995	>23	Paved road; salt shrub; maritime dunes; seawall.	Good	2
Bulkhead 7	Steel	60	No dates available / 2001	17	Maritime beach; salt panne; paved road; maritime dunes.	Good	N/A

[1]Construction and maintenance dates are from Dallas et al. (2013).

4.2 Staten Island Unit

Shore-parallel protection structures on estuarine beaches within the Staten Island Unit (STIS) of GATE are identified in Figure 9. Fourteen structures that meet the criteria for this study (three bulkheads, nine revetments, and two seawalls) were identified (Table 4). All of the bulkheads are wood, all revetments are stone riprap, and all seawalls are concrete. Most structures are in good condition (six) or fair condition (six); two are in poor condition. All stages are represented in STIS, with the largest number of structures (five) being in Stage 3.

All structures that protect visitor use or access infrastructure bordering Great Kills Harbor were constructed or renovated in the 1980s and were in good condition at the time of this study. The wood bulkheads in this area are the newest and in the best condition out of all of GATE, and are the only wood bulkheads in Stage 1. For this reason, Great Kills Harbor was chosen as a case study site for a wood bulkhead.

Table 4. Inventory of shore-parallel protection structures on estuarine beaches in the Staten Island Unit of Gateway National Recreation Area

Structure ID	Material	Length (m)	Year constructed/ maintained[1]	Effective Age (yrs)	Landward habitat/infrastructure	Condition	Stage
Seawall 1	Concrete	190	circa 1938	80	Successional southern hardwoods; shallow emergent marsh.	Fair	N/A
Seawall 2	Concrete	260	1855-1871/ 2006	12	Fort Wadsworth Bunker; Battery Weed; paved road; successional southern hardwoods.	Fair	N/A
Revetment 12	Rock	450	Before 1994	>24	Successional southern hardwoods; paved road.	Poor	3
Revetment 13	Rock	90	Before 1974	>44	Developed grassy area.	Fair	3
Revetment 14	Rock	110	Before 1974	>44	Unpaved road; developed grassy area.	Fair	3
Revetment 15	Rock	190	Before 1974	>44	Bay; maritime beach; Revetment 14.	Poor	4
Revetment 16	Rock	680	2002	16	Unpaved road; maritime dunes; estuarine reedgrass marsh.	Fair	3
Bulkhead 8	Wood	120	1947	71	Maritime beach; estuarine reedgrass marsh.	Fair	2
Revetment 17	Rock	140	1960	58	Maritime beach; marine intertidal mudflats; estuarine reedgrass marsh.	Good	3
Bulkhead 9	Wood	860	1943; late 1980s	~30	Estuarine reedgrass marsh; successional northern hardwoods; road.	Good	1
Revetment 18	Rock	25	1980s	~35	Developed area.	Good	2
Revetment 19	Rock	420	late 1980s	~30	Developed area; paved road; maritime shrubland.	Good	2
Bulkhead 10	Wood	550	1935 / late 1980s	~30	Developed area; paved road; successional maritime forest.	Good	1
Revetment 20	Rock	550	late 1980s	~30	Road; successional southern hardwoods; maritime shrubland; estuarine reedgrass marsh.	Good	2

[1]Construction and maintenance dates are from Dallas et al. (2013).

4.3 Jamaica Bay Unit

Shore-parallel protection structures within the Jamaica Bay Unit (JABA) of GATE are identified in Figure 16. Thirty-two structures that meet the criteria of this study are identified, including 12 bulkheads, 18 revetments, and two breakwaters (Table 5). More than half (18) of the structures are riprap; six are wood; five are steel; two are concrete; and one is composed of tires. Almost all wood bulkheads (four) are in poor condition, while more than half of the riprap revetments (nine) are in good condition. All stages are represented in JABA, with the largest number of structures (12) being in Stage 3.

The Jamaica Bay Unit contains the widest variety of structures in terms of construction material, and the structures are on average the newest out of the three units, with the newest being a riprap breakwater on Plumb Beach constructed in 2013.

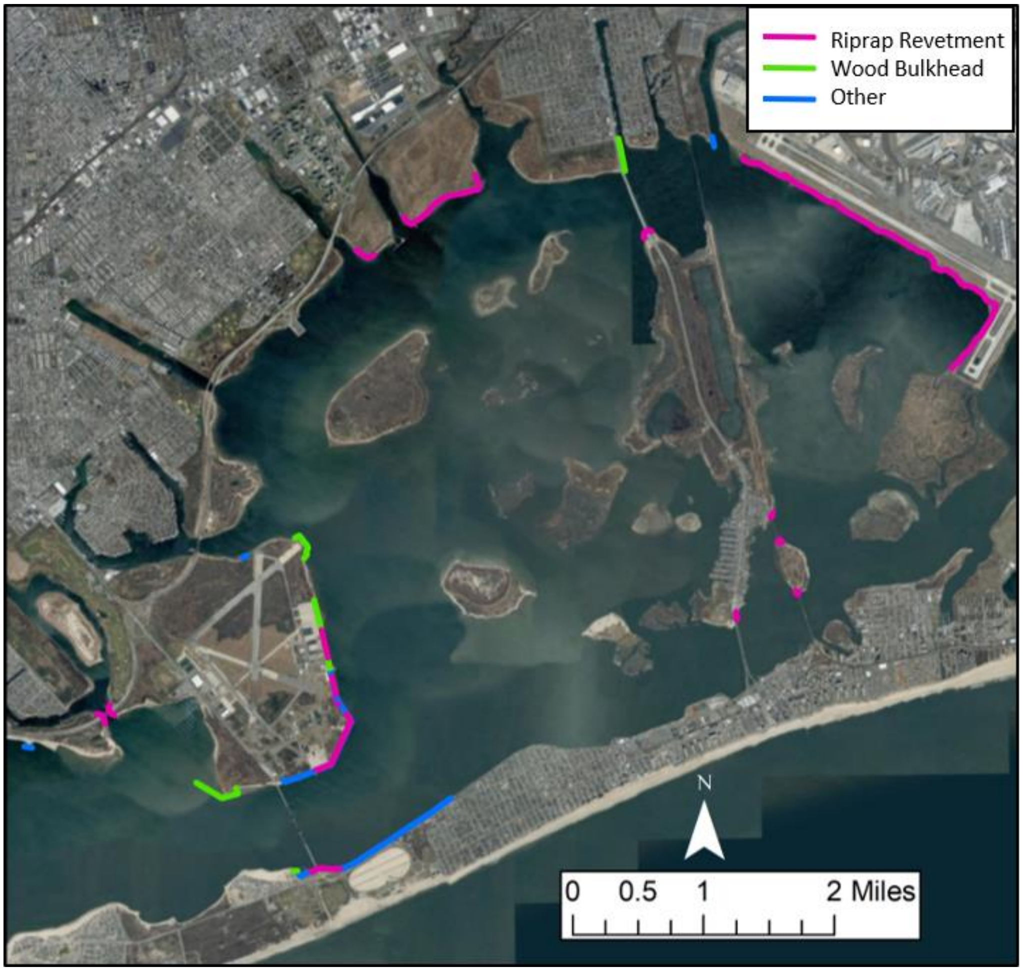

Figure 16. Shore-parallel protection structures on estuarine beaches in the Jamaica Bay Unit of Gateway National Recreation Area. Base imagery source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

Table 5. Inventory of shore parallel protection structures on estuarine beaches in the Jamaica Bay Unit of Gateway National Recreation Area

Structure ID	Material	Length (m)	Year constructed/ maintained[1]	Effective Age (yrs)	Landward habitat/infrastructure	Condition	Stage
Revetment 32	Riprap	170	No dates available.	Unknown	Paved road; developed area; maritime beach.	Poor	3
Bulkhead 19	Concrete	120	No dates available.	Unknown	Bay; developed area; maritime beach; low salt marsh.	Poor	3
Revetment 33	Riprap	4750	No dates available.	Unknown	John F. Kennedy International Airport; developed area.	Good	2
Revetment 34	Riprap	90	No dates available.	Unknown	Railroad; maritime beach; low salt marsh; estuarine reedgrass marsh.	Fair	3
Revetment 35	Riprap	90	No dates available.	Unknown	Railroad; maritime beach; low salt marsh; estuarine reedgrass marsh.	Fair	3
Revetment 36	Riprap	60	No dates available.	Unknown	Railroad; maritime beach; low salt marsh; estuarine reedgrass marsh.	Fair	3
Revetment 37	Riprap	100	No dates available.	Unknown	Paved road; developed area.	Good	2
Bulkhead 20	Steel	1630	circa 1940	~78	Paved road; developed area; maritime dunes; maritime shrubland; pine plantation.	Good	N/A
Revetment 38	Riprap	410	1945	73	Paved road; developed area.	Good	N/A
Bulkhead 20	Steel	160	late 1920s / 1943	75	Developed area.	Good	N/A
Bulkhead 21	Wood	50	early 1920s	~96	Developed area.	Poor	3

[1]Construction and maintenance dates are from Dallas et al. (2013).

Chapter 5

Wood Sheet Pile Bulkheads

Five case study sites containing wood sheet pile bulkheads that displayed a range of structure conditions and associated nearshore morphology were investigated to define distinguishable features for each stage of the proposed protection structure model. Results are presented in an order of decreasing structure effectiveness and ending with a natural site that has no history of shore protection.

5.1 Great Kills Site (Stage 1)

The wooden bulkhead at this site (Bulkhead 9, Figure 9) was built on the northern shore of the boat basin in 1943 (NYCDP 1943) (Dallas et al. 2013). Backfilling the structure continued from 1944 through 1948 (Baker and Honig 1982). Maintenance was performed on the bulkhead in the late 1980s (Dallas et al. 2013). The bulkhead remains intact with no gaps or open water or sand landward of the structure. There is no beach present, only upland composed of fill landward of the bulkhead (Figure 17).

Individual sheet piles of the bulkhead display some surficial wear due to age; the cap board is missing in some locations and portions of the interior of sheet piles are slightly degraded (Figure 18), but the overall integrity of the structure remains. The fill directly landward of the bulkhead is level with the bulkhead and increases in elevation with distance landward. The fill is covered with vegetation, primarily low grasses and shrubs, with no bare sediment exposed except for an unpaved access road located approximately 10 m landward of the bulkhead.

RTK GPS data were not collected at this site. One-meter resolution NED data were sufficient to describe the morphology landward of the bulkhead due to the minimal variability in elevation over short distances. Bulkheads are generally backfilled to a relatively uniform elevation in order to reduce pressure differentials along the structure (Department of Defense 2006).

Figure 17. Bulkhead 9 at the Great Kills site contains no gaps erosion landward.

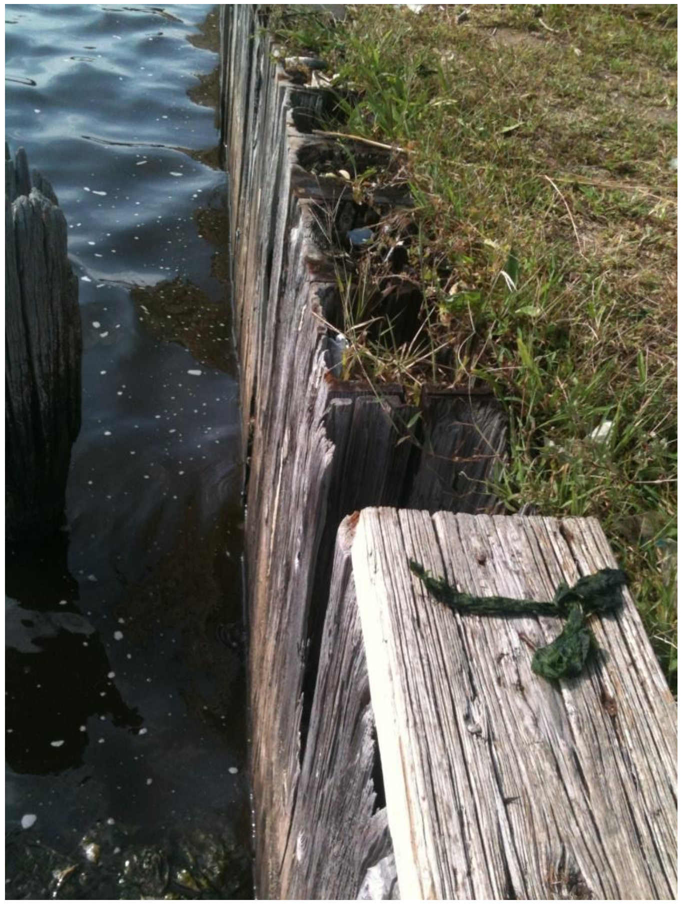

Figure 18. Sections of the cap board are missing and portions of the interior of the sheet piles are eroded on Bulkhead 9 at the Great Kills site.

The elevation of the bulkhead is approximately 1.9 m; the elevation of the ground surface directly landward, between the bulkhead and dirt road, is approximately 2.0 – 3.0 m. Elevation increases gradually with distance landward from the bulkhead, across the dirt road, indicating a lack of erosion of the emplaced backfill and continued structural integrity of the bulkhead (Figure 19).

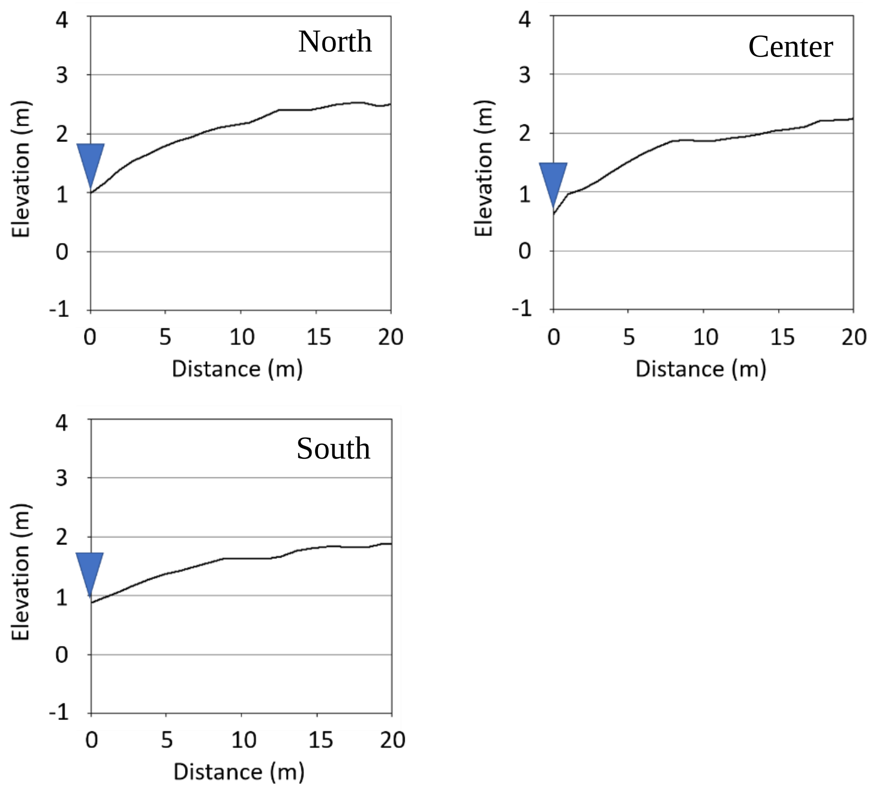

Figure 19. North, center, and south shore-normal beach profiles at the Great Kills site. Black lines represent the National Elevation Dataset surface. Blue arrows point to the location and elevation of the bulkhead.

Shore-parallel profiles were taken at distances of approximately 2 m, 6 m, and 10 m landward from the bulkhead. Elevation decreases slightly (~0.5 m over 50 m) from the western to eastern end of the site (Figure 20). There are no sudden changes in slope along the profiles that would indicate areas of erosion.

Historical aerial images are available for this site for dates between 1995 and 2016 (Table 2). All images post-date the installation of the bulkhead, the fill, and the maintenance period in the late 1980s. Because the bulkhead remains intact and fully functional, visible shoreline changes through time are not seen in the images (Figure 21). However, if the bulkhead is not periodically maintained in the future, it will eventually experience structural failure of sheet piles based on the lifetime of wood material, reflecting the kinds of change illustrated by the bulkheads in later stages described below.

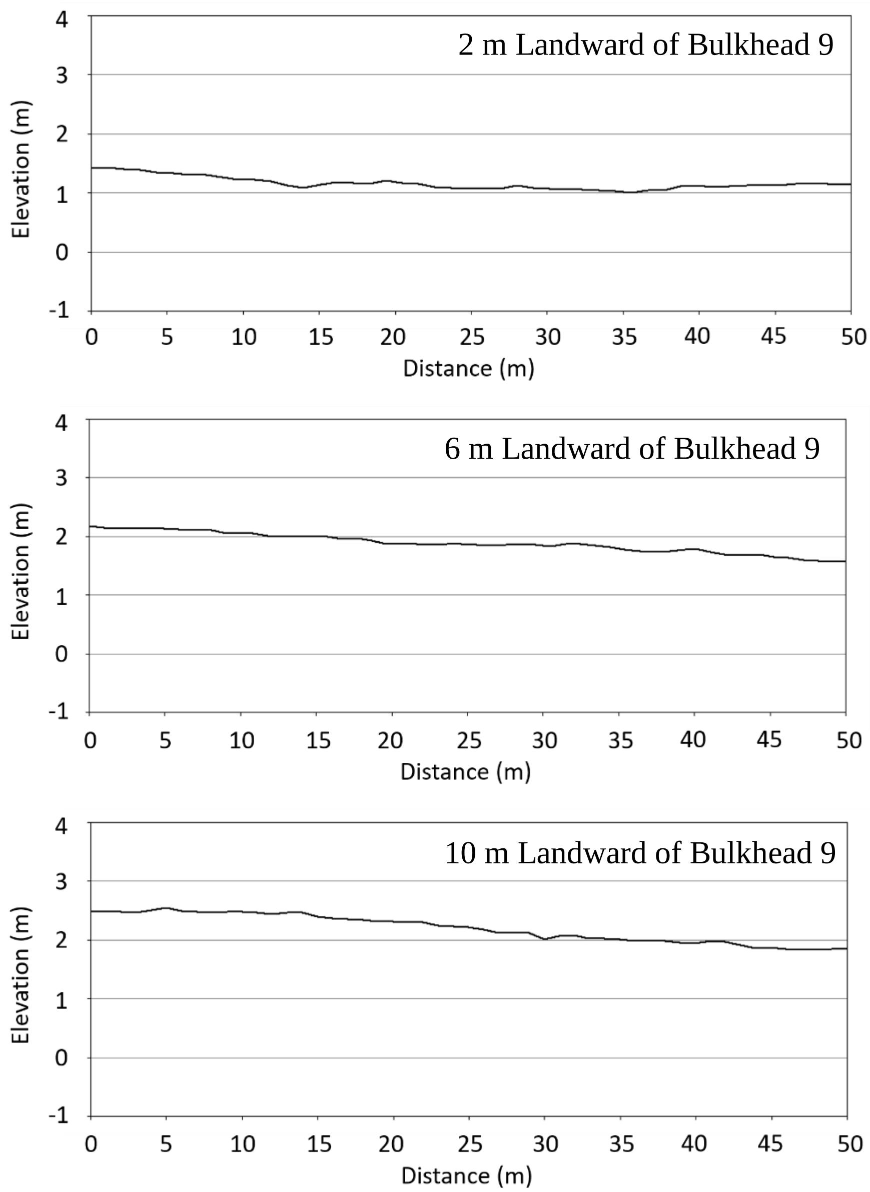

Figure 20. Shore-parallel National Elevation Dataset beach elevations at the Great Kills site. Elevations were taken 2 m landward of the structure, 6 m landward of the structure, and 10 m landward of the structure.

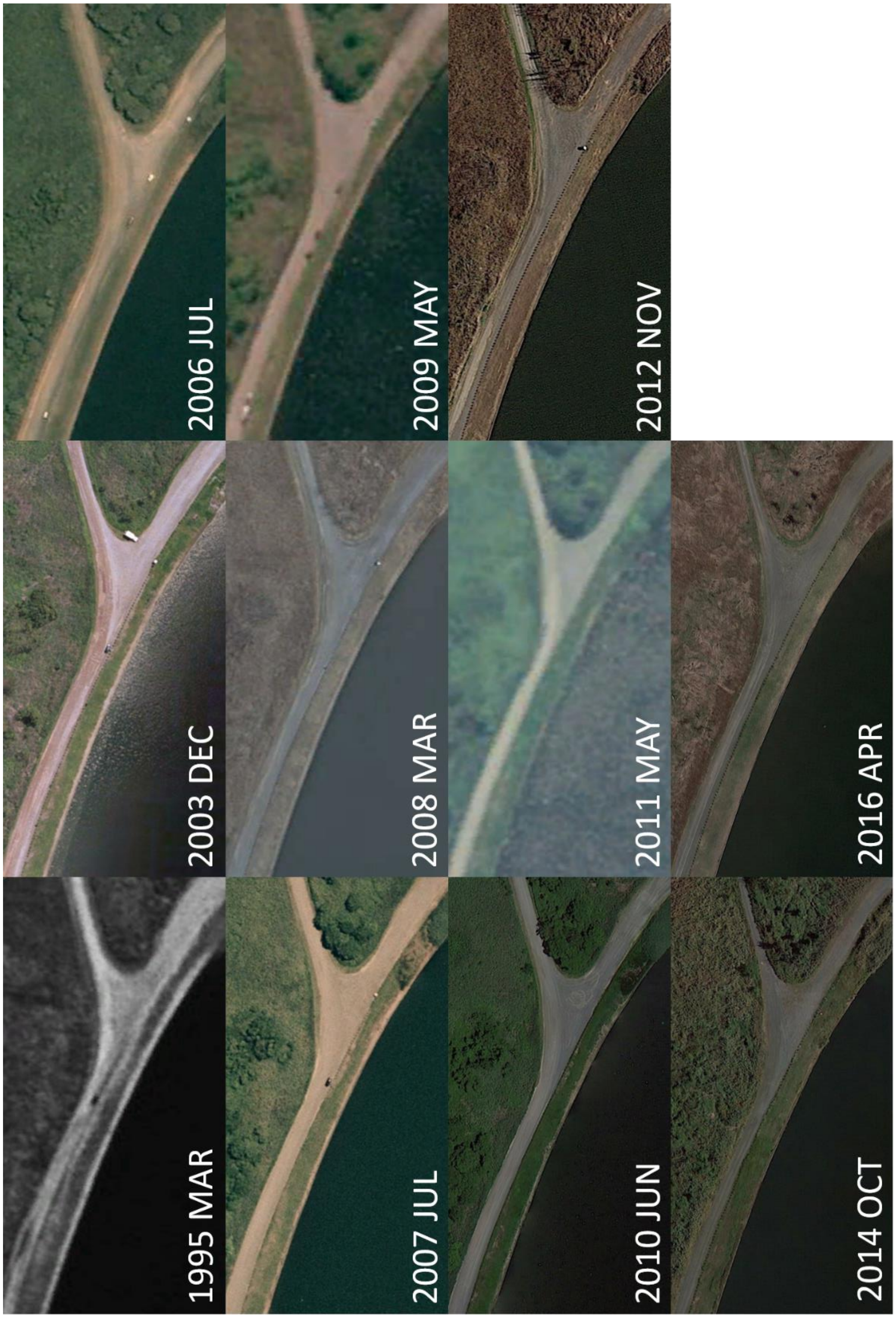

Figure 21. Bulkhead 9 at the Great Kills site has remained intact over the last 26 years. Historical imagery obtained from Google Earth.

5.2 Chapel South Site (Stage 2)

This site (Figure 8) contains two wooden bulkheads (Bulkhead 1 and Bulkhead 2) and a riprap revetment (Revetment 1). Bulkhead 1 and Bulkhead 2 are oriented northwest-southeast. They are parallel to one another and are spaced approximately 1 m apart. Revetment 1 has a north-south orientation and acts as a breakwater to protect the bulkhead, with an approximate 40-degree angle between the bulkheads and the revetment.

This site was chosen because it contains a wooden bulkhead that possesses multiple small gaps approximately 15 cm across or less with evidence of erosion landward of the gaps. The site was also chosen because there is an active beach landward of the bulkhead with sediment subject to reworking, which may indicate the structure is of insufficient height to prevent overtopping (Figure 22). A dune with natural vegetation of grasses, shrubs, and trees is present between the beach and manicured lawn grass that surrounds the chapel. Smaller patches of grass are present on the beach face adjacent to the bulkhead.

The southernmost 120 m of the bulkheads are more intact than portions to the north. Most sheet piles along Bulkhead 1 are present, with some extending to their original height while others do not extend far above the ground surface. All sheet piles show visible damage or deterioration. Upper wales and tie rods are not present. Deadmen are not visible but may remain buried below the beach surface (Figure 22).

Figure 22. Structures at Chapel South site, including Bulkhead 1 (landward) and Bulkhead 2 (seaward). Photo was taken looking to the southeast. Officer's Row is in the distance.

Bulkhead 2 is in good condition, and largely maintains its structural integrity (Figure 23). The elevation of Bulkhead 2 is approximately 1.33 m along its entirety (Figure 26). The only perceivable impediment to its full functionality above the water line is a number of small (< 15 cm wide) gaps where sheet piles have eroded or separated. The largest observed gap in the bulkhead is approximately 15 cm wide where an outflow pipe extends from the upland to the beach on the seaward side of the bulkhead (Figure 24). Most gaps in the structure are smaller than 2 cm (Figure 25). All gaps allow for water and sediment transfer, permitting outflow through the structure as indicated by reentrants in the beach occurring directly landward of the gaps (Figure 24, Figure 25). The majority of water during falling stages of the tide flows through a large gap to the west.

Figure 23. Bulkhead 2 at the Chapel South site is largely intact. Revetment 1 is subaerial during low portions of the tidal cycle. Photo was taken looking to the southeast. Fort Hancock infrastructure is in the distance.

Figure 24. The largest gap (approximately 15 cm wide) in Bulkhead 2 at the Chapel South site allows an outflow pipe to pass through.

Figure 25. Most gaps in Bulkhead 2 at the Chapel South site are smaller than approximately 2 cm. Drainage cusps are found landward of the gaps.

The elevation directly landward of Bulkhead 2 was approximately 0.49 m. The elevation of the ground surface directly landward of the bulkhead was on average 0.19 m higher than the seaward side, indicating the structure is still able to retain sediment despite erosion of the upland. A small drainage cusp as seen in the alongshore profile adjacent to the bulkhead is due to erosion landward of the 15 cm gap previously mentioned (Figure 26). The ground elevation on either side of Bulkhead 1 is similar, which indicates the structure is no longer acting as a barrier to sediment transport or protecting against wave attack.

The elevations on the beach landward of Bulkhead 2 were generally lower at the northern and southern ends and highest towards the center. This is also true for the profile along the dune ridge (Figure 26). This topography implies that flanking of Bulkhead 2 may be taking place, which is supported by aerial imagery (Figure 29).

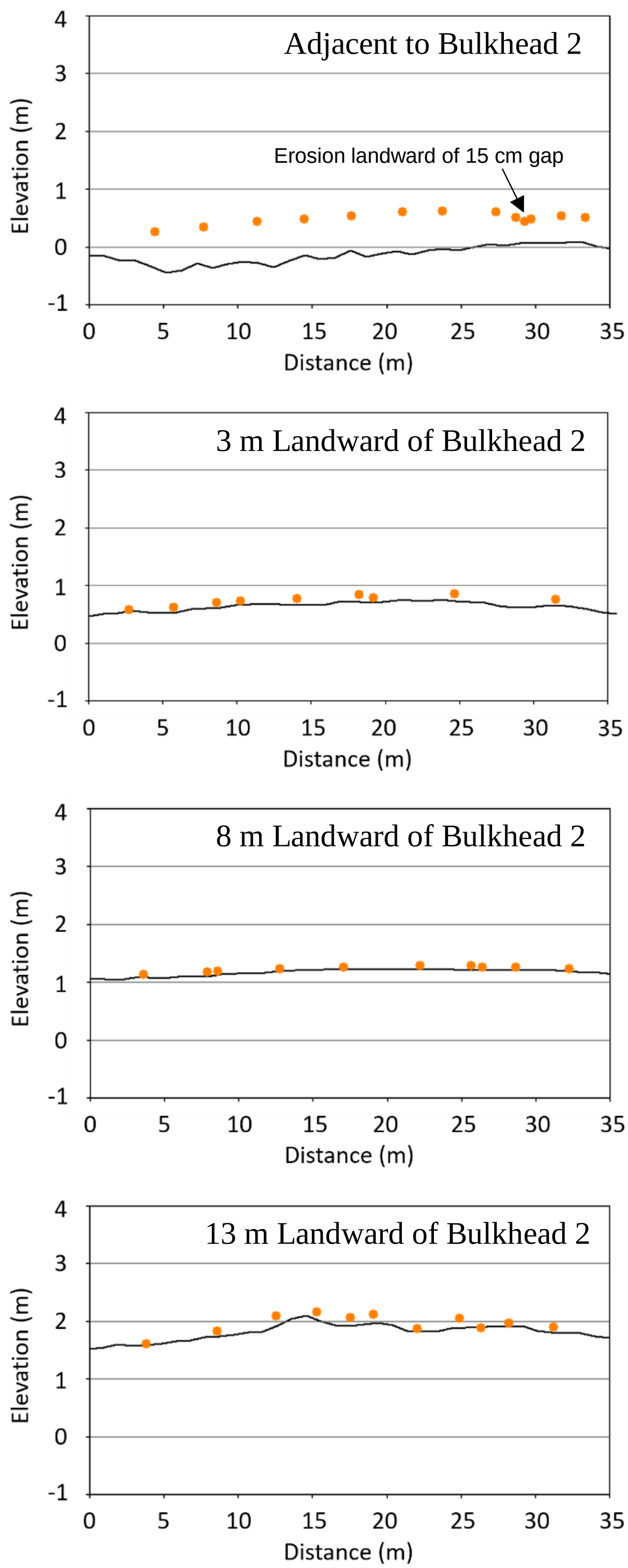

Figure 26. Shore-parallel beach elevations at the Chapel South site. Elevations were taken on the ground surface on the landward side of Bulkhead 2, 3 m landward of the structure, 8 m landward of the structure, and 13 m landward of the structure. GPS data points are depicted as orange dots. National Elevation Dataset surface is depicted as a black line.

The horizontal distance between the bulkhead and the dune ridge varies between 12 m and 15 m (Figure 27). The greatest distance occurs at the northern end of the site where vegetation coverage of the upland area is less dense, implying that the upland has experienced more erosion there. Smaller patches of grassy vegetation are present on the beach face adjacent to the bulkhead landward of sections without gaps in the structure where there is more protection from water movement. The beach has a slight concave shape, with an average slope between the structure and the dune toe of approximately 0.1.

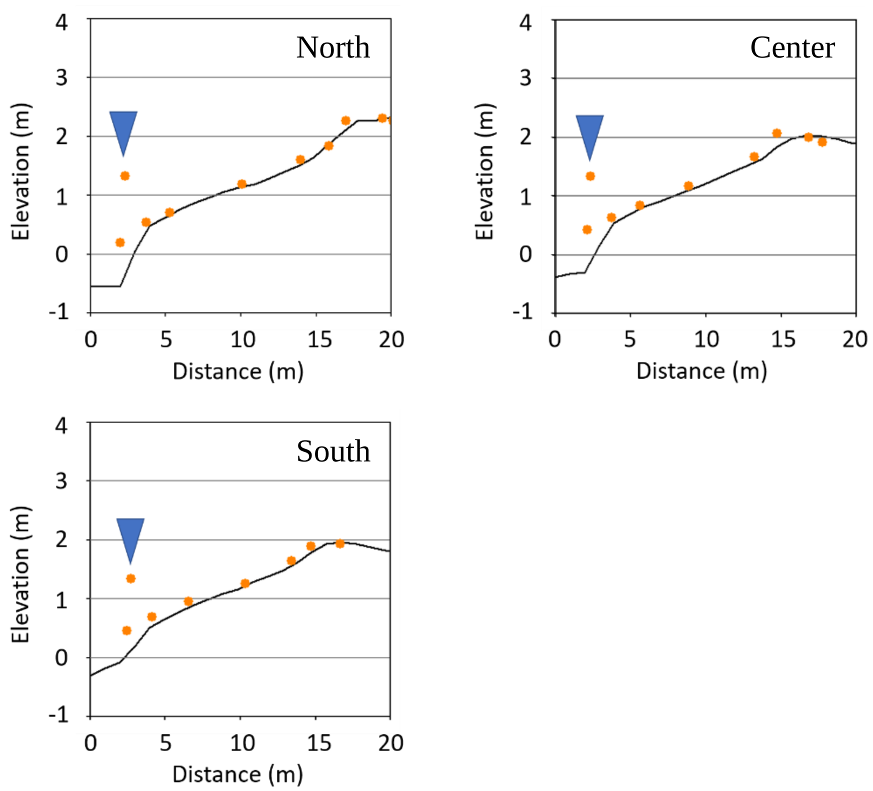

Figure 27. North, center, and south shore-normal beach profiles at the Chapel South site. GPS data points are depicted as orange dots. National Elevation Dataset surface is depicted as a black line. Blue arrows indicate the position and elevation of the top of Bulkhead 2.

Divergence between the GPS topographic data and the NED data is evident at and seaward of the bulkhead. This may be because this area is highly dynamic and affected by tidal and seasonal changes, as well as storm events, and the data represent two different times. In addition, the NED does not provide accurate elevations for submerged land surfaces, and has a 1 m resolution that cannot accurately represent the small changes in elevation that occur alongshore.

Topographic data were collected surrounding the reentrant landward of the 15 cm gap using the RTK GPS unit. NED data were not used because of the small size of the feature. Elevations were measured down the center of the reentrant normal to the bulkhead and alongshore directly landward of the bulkhead. The dimensions of the reentrant were approximately 8.5 m (alongshore) by 6 m (cross-shore) by 0.2 m deep (Figure 28). The ground surface seaward of the bulkhead in the vicinity of the gap (Figure 28) was also approximately 0.2 m lower in elevation than similar points in the Central and South shore-normal profiles (Figure 27), indicating erosion both seaward and landward of the gap.

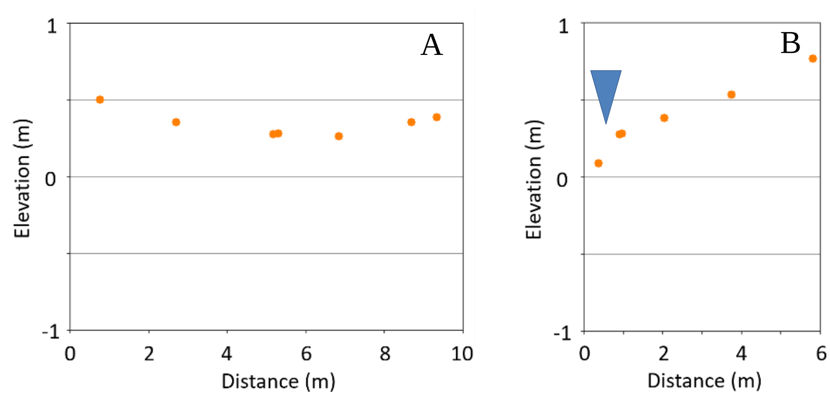

Figure 28. Shore-parallel (A) and shore-normal (B) beach profiles at a 15 cm wide gap in Bulkhead 2 at the Chapel South site, Sandy Hook Unit, Gateway National Recreation Area. The blue arrow indicates the position of Bulkhead 2.

Historical imagery shows that the presence of an active beach landward of the bulkheads predates the earliest image available (1991, Figure 29) and has increased over the past 26 years, creating a more linear boundary between the upper beach and vegetated area (Figure 29). Further deterioration and an increase in the number of gaps in the bulkhead is expected to cause transgression and decreased elevation of the beach landward and seaward of the bulkhead and further erosion of the upland.

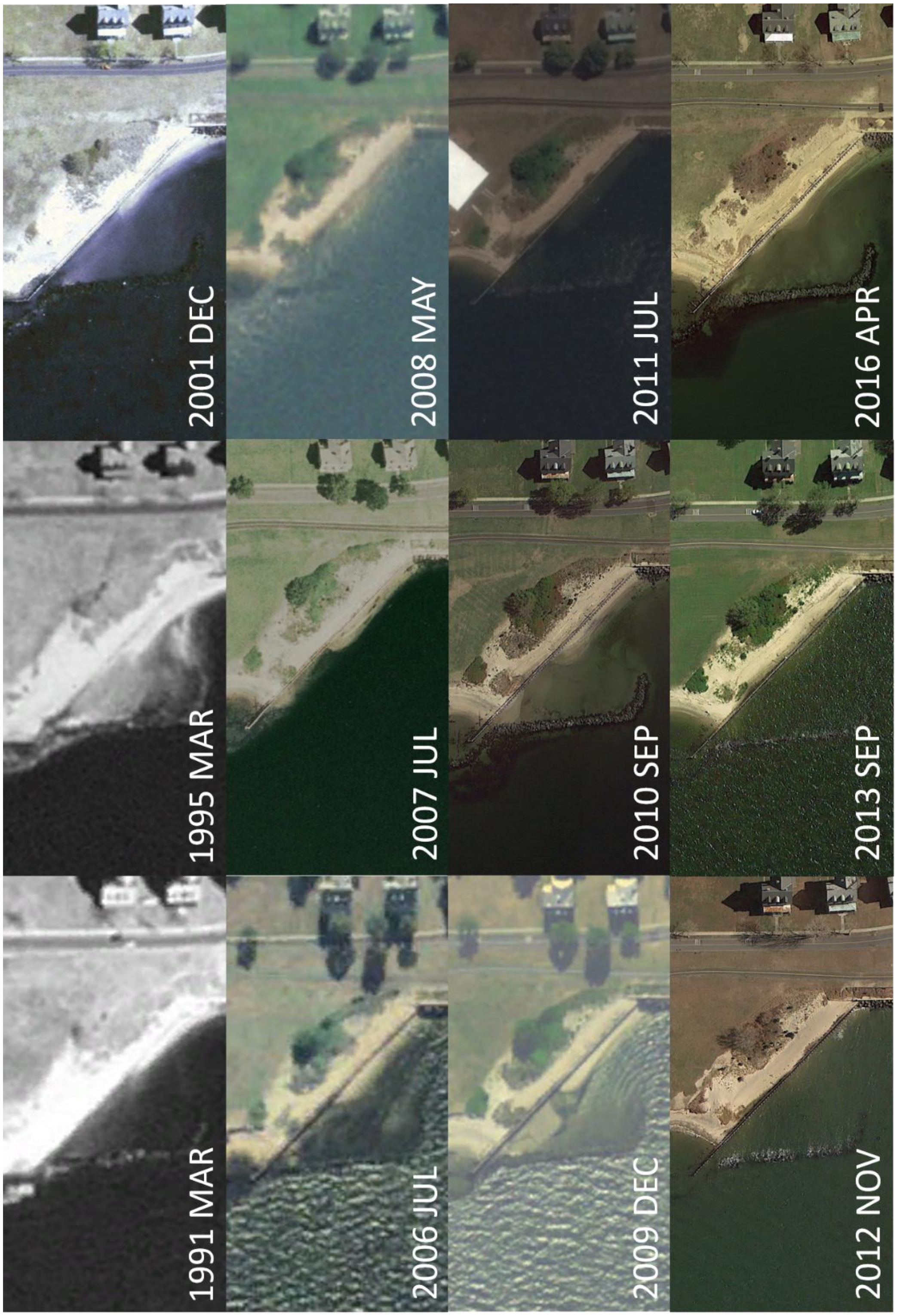

Figure 29. The width of the beach landward of Bulkheads 1 and 2 at the Chapel South site has increased over the past 26 years. Historical imagery obtained from Google Earth.

5.3 Chapel North Site (Stage 3)

This site is located seaward of the chapel (Figure 8 and Figure 10). The site was chosen because there is erosion and open water landward of gaps in the bulkhead. The upland area, while not naturally vegetated and capped with fill, is not hardened and is subject to further erosion if the present protection structures remain unaltered. The chapel is utilized regularly for private and public functions, and so is a source of income and of high importance, a use that is not aligned with the current condition of the protection structures surrounding the chapel.

The Chapel North site contains the same three structures that are present at the Chapel South site, but with a different relative orientation between the bulkheads and the revetment. All three structures run parallel to one another in a north-south direction. The northern portions of the structures lie within the area controlled by the U.S. Coast Guard, where the condition of these structures is markedly better. Construction debris is scattered across the beach in the Park Service portion and primarily consists of wood, broken concrete, and sections of broken pipe that have been exposed due to beach erosion and landward transgression of the shoreline.

Bulkhead 1 was constructed in 1878 (Dallas et al. 2013) and is mostly deteriorated (Figure 30). Remnants of piles and deadmen are found along most of the structure, though they are significantly worn. The upper portion of the piles are deteriorated, so the height of the original structure has been greatly reduced. Upper wale and tie rods are not present (Figure 30).

Figure 30. Bulkhead 1 (landward) is deteriorated; only remnants of piles and deadmen remain. Bulkhead 2 (seaward) is largely intact in some areas, while deteriorated in others. Photo was taken at the Chapel North site, looking northwest towards Sandy Hook Bay.

Bulkhead 2 was constructed of wood in 1897 and maintained periodically until 1965 (Dallas et al. 2013). Piles and wales are largely intact along sections of the structure, but considerably deteriorated in two locations where there are large gaps. Deadmen are exposed less than a meter above the ground surface. Steel tie rods are also exposed (Figure 30).

Revetment 1 is approximately 8 m seaward of Bulkhead 2. It is lower than the bulkheads. Revetment 1 is submerged at higher stages of the tidal cycle and exposed during lower stages. The structure is in a better condition and has a greater height within the Coast Guard property. When the water level is below the top of the revetment, the structure acts as a breakwater and reduces the impact of waves on the bulkheads and shoreline (Figure 31).

Figure 31. Three structures are present at the Chapel North site. Revetment 1 (far right) acts as a breakwater during low tidal stages. Photo was taken looking towards the south.

The beach at the Chapel North site is backed by an active erosional scarp (Figure 32). The upland consists primarily of natural sediments, capped with fill. Vegetation surrounding the chapel is manicured lawn grass. There is an area of open sand with no vegetation as well as a concrete walkway directly seaward of the chapel near the rear entrance. At the northern and southern portions of this site, there is a small amount of natural vegetation consisting of grasses and shrubs. Few small patches of grasses are also scattered along the backshore.

Figure 32. The beach at the Chapel North site is backed by an active erosional scarp, which is encroaching on the Chapel (right of center on the upland area).

Historical imagery reveals that erosion landward of the bulkhead was occurring as early as 1991 where a darker patch of sand can be seen in the southwest corner of the bulkhead (Figure 33), similar to what is seen over the last decade at the Chapel South site (Figure 29). By 2001, despite the entire length of the bulkhead remaining visible in the imagery, this area of erosion increased in size and a second area of erosion is seen at the top of the photo west of the parking lot and north of the pier. A gap in the southwest corner of the bulkhead formed by 2006 with a clearly defined reentrant landward. A second reentrant north of the pier is present by 2008. Erosion continued and these two reentrants merged by 2011, resulting in a sinusoidal shoreline that remains to the present (Figure 33). The natural vegetation that was southwest of the chapel in the earlier images is absent beginning with the 2007 image due to erosion of the upland area. The erosional reentrants continue to encroach upon the chapel.

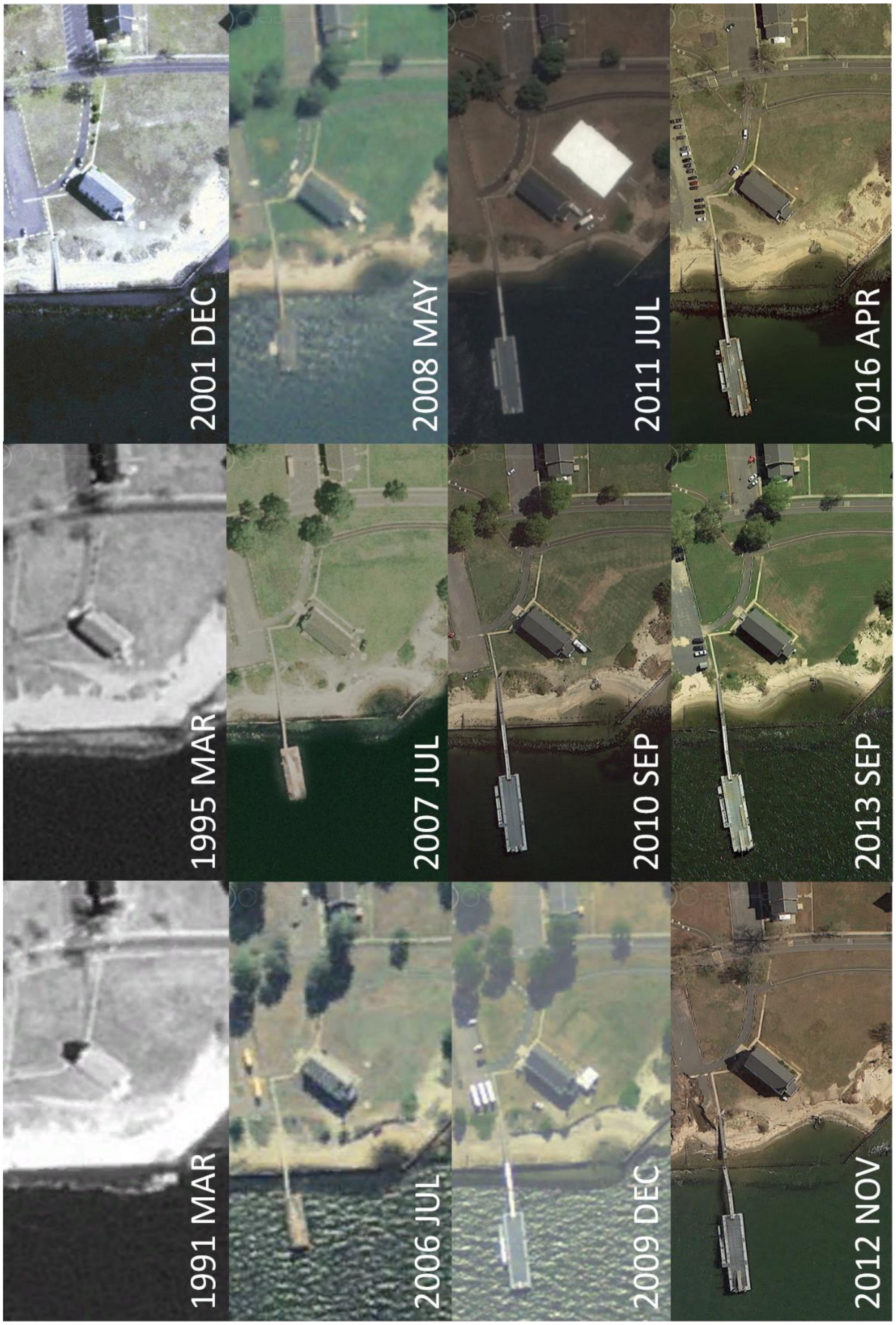

Figure 33. The shoreline at the Chapel North site has transitioned over the course of 25 years from being linear with an intact bulkhead to sinusoidal with open water landward of the bulkhead as gaps in the structure were created. Historical imagery obtained from Google Earth.

Elevation data collection using the RTK GPS focused around the reentrant in the southwest corner of the bulkheads. The largest gap in the bulkheads is 22 m long along the north-south trending segment. Open water was present landward of the gap in the bulkhead during all portions of the tidal cycle. There was water on the seaward side and bare sand on the landward side during lower tidal stages along the more intact portions of the bulkhead (Figure 34 and Figure 35). The elevation of Bulkhead 2 was approximately 1.32 m at the southern portion of the site where the structure was most intact, comparable to the elevation of the same structure at the Chapel South site.

Figure 34. A large reentrant is located landward of a 22 m-wide gap in the bulkheads at the Chapel North site at low tide. Red triangle corresponds to the feature identified in Figure 35.

Figure 35. An active erosional scarp at Chapel North site. Red triangle corresponds to the feature identified in Figure 34.

The greatest erosion is found at the center of the gap in the bulkhead, in both the alongshore and shore-normal directions, as indicated by the lower elevations in Figure 36 and Figure 37. The greatest elevations at this site (approximately 2.1 – 2.8 m) represent undisturbed upland fill (Figure 36) and were higher than the dune ridge at the nearby Chapel South site (approximately 2.0 – 2.3 m). This implies that the ground area surrounding the chapel was filled to an elevation higher than the area of natural vegetation at the Chapel South site. Backfilled sediment is now being eroded, confirming this portion of the structure is at a more advanced stage of deterioration. The widest portion of the reentrant from the bulkhead to the eroding upland is approximately 35 m (Figure 37).

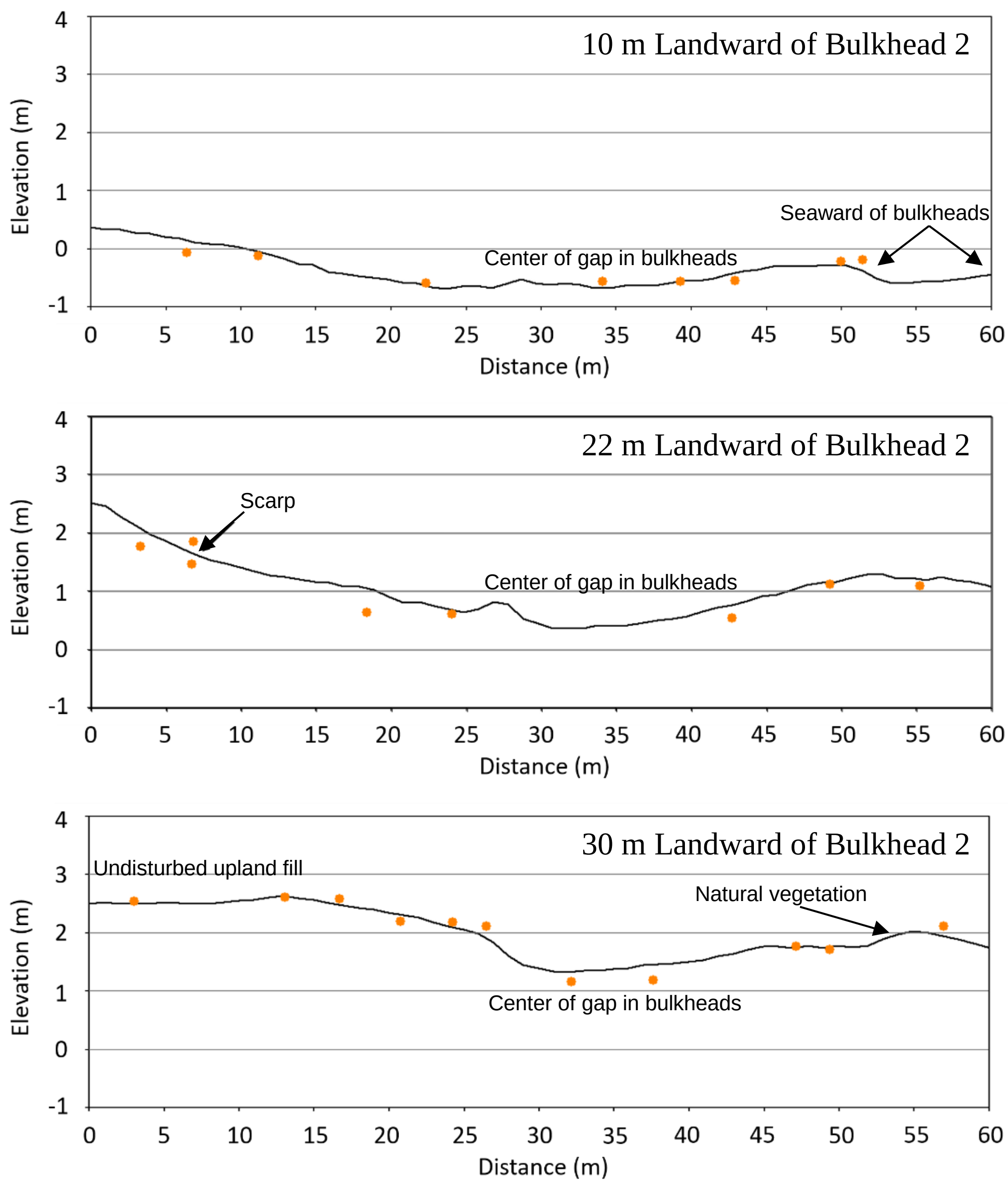

Figure 36. Shore-parallel beach elevations at the Chapel North site. Elevations were taken 10 m landward of the structure, 22 m landward of the structure, and 30 m landward of the structure. GPS data points are depicted as orange dots. National Elevation Dataset surface is depicted as a black line. The first profile intersects the northwest-southeast segment of the bulkheads.

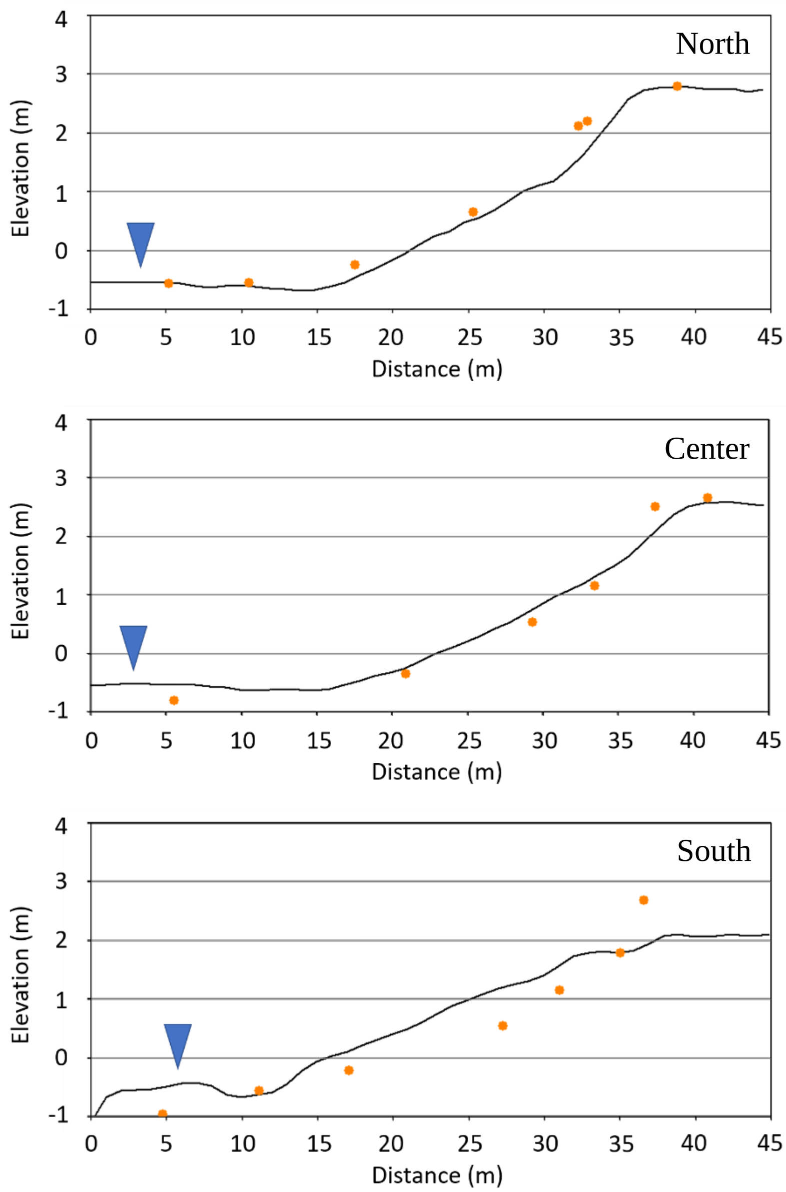

Figure 37. North, center, and south shore-normal beach profiles at the Chapel North site. GPS data points are depicted as orange dots. National Elevation Dataset surface is depicted as a black line. Blue arrows represent the location that is in line with the intact portions of the bulkhead.

The NED does not accurately represent the ground surface elevation where there are changes in elevation over short times and distances, as is evident in Figure 36 at the location of the scarp. However, descriptions of small features such as the scarp may not be essential to characterizing the condition of late stages of the structure. NED can clearly define the large reentrant and sinusoidal shoreline landward of the bulkhead. The NED showed divergence from the GPS data in the southern shore-normal profile on both the beach and upland areas, which may be due to the time difference between collections of the two data sets. This profile is at the corner of the bulkhead and may be subject to greater sediment reworking because it can be affected by wave attack from both westerly and southerly directions.

5.4 Battery Kingman North Site (Stage 4)

This site (Figure 8) was chosen because it contains a wood bulkhead, Bulkhead 5, which is easily identifiable via site visits and satellite imagery but retains little structural integrity (Figure 38 and Figure 39). Bulkhead 5 is 1400 m long and was constructed in 1961 (Dallas et al. 2013). A winter storm in 1974 breached the bulkhead and removed several pilings from the structure. Further storm damage took place in the 1970s, damaging the bulkhead and eroding the shoreline (Layton and Foulds 2010). There has been open water landward of Bulkhead 5 for at least part of tidal cycle since at least 1995, with noticeable erosion following Hurricane Sandy in 2012 (Figure 40).

The total length of gaps in the structure far exceeds that of the intact portions. Bulkhead 5 is approximately 20 m offshore, with open water present between the structure and sandy beach along the length of the structure. Pilings and fragments of the upper wale are all that remain of the bulkhead above water during higher portions of the tidal cycle (Figure 38). Lower wales and portions of sheet piles are present but heavily deteriorated (Figure 39). The shore-oblique northernmost portion of the bulkhead that ties into the upland is the only intact section of the structure, with full boards and both wales present. The difference in integrity between this shore-oblique portion and most of the structure is likely due to the lack of direct wave impact. The shore-oblique orientation of the structure causes it to act a groin and trap sediment on its south side.

The intact portion of the bulkhead extends for only 20 m from the vegetated upland and sediment is able to pass seaward of the structure.

Figure 38. Pilings and fragments of the upper wale are all that remain of Bulkhead 5 above water during higher tidal stages at the Battery Kingman North site.

Figure 39. Low tide reveals some sheet piles and lower wales on Bulkhead 5 at the Battery Kingman North site.

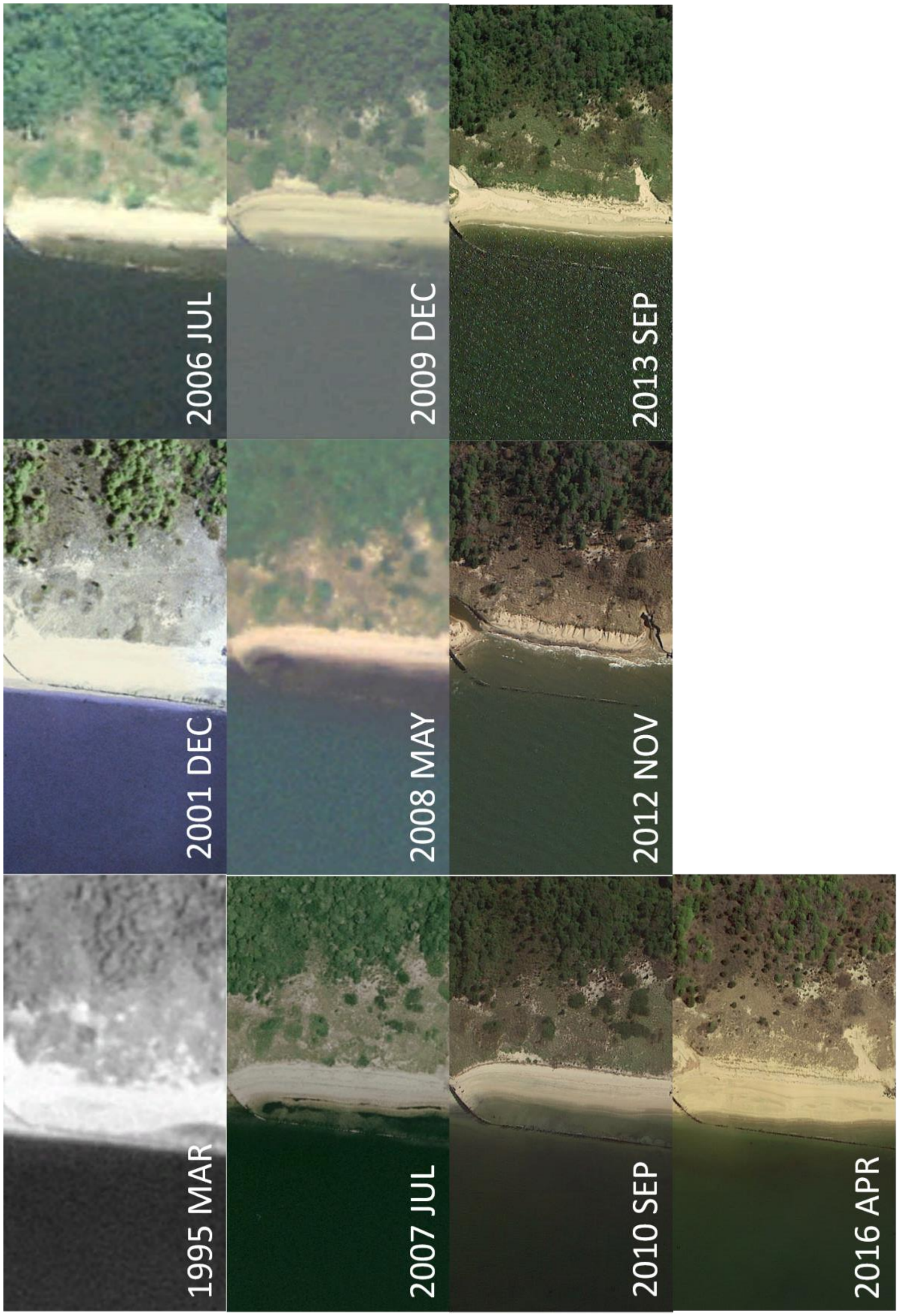

Figure 40. A linear active beach has been present landward of the Battery Kingman North site for at least the last 21 years. Imagery obtained from Google Earth.

The beach at this site is linear and has a constant width of approximately 30 m between the dune toe and the break in slope between the foreshore and low tide terrace. At the time of GPS data collection, there was a prominent berm crest approximately 2 m seaward of the dune toe with an elevation of approximately 1.5 m (Figure 41 and Figure 42). The vegetation line landward of the berm crest is linear and extends past the northern extent of the bulkhead through the Natural site discussed in the next section. The dune crest elevation is approximately 2.0 m (Figure 41 and Figure 42). The dune is backed by a heavily vegetated upland, with grasses, shrubs, and sparse trees.

The difference between the elevation of the ground directly landward and directly seaward of the bulkhead was up to 0.25 m where the bulkhead was more intact (Figure 42) and negligible where there were gaps in the bulkhead. This trapping of sediment and a greater amount of submerged vegetation growth landward of the bulkhead than on nearby beaches with no history of protection structures indicates that deteriorated portions of structures can provide localized protection although they may not protect the upland farther landward. During site visits, waves were observed to partially break at the bulkhead during low tide and subsequently reform behind the structure indicating that this structure is now acting more like a permeable breakwater than a bulkhead. Noticeable wave diffraction occurred landward of the gaps in the bulkhead, which may contribute to the accretion in the lee of more intact sections of the structure.

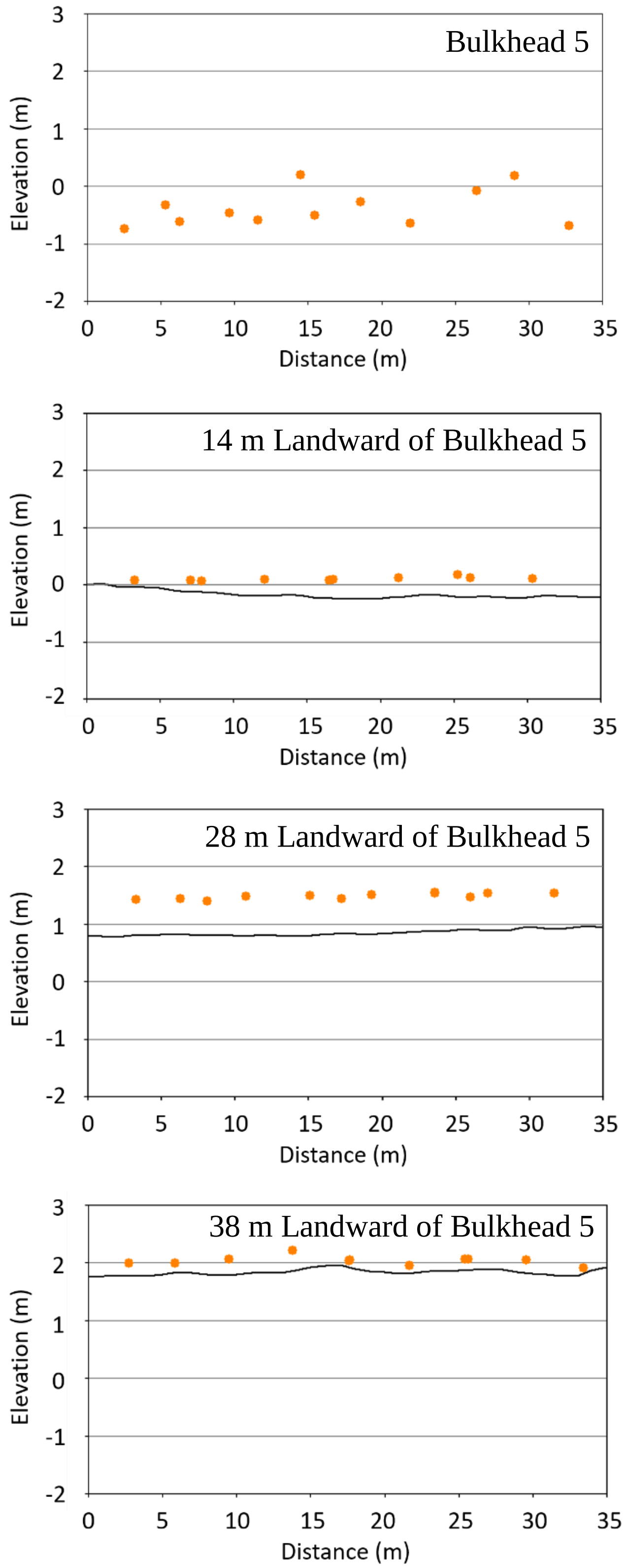

Figure 41. Shore-parallel beach elevations at the Battery Kingman North site. Elevations were taken on top of the bulkhead, 14 m landward of the bulkhead, 28 m landward of the bulkhead at the berm crest, and 38 m landward of the structure at the dune crest. GPS data points are depicted as orange dots. National Elevation Dataset surface is depicted as a black line.

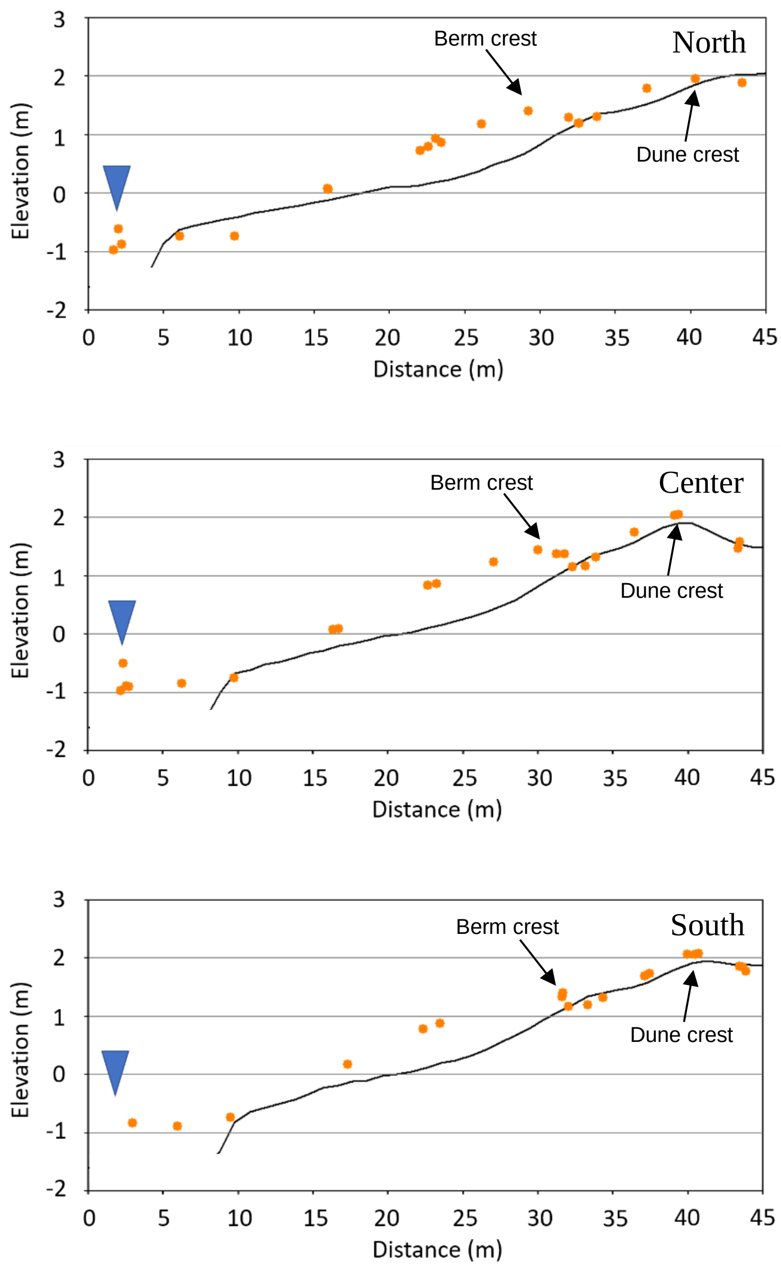

Figure 42. North, center, and south shore-normal beach profiles at the Battery Kingman North site. GPS data points are depicted as orange dots. National Elevation Dataset surface is depicted as a black line; there is no NED data for the area surrounding the structure because the ground surface is submerged. Blue arrows represent the location and elevation of the bulkhead.

There is divergence between the GPS and NED data along the majority of the beach face and surrounding the berm crest (Figure 41 and Figure 42) where sediment movement is greatest. Beach profiles change seasonally and as a result of erosional events or periods of accretion (Larson and Kraus 1994), which may account for the differences between the datasets. The NED surface diverges from the GPS data at low elevations because NED cannot be used for subaqueous surfaces.

5.5 Natural Control Site

The Natural Control site is located approximately 100 m north of the Battery Kingman North site. The closest structure is a wood bulkhead approximately 75 m to the south and a riprap revetment approximately 165 m to the north. The main paved access road of the park is approximately 90 m landward. It was not possible to have a second natural site closer to the sites at the northern end of Sandy Hook because of the extent of structures alongshore (Figure 8). This site is the closest natural, unmodified stretch of beach that is oriented towards waves coming from the west, similar to the case study sites.

The shore-normal profile of this site is typical for a low energy beach, with a steep and narrow foreshore and no backshore (Figure 43) (Jackson and Nordstrom 1992, Jackson et al. 2002). The beach is linear and alongshore with little to no variation in elevation; the three shore-normal profiles show similar beach widths and elevations, and dune crest heights. The slope of the foreshore is constant (Figure 44).

There is some divergence in the NED and GPS profiles, especially on the foreshore (Figure 44). The two datasets differ by no more than 0.3 m at any point, and can be attributed to typical seasonal or post-storm changes.

Figure 43. The beach at the Natural Control site is linear. Densely vegetated grasses and shrubs occur landward of the backshore.

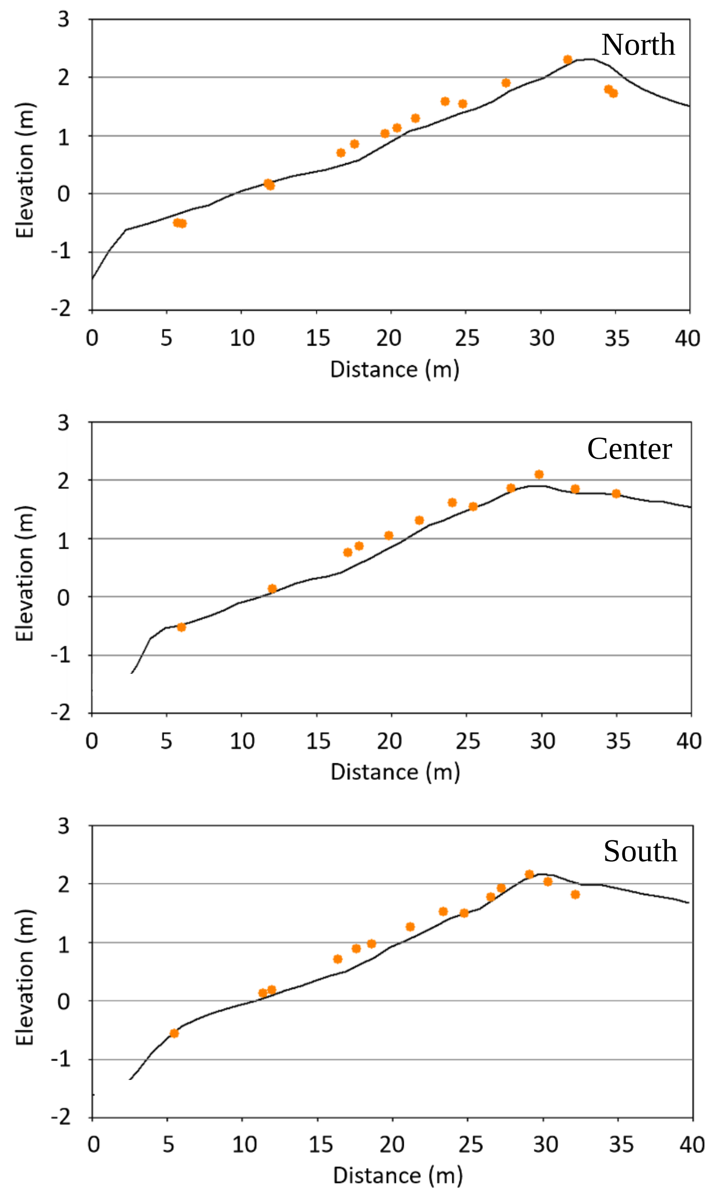

Figure 44. North, center, and south shore-normal beach profiles at the Natural Control site. GPS data points are depicted as orange dots. The National Elevation Dataset surface is depicted as a black line.

Twenty-two years of historical imagery show a shoreline that has been consistently linear alongshore, with a lack of evidence of reentrants (Figure 45). Some visible differences in vegetation and beach width occur, but changes of these characteristics are not similar to sites with a bulkhead that have a more homogenous upland instead of an established dune with crest and leeward slope.

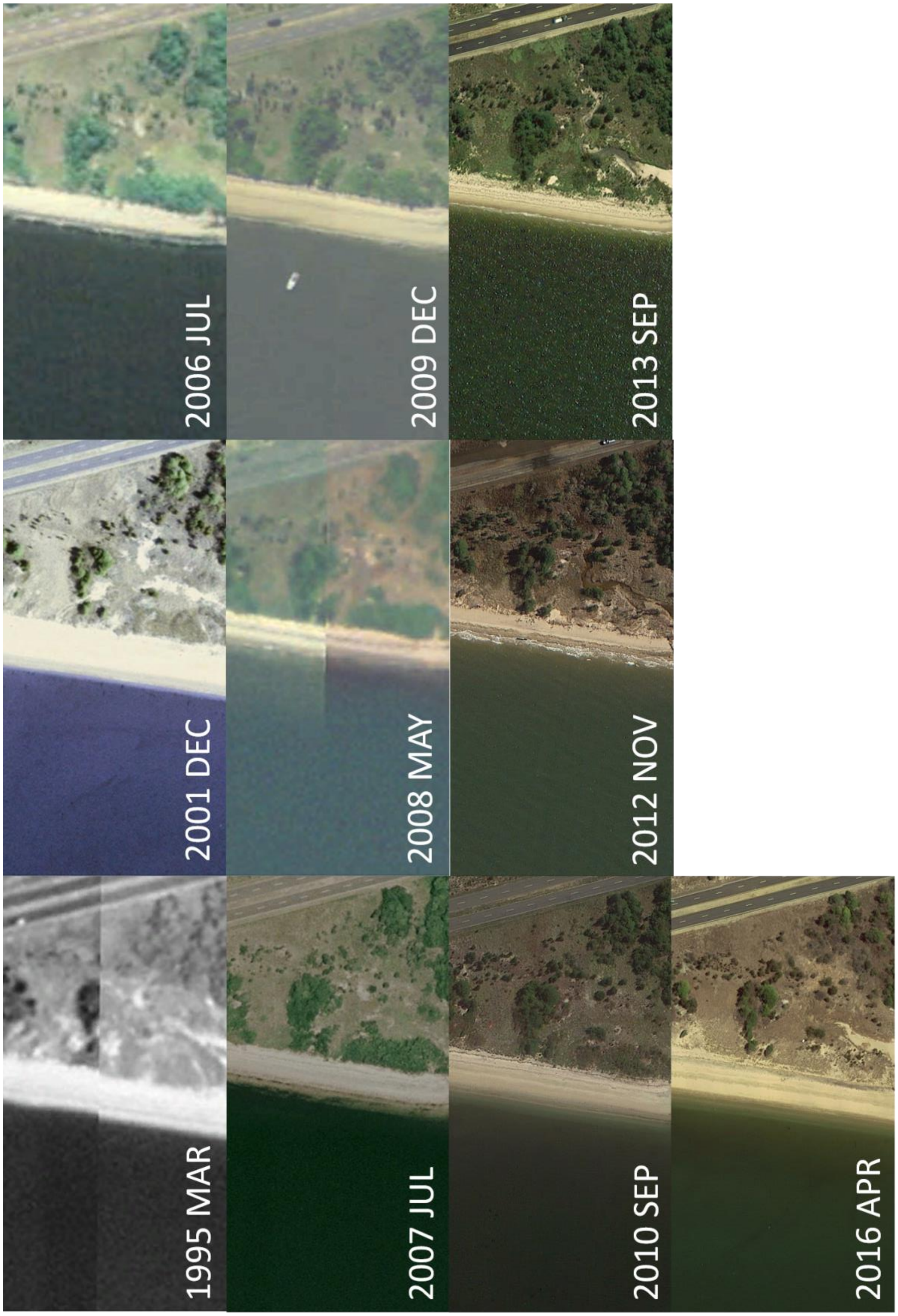

Figure 45. The Natural Control site has been consistently linear over the last 21 years. Historical aerial imagery obtained from Google Earth.

Comparisons of beach characteristics between the control and bulkhead case study sites reveal that the Natural Control site is most similar to the Battery Kingman North site, where a linear active beach and dune are established landward of the bulkhead. There are some similarities between the Natural Control site and the Chapel South site because they are both linear, but the beach at the Chapel South site is truncated by the bulkhead. It also does not share linear berm or dune features with the Natural Control site, and contains small reentrants that are not found at any other site.

5.6 Conclusions

The four bulkhead sites and natural site discussed in this chapter illustrate distinct stages in the deterioration of a wood sheet pile bulkhead. There are notable diagnostic features that occur in the landscape as a site progresses, particularly: 1) intact backfill with no erosion; 2) erosion hotspots and isolated reentrants on a linear shoreline; 3) merged reentrants resulting in a sinusoidal shoreline; and 4) a linear shoreline with features similar to a nearby natural one.

The Great Kills site illustrates how a bulkhead can remain in an early stage for over 70 years if it is adequately maintained to compensate for deterioration. If a bulkhead experiences minor deterioration such as small gaps like those at the Chapel South site, it can result in some erosion of backfill. If a bulkhead continues to deteriorate and large gaps in the structure occur, it will progress to a stage that looks similar to the Chapel North site where there is a sinusoidal shoreline and open water landward of the bulkhead. Conversely, if a bulkhead is at an elevation that is not sufficient to prevent frequent overtopping, a linear beach may form landward of the structure even if it remains mostly intact (e.g. Chapel South). The condition of the bulkhead rapidly degrades once backfill begins to erode because the fill is no longer present to provide support to the structure against wave attack. Flanking may contribute to erosion of the upland, regardless of gaps in the structure.

The NED is a bare-earth surface, and by definition does not include elevations for the top of man-made structures above the ground surface. The best situation to obtain an accurate elevation measurement of a bulkhead remotely with the NED is if the bulkhead is intact and at the same elevation as the ground surface landward. The two datasets showed divergence along the foreshore where a variation in wave regime can result in changes in the beach profile on seasonal or shorter timeframes. The NED did not accurately reflect elevations of small features that occur directly adjacent to bulkheads at elevations below approximately -0.5 m, in areas where small features are found. GPS data are considered more accurate and reliable for all elevations of the case study sites, but would be impractical at the wide coverage available with the NED. The NED can be used to describe the overall landscape of morphology of the upper foreshore and upland, but ground surveys are recommended to gain the best insight into small-scale erosional features such as isolated reentrants or scarps and the elevations of bulkheads.

Chapter 6

Stone Riprap Revetments

The four case study sites containing stone riprap revetments exhibit a wide range of structure condition and surrounding morphological features. All sites are located in the Sandy Hook Unit and are presented in an order of decreasing structure effectiveness, ending with a natural site with no history of shore protection.

6.1 Battery Kingman South Site (Stage 1)

This site contains two structures, Revetment 8 and Bulkhead 4 (Figure 8). There is no evidence of raveling or erosion landward of Revetment 8, which makes this site an example of an intact revetment (Figure 46). Revetment 8 was built between 1995 and 2001 to provide protection to Battery Kingman (Dallas et al. 2013). The revetment continues to provide protection to the battery and a dirt road where a railroad was previously located. Site visits in March 2017 revealed that some fill, including cobbles, had been recently dumped at the landward edge of the revetment to help fill gaps in the structure. This indicates that the revetment has undergone preventative maintenance to preclude deterioration of the structure and landward erosion, retaining its structural integrity.

Beach width has been consistently greater along the northern portion of the revetment and narrower in the southern portion (Figure 47). The ground surface between the revetment and the dirt road has remained covered in herbaceous grassy vegetation, with tree coverage on Battery Kingman landward of the dirt road. No evidence of erosion or water overtopping the structure is present in the aerial images, including immediately following Hurricane Sandy in 2012 (Figure 47).

Beach profiles are centered on the middle of the revetment to reduce edge effects of the structure and maintain consistency in shoreline orientation among sites. This site is at approximately the same orientation as the Natural Control site and the Horseshoe Cove revetment site to the north (Figure 8). Bulkhead 4 has minimal impact on the shoreline at this site due to its severe deterioration (Figure 48).

Figure 46. There is no evidence of raveling or erosion landward of Revetment 8 at the Battery Kingman South site.

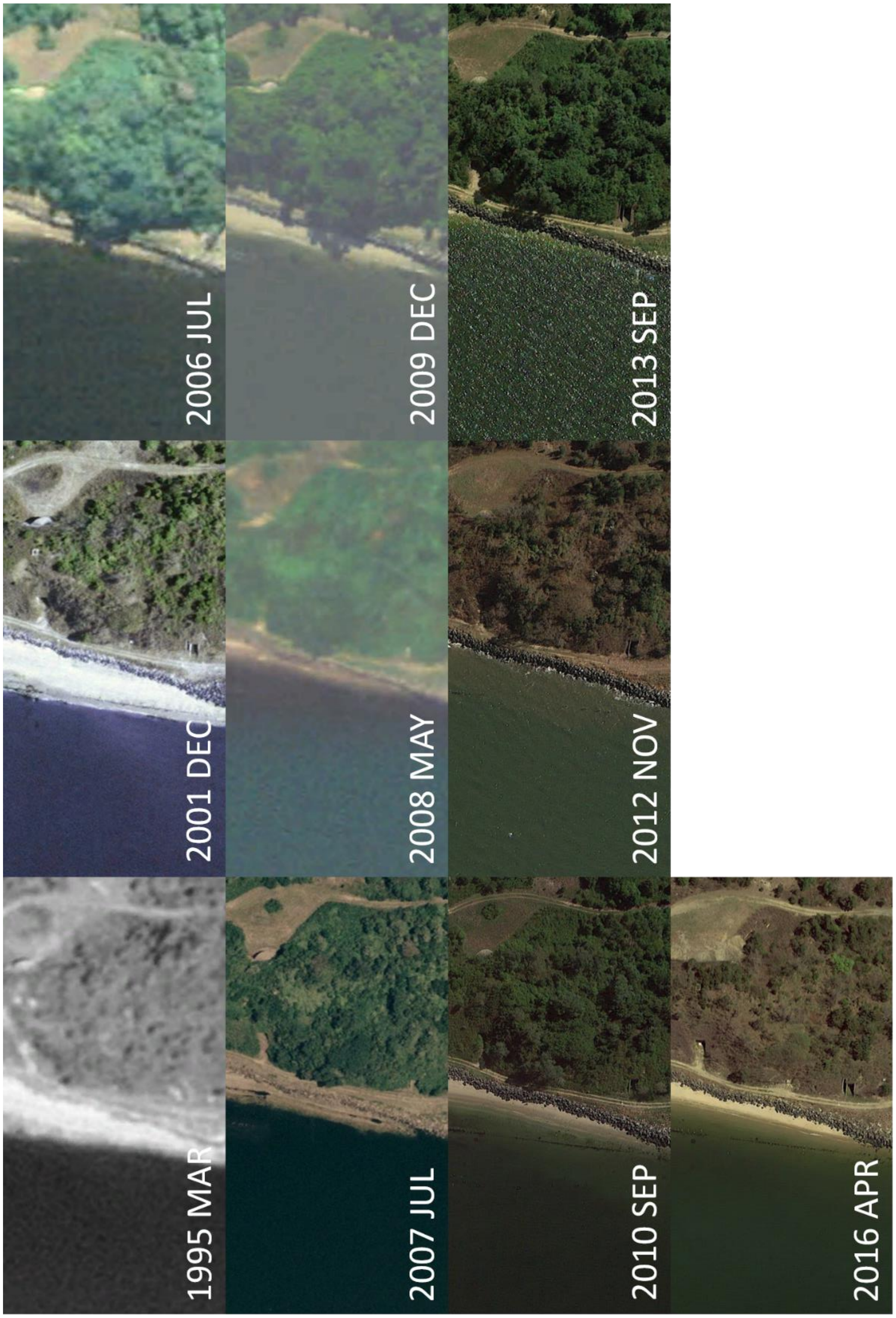

Figure 47. Beach width has been consistently greater along the northern portions of Revetment 8 at the Battery Kingman South site. No evidence of erosion landward of the revetment is present in the last 21 years of imagery. Historical imagery obtained from Google Earth.

Figure 48. Bulkhead 4 is severely deteriorated and has little effect on the beach fronting Revetment 8 at the Battery Kingman South site.

The elevation of the top of Revetment 8 ranges between 2.7 and 3.4 m, with most measurements lower than 3.0 m (Figure 49). The revetment is higher than the ground surface landward of it where the elevation decreases with distance landward, with the exception of the earth mound built over Battery Kingman (Figure 50). The elevation of the structure and ground surface landward is highest towards the center of the structure and decreases to both the north and south (Figure 49).

The ground elevation directly seaward of the revetment is constant along the length of the structure, approximately 0.0 m closest to the revetment and gradually decreasing with distance offshore. The entire beach seaward of the structure is submerged during higher portions of the tidal cycle (2012NOV and 2013SEP images in Figure 47).

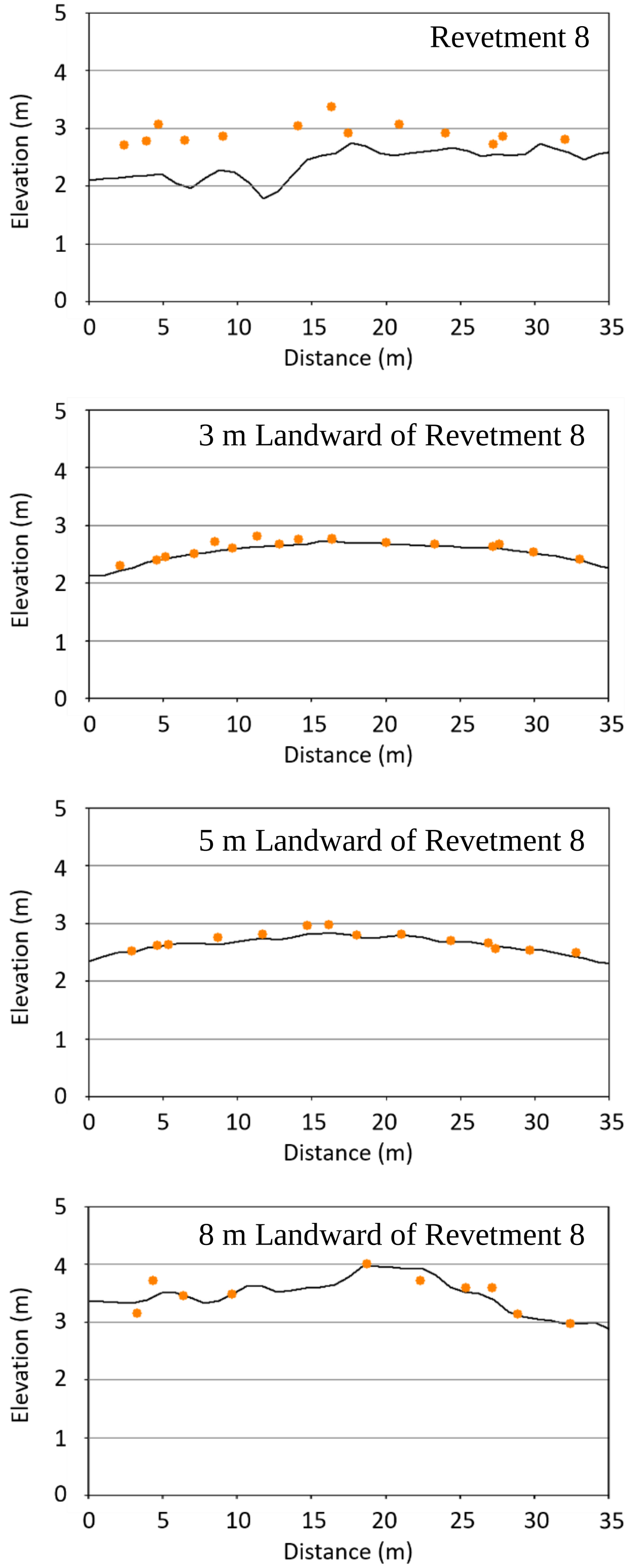

Figure 49. Shore-parallel beach elevations at the Battery Kingman South site. Elevations were taken at the revetment crest, 3 m landward of the structure, 5 m landward of the structure, and 8 m landward of the structure. GPS data points are depicted as orange dots. National Elevation Dataset surface is depicted as a black line.

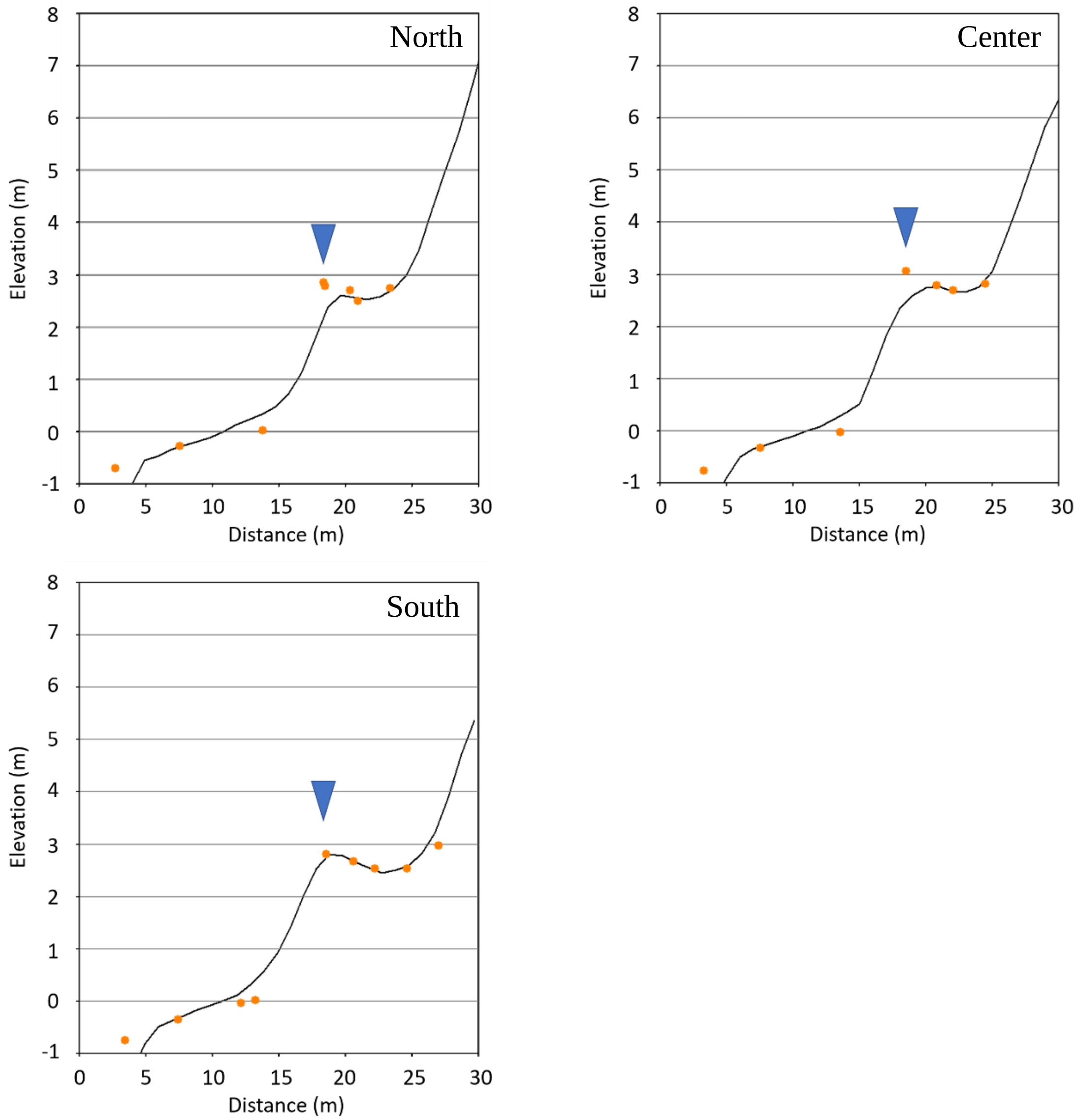

Figure 50. North, center, and south shore-normal beach profiles at the Battery Kingman South site, Sandy Hook Unit, Gateway National Recreation Area. GPS data points are depicted as orange dots. National Elevation Dataset surface is depicted as a black line. Blue arrows represent the location and elevation of the revetment.

The NED is a bare-earth surface and does not represent the revetment elevation (Figure 49), though elevations for the revetment in the two datasets are comparable along some areas of the structure (Figure 50). The NED surface diverges from the GPS data at low elevations of the beach because it cannot provide true values for submerged ground surfaces.

6.2 Officer's Row South Site (Stage 1)

This site is located in the Fort Hancock area of Sandy Hook, seaward of the southernmost building in Officer's Row (Figure 8). This site was chosen because there is no visible evidence of erosion or reworking of sediment landward of the structure (Revetment 2), and there is a wider undeveloped area landward than at the Battery Kingman site. A series of approximately 30 m-long groins exists along the length of the revetment, spaced approximately 50 m apart. The ground surface landward of the revetment is primarily lawn grass with very small areas of bare sand close to the structure, and one patch of shrubs (Figure 51).

Figure 51. The ground surface landward of Revetment 2 at Officer's Row South site is primarily covered with lawn grass. Photograph was taken looking north.

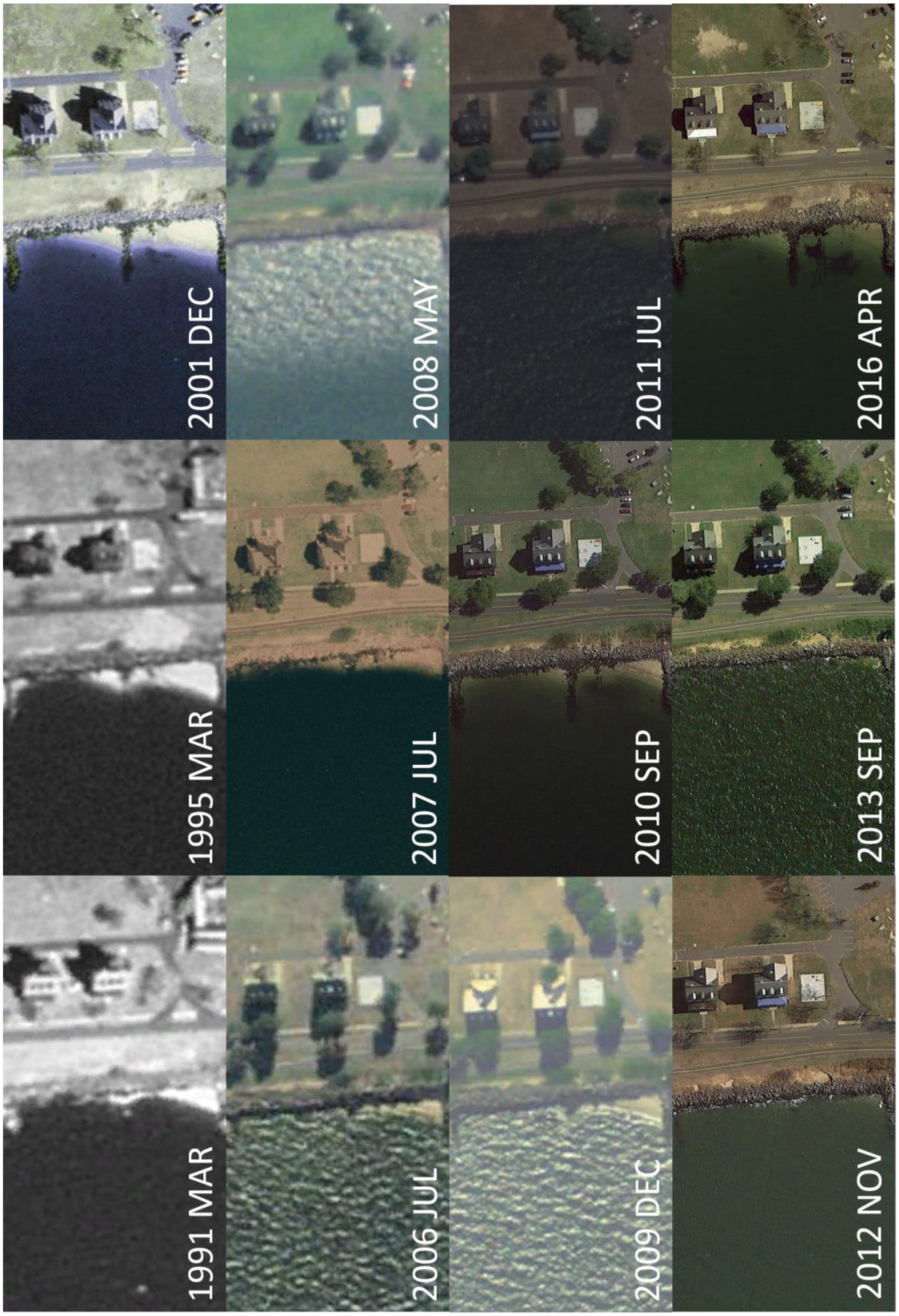

Figure 52. Small areas of bare sand landward of the revetment are present over the last 25 years of imagery at the Officer's Row South site. Historical imagery obtained from Google Earth.

Historical aerial images reveal small areas of bare sand landward of the structure during the entire period of coverage (Figure 52), but they have not experienced a noticeable increase in size, indicating a lack of erosion. The beach fronting the revetment is subaerial in the earlier images and submerged in the more recent images, but this may be due to differences in the tidal cycle at the time the image was captured rather than erosion of the beach.

The elevation of the top of the revetment ranges between 2.8 and 3.4 m. The elevation is lowest at the northern end of the site and increases to the south. The top of the revetment extends about 1 m above the landward ground surface (Figure 53). No evidence of sediment movement or removal, or erosional features such as scarps are present landward of the structure. The cross-shore slope of the ground surface is relatively constant between the structure and the paved recreational path approximately 10 m landward of the structure (Figure 54).

The NED is a bare-earth surface and does not represent the structure elevation. It also diverges from the GPS data along the shore-parallel profile 2 m landward of the revetment, especially at the southern end of the site where the NED elevation is approximately 0.3 m lower than the GPS data. It is possible that this area was filled after the NED data were gathered, but there was no evidence of recent fill during site visits or in aerial imagery (Figure 52).

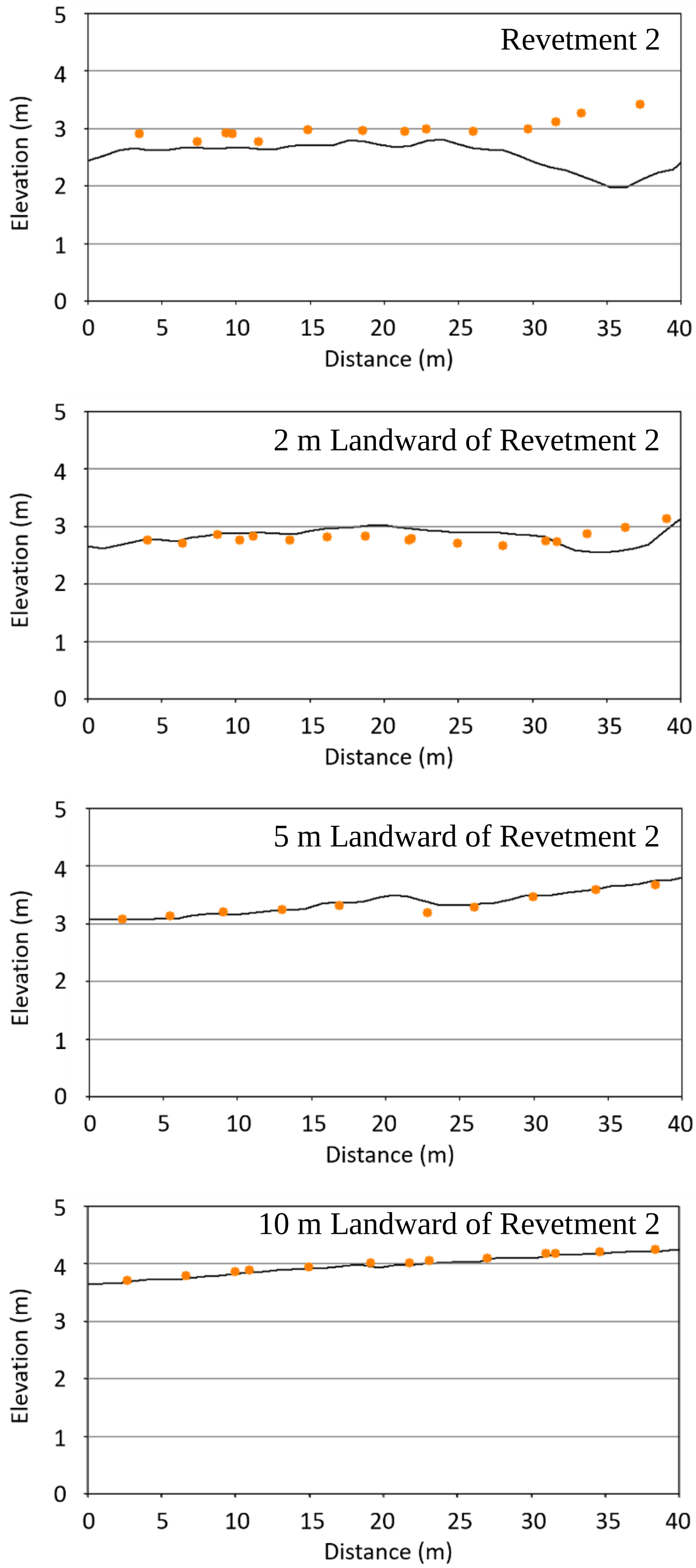

Figure 53. Shore-parallel beach elevations at the Officer's Row South site. Elevations were taken at the revetment crest, 2 m landward of the structure, 5 m landward of the structure, and 10 m landward of the structure. GPS data points are depicted as orange dots. National Elevation Dataset surface is depicted as a black line.

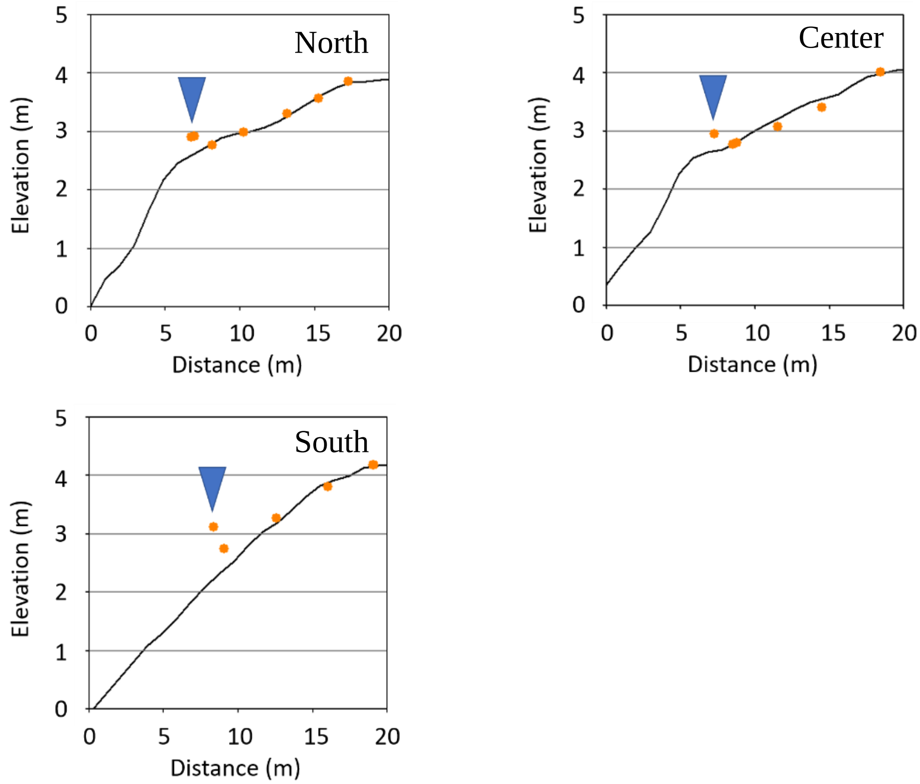

Figure 54. North, center, and south shore-normal beach profiles at the Officer's Row South site. GPS data points are depicted as orange dots; no GPS data were gathered along the seaward face of the revetment due to safety concerns. National Elevation Dataset surface is depicted as a black line. Blue arrows represent the location and elevation of the crest of the revetment.

6.3 Officer's Row North Site (Stage 2)

This site is located approximately 85 m north of the Officer's Row South site. It was chosen because it contains the same revetment as the nearby Officer's Row North site (Revetment 2), but with more evidence of erosion landward. There is a scarp at the interface between bare sand and grass landward of the structure (Figure 55). The ground surface landward of the revetment is approximately 2 m to 5 m wide bare sand and pebble surface, with lawn grass and some natural herbaceous vegetation further landward near a paved recreation path. Wrack deposits were present on the landward side of the revetment during site visits. The differences between Officer's Row North and South sites illustrate that stage is not always consistent along a structure, and age of a structure alone may not be indicative of the conditions landward.

Figure 55. Wrack deposits and evidence of erosion are found landward of the revetment at Officer's Row North site, Sandy Hook Unit, Gateway National Recreation Area. Photo was taken looking south.

Revetment 2 was constructed in 1901 to protect the upland and a pre-existing bulkhead from further deterioration (Bearss 1981). According to Bearss (1981), the sand surface was approximately 8 ft (2.4 m) below the top of that bulkhead in 1901. The revetment that now covers the original bulkhead is currently approximately 3.5 m above the beach surface. The elevation of the beach obtained by RTK GPS just seaward of the revetment is approximately -0.6 to -1.5 m (Figure 56).

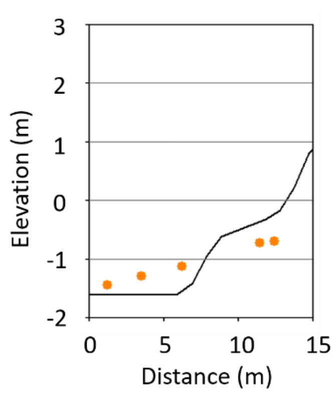

Figure 56. Shore-normal beach profile seaward of Revetment 2. GPS data points are depicted as orange dots. National Elevation Dataset surface is depicted as a black line.

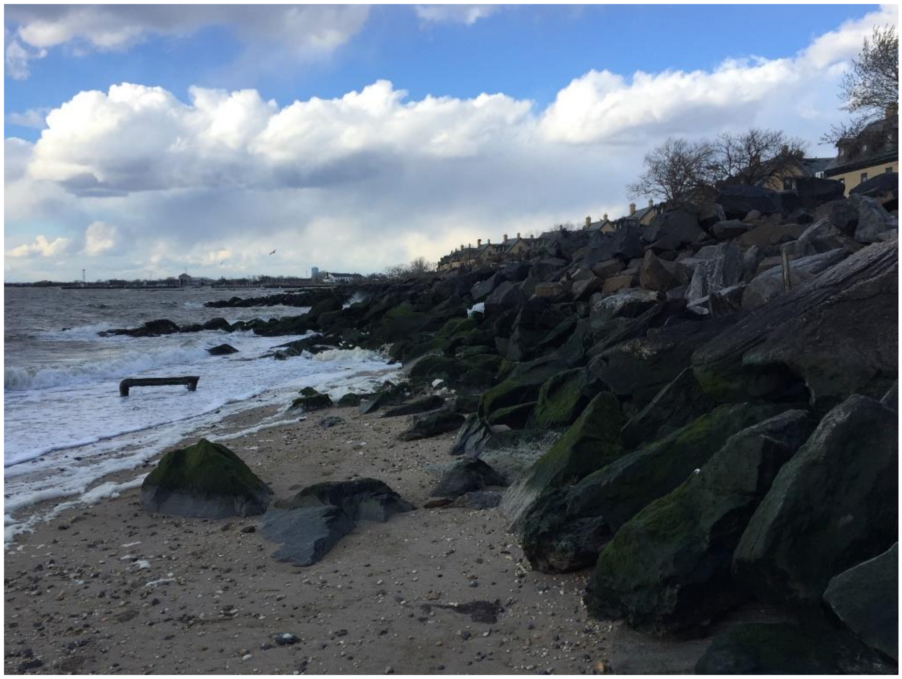

Figure 57. At low tide, the beach seaward of Revetment 2 is subaerial at the southern ends of groin compartments and submerged at the northern ends. Photograph was taken looking north.

GPS beach elevation measurements at Officer's Row North and Officer's Row South sites were not obtained because of concern about the safety of descending the face of the structure and collecting data within the submerged boulders. Accordingly, beach elevation measurements were collected in the groin compartment approximately 40 m south of the Officer's Row South site that provided the best vertical access. Beaches within each groin compartment along Revetment 2 share similar characteristics. At low tide, the northern halves of the beaches within each compartment remained submerged while accreting beaches at the southern halves were subaerial (Figure 57).

The area of bare sand landward of the revetment has increased in width over the 25-year time period covered in the aerial images (Figure 58). The increase is greatest towards the northern portion of the site where elevations are lower, indicating that elevation of the ground surface landward of a revetment may help determine where erosion is most likely to occur in early stages of deterioration. The November 2012 image shows fan deposits of sand on top of the lawn grass, which indicate that water overtopped the structure during Hurricane Sandy (Figure 58).

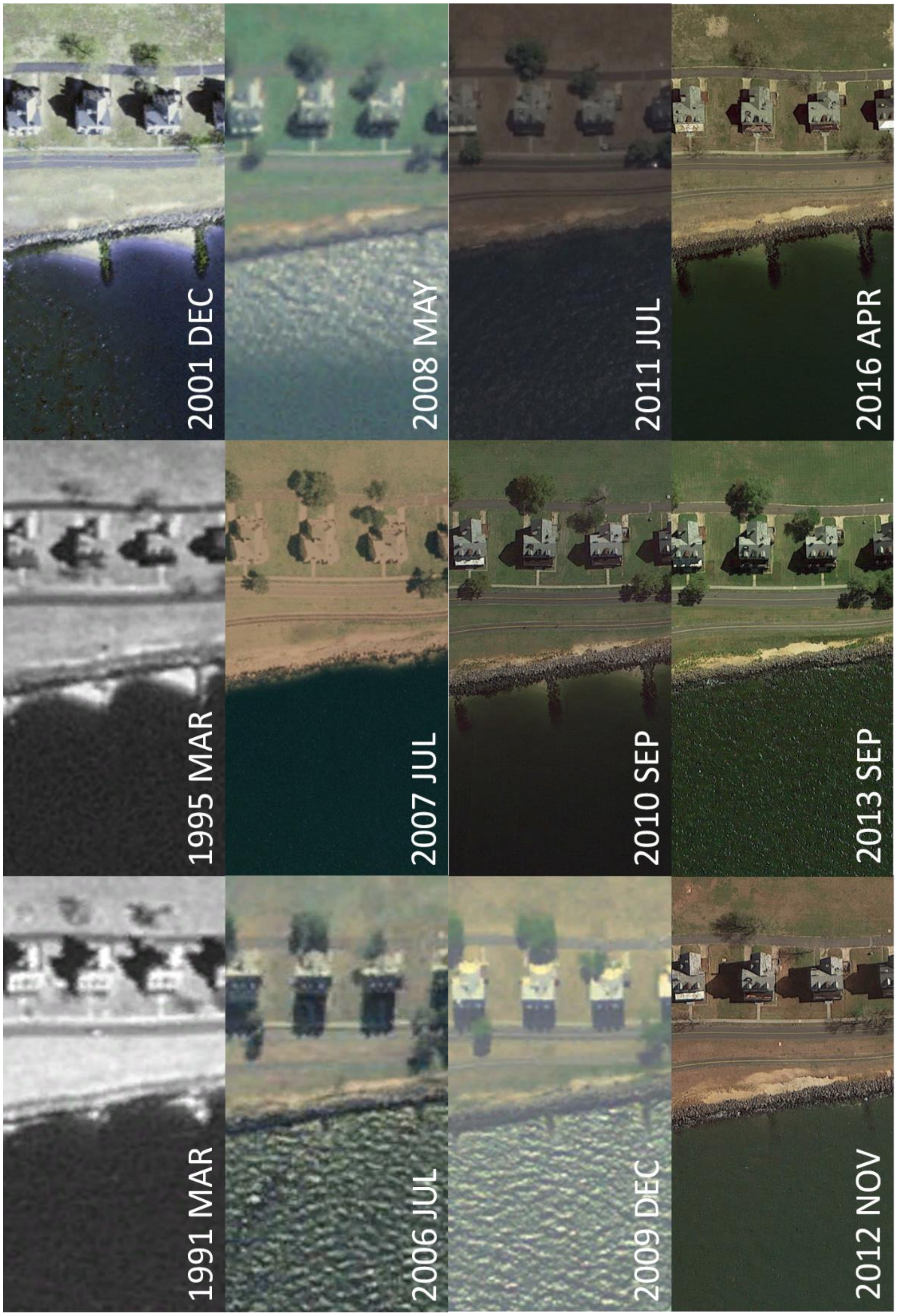

Figure 58. An area of bare sand landward of the revetment at the Officer's Row North site has increased in width over the last 25 years. Historical imagery obtained from Google Earth.

The elevation of the top of the revetment ranges between 1.4 and 2.4 m; the elevation is lowest at the center of the site and increases north and south. Elevation of the revetment is greater where groins attach to it; the profiles are located between two groins. Highest elevations of the structure (2.2-2.4 m) were at the southern extent of the data; elevations at the northern extent were about 1.9-2.2 m (Figure 59).

The elevation of the bare sand surface immediately landward of the revetment is highest in the southern half of the site and decreases northward, and is equal or lower in elevation than the structure. The ground elevation varies between approximately 1.5 and 2.6 m elevation at a distance of 3 m from the structure (Figure 59). The vegetated ground surface farther landward where no erosion has taken place displays a smaller range of elevations with increased distance from the revetment. The variations are 2.6 m to 3.1 m elevation at 9 m distance and 3.0 m to 3.4 m elevation at 12 m distance, indicating that an increase of irregularity in topography may occur when the land behind a revetment begins to erode. The scarp at the sand-vegetation boundary was more prominent in the north end of the site where the elevation of the structure was lower. The vertical distance between the top and bottom of the scarp was on average approximately 0.2 m (Figure 60).

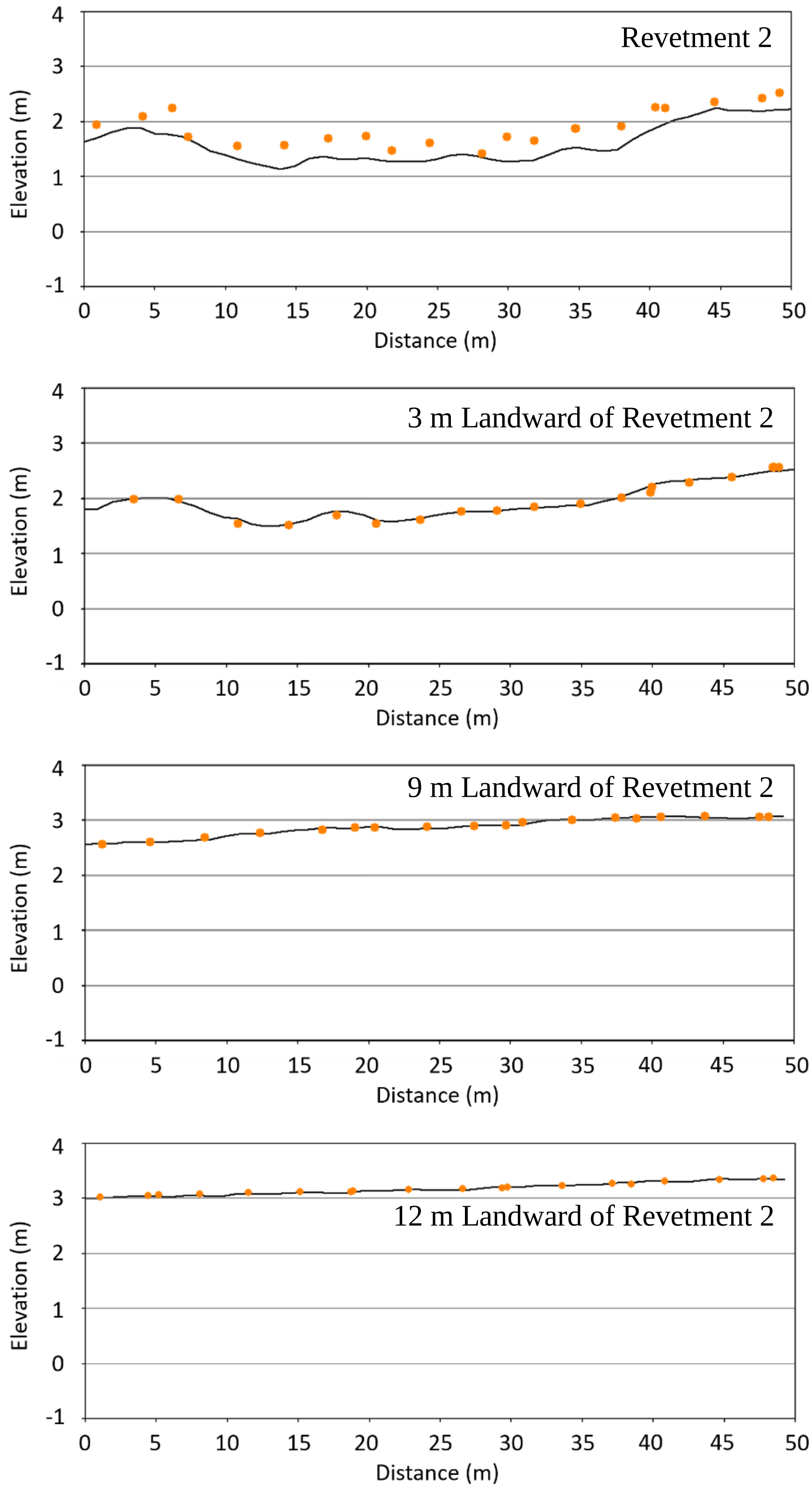

Figure 59. Shore-parallel beach elevations at the Officer's Row North site. Elevations were taken at the revetment crest, 3 m landward of the structure, 9 m landward of the structure, and 12 m landward of the structure. GPS data points are depicted as orange dots. National Elevation Dataset surface is depicted as a black line.

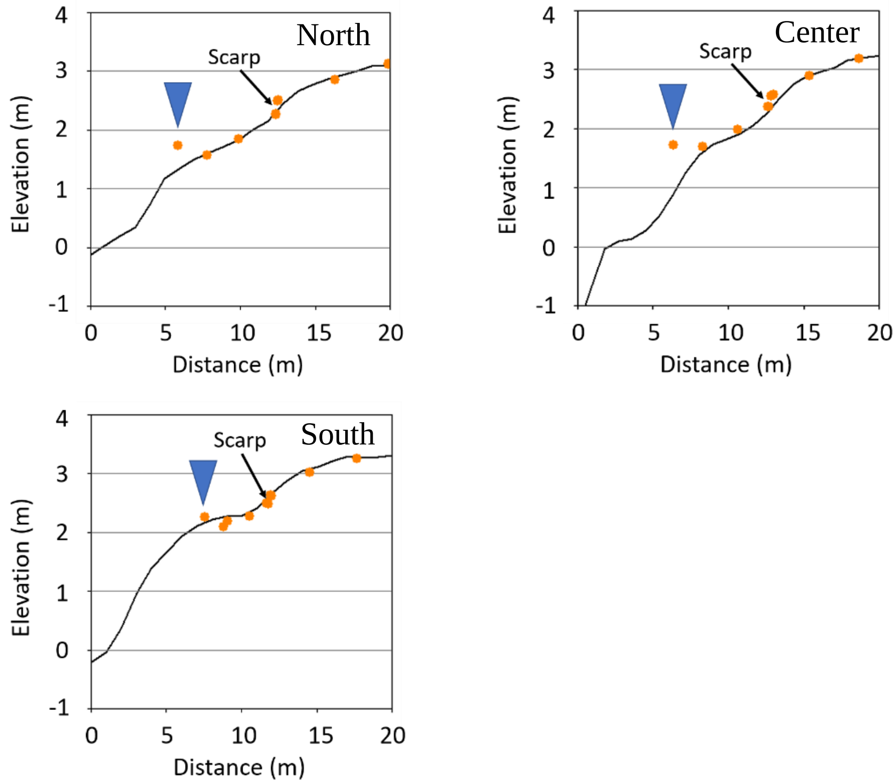

Figure 60. North, center, and south shore-normal beach profiles at the Officer's Row North site. GPS data points are depicted as orange dots. National Elevation Dataset surface is depicted as a black line. Blue arrows represent the location and elevation of the revetment.

The NED does not provide accurate elevations for submerged ground surfaces seaward of Revetment 2 (Figure 56), or for the structure itself (Figure 59). GPS and NED elevations landward of the structures are comparable (Figure 59). The one critical feature that is not captured in the NED is the scarp at the landward edge of the bare sand (Figure 60).

6.4 Horseshoe Cove Site (Stage 3)

The revetment at this site (Revetment 7) was constructed in 1988 (Dallas et al. 2013) to armor the shoreline where Hartshorne Drive is approximately 20 m landward. Hartshorne Drive provides the only road access to the northern portion of Sandy Hook and is critical for use by the United States Coast Guard, visitors, and the multiple organizations located in the Fort Hancock area. This site was chosen because the revetment is situated on the active backshore of the beach.

Bare sand is present landward of the revetment for the entire period covered by aerial imagery (Figure 61). The center portion of the site appears to historically experience more overwash than other areas, as indicated by the wider area covered by bare sand. It is difficult to assess the long-term trend in the amount of coverage of natural vegetation versus bare sand because the available historical images were taken during various times of the year. The entire beach seaward of the structure has been completely submerged during periods of high tide since at least 2006.

Most of the ground surface between the revetment and Hartshorne Drive is bare sand, with patchy dune grass and lawn grass within approximately 10 m of the road. Low-lying portions have overwash fans directly landward. These deposits cover riprap as well as live vegetation, indicating their relatively recent deposition and landward migration of the beach. Storm wrack lines were present landward of the revetment, at a distance of approximately 8 m, during the site visit (Figure 62).

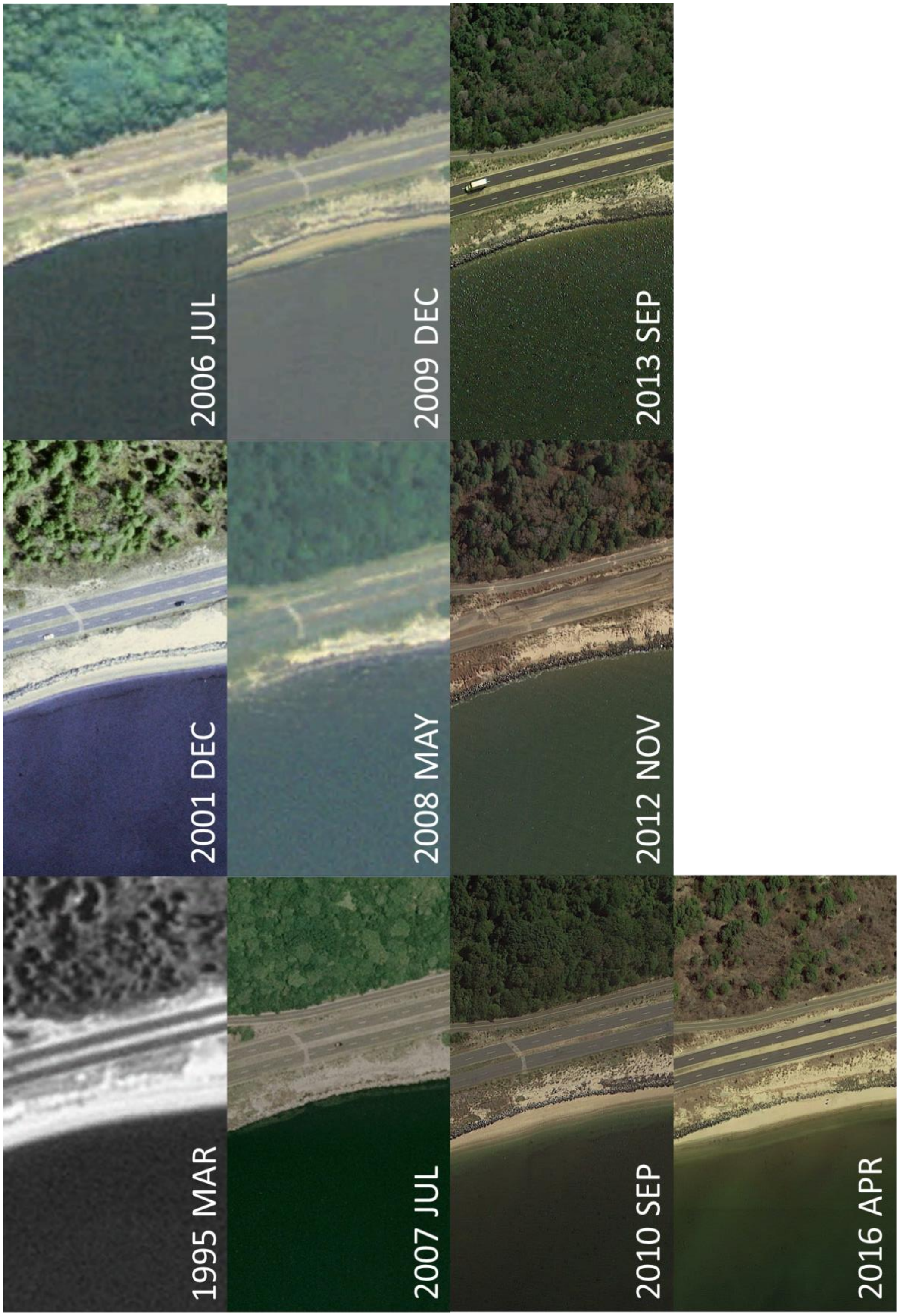

Figure 61. Bare sand has been present landward of the revetment at the Horseshoe Cove site over the past 21 years. Historical imagery obtained from Google Earth.

Figure 62. Bare sand including fan deposits and wrack lines are present landward of the revetment at Horseshoe Cove site, Sandy Hook Unit, Gateway National Recreation Area. Photograph was taken looking south.

The highest elevations of the top of Revetment 7 at the Horseshoe Cove site range between 1.1 and 1.6 m (Figure 63), similar to the lowest elevations of the structure at the Officer's Row North site, and approximately 1.0 m above the elevation of beach directly seaward of the structure (Figure 64). The elevation is generally lower towards the center of the site and increases slightly to the north and south (Figure 63). The elevation of the top of the revetment is lower than that of the dune crest (Figure 64), and the elevation at the center of the revetment is lower than the storm wrack line landward of the beach. This indicates that during periods of high water, there are segments of the structure that may be submerged. The beach seaward of the revetment is completely submerged during high tide (Figure 61).

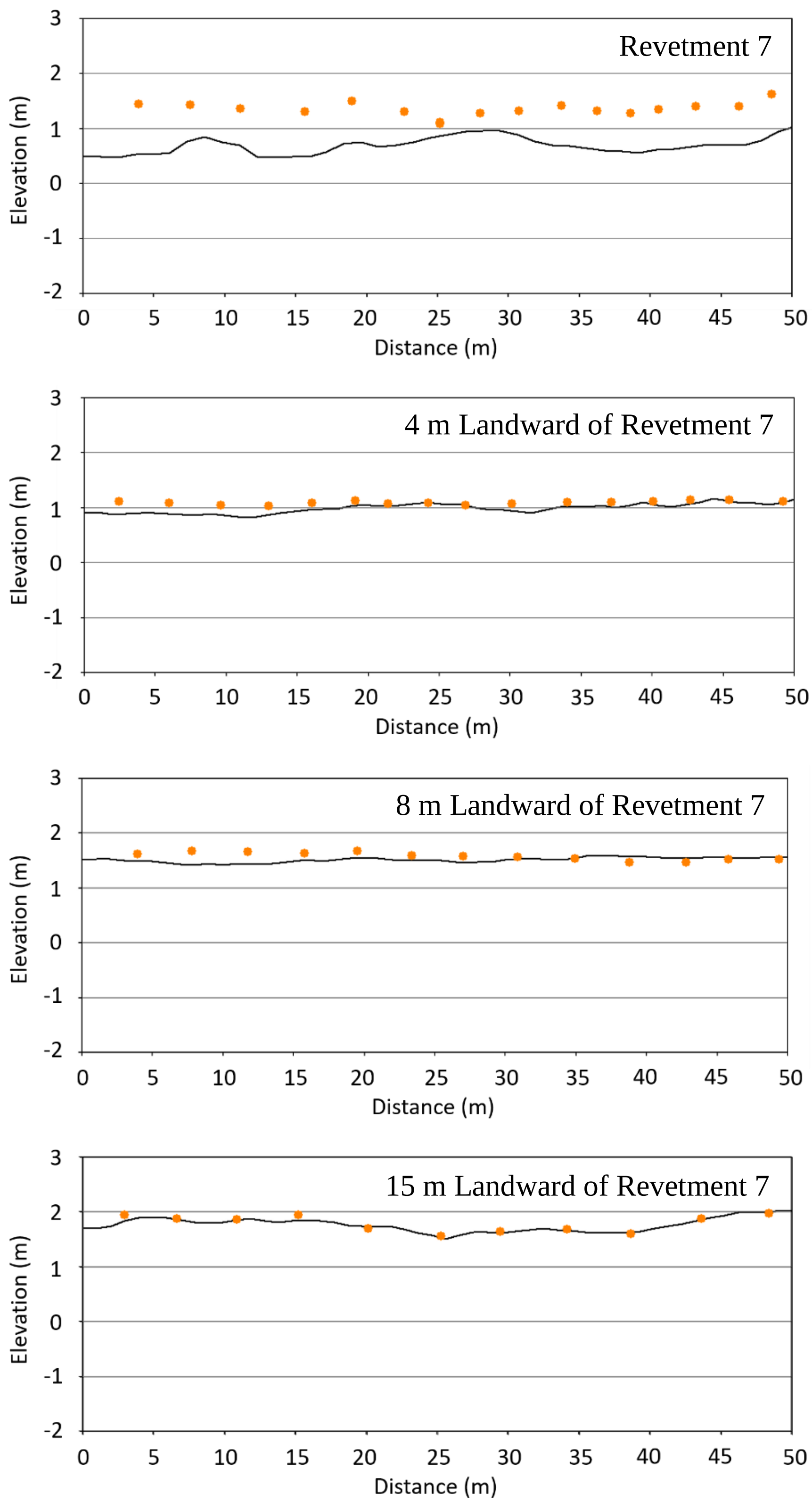

Figure 63. Shore-parallel beach elevations at the Horseshoe Cove site. Elevations were taken at the revetment crest, 4 m landward of the structure, 8 m landward of the structure, and 15 m landward of the structure. GPS data points are depicted as orange dots. National Elevation Dataset surface is depicted as a black line.

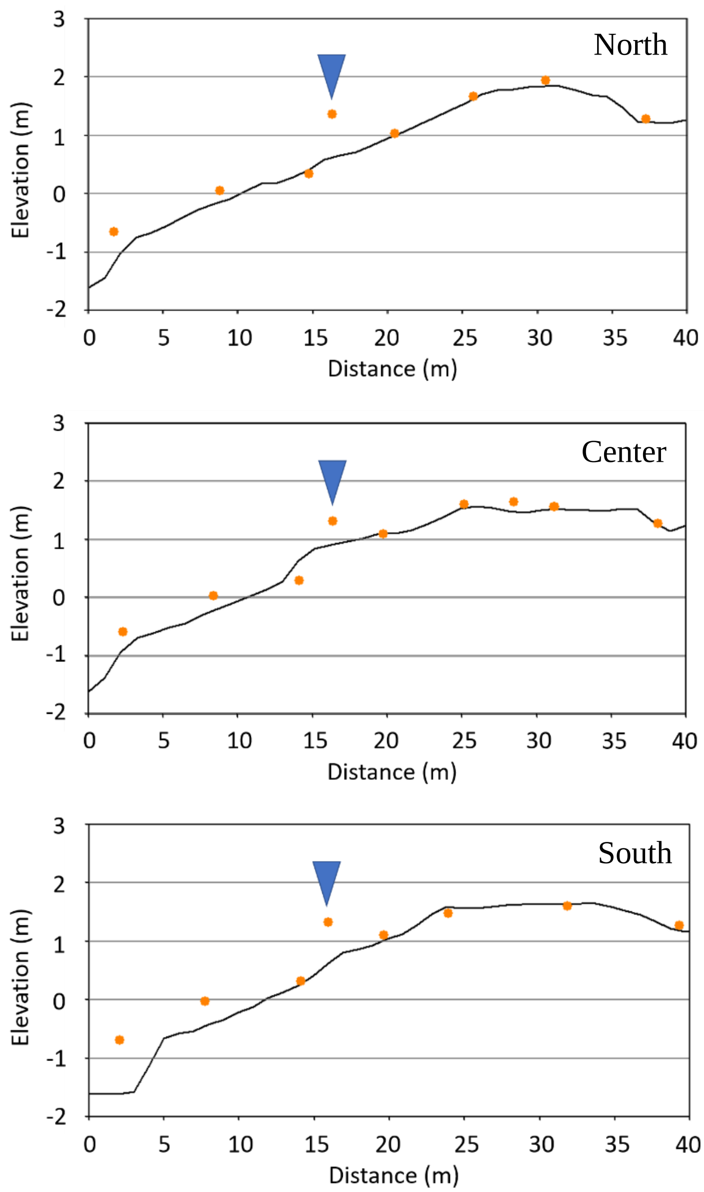

Figure 64. North, center, and south shore-normal beach profiles at the Horseshoe Cove site. GPS data points are depicted as orange dots. National Elevation Dataset surface is depicted as a black line. Blue arrows represent the location and elevation of the revetment.

The NED diverges from GPS data on the lower foreshore, at submerged elevations, and at the location of the revetment (Figure 64) for the reasons mentioned earlier.

6.5 Natural Control Site

The natural site (discussed in more detail in Chapter 5) is linear with little variation alongshore. Shore-normal profiles show similar beach widths and elevations, and dune crest heights (Figure 44). Shorelines at all revetment sites are linear. The Horseshoe Cove site is most similar to the Natural Control site in terms of beach width, elevations, slope, and vegetation. The shore-normal slope is steeper at the Battery Kingman South Site and the two Officer's Row sites, where the revetment covers the entire width between the upland and lower beach face.

6.6 Conclusions

The case study sites in this chapter display a variety of key morphological characteristics that help further refine the stages of a riprap revetment as it deteriorates. Key features in the landscape as a site progresses include: 1) intact upland with no erosion; 2) erosion of the upland directly landward of the revetment, especially where structure elevation is lower; 3) an active beach area landward of the revetment; 4) open water landward of the revetment.

Based on the case study sites in this chapter, elevation of the structure and landward ground surface may be correlated to the stage of the revetment where a higher elevation is related to a lower stage. The Officer's Row sites demonstrate that it is possible for a revetment of sufficient elevation to protect an upland area for over a century with minimal maintenance. It is likely that the Battery Kingman Site will remain in an early stage for a comparable length of time because the two structures are similar in elevation, width, material, and upland elevations.

At Horseshoe Cove where the revetment is newer but lower, water is not prevented from passing over or through it, causing sediment transport landward of the structure. It is likely that the revetment at Horseshoe Cove was never in Stage 1 due to the methods of construction. An increase in water level may cause an increase in overtopping of any given structure, with further erosion of the upland, resulting in an active beach landward as illustrated at the Horseshoe Cove site.

For areas landward of the revetments, the NED and RTK GPS datasets were in agreement for all areas except where small features are found, such as the scarp present at the Officer's Row North site. The wide footprint of revetments (up to 10 m wide at the case study sites) means that the NED does not provide reliable elevations for a large portion of the beach profile. The NED is also not accurate seaward if the ground elevation is submerged. GPS data are considered to be more accurate and reliable overall, and provide coverage over the entirety of a site, including the revetment. The NED should only be used for subaerial elevations landward and seaward of the structure.

Chapter 7

Discussion

The wood bulkhead and riprap revetment case studies in Chapters 5 and 6 provide details of the progression or stages through which a given structure will transition if there is no or minimal human interference, including maintenance of the structure. Using the understanding gained from these case studies by analyzing the differences in structure integrity and landscape features, the original proposed model introduced in Chapter 1 is modified to include more distinction in the stages. Notable differences in the signature landscape features between deteriorating bulkheads and revetments include the amount of shoreline irregularity and the rate of deterioration.

Instead of the identifying feature of each stage being the physical condition of the structure, I propose that landscape features large enough to identify from open source satellite imagery be used to indicate the current stage of a structure. Ground elevation data is preferred to conduct an analysis, but raster elevation datasets such as the NED may provide sufficient description of the landward topography. While only two specific types of structures are addressed here, parallels may be drawn to other materials and structure types. It is acknowledged that there may be exceptions that do not follow the proposed model.

There is a fundamental difference between the area landward of bulkheads and revetments. To install a bulkhead, the land behind the structure is excavated to anchor or place the sheet piles. The land is then backfilled, so that the area directly landward of a bulkhead has been disturbed when the structure is new. The backfill is generally graded to an elevation similar to the bulkhead. In contrast, riprap revetments are typically placed on the existing ground surface, without excavation or much backfill. Because the land behind an intact bulkhead will look similar from one structure to the next, the starting geomorphological stage of bulkhead deterioration is more easily defined than that of riprap revetments. The characteristics of the starting morphological stage of revetments is partly determined by the pre-structure morphology.

There are notable differences in the signature landscape features between deteriorating bulkheads and revetments. One key difference is that the deterioration of sheet piles allows the upland to erode and removes the component of the structure design that resists the force of wave attack. The resultant sinusoidal shoreline is distinctive to deteriorating bulkheads. Riprap revetments do not rely on the pressure of the landward fill to resist wave attack; the stone material provides the protection. The shoreline remains more linear throughout the deterioration of a riprap revetment. The landward area erodes primarily due to the insufficient elevation of the revetment and low elevation of the ground surface, where areas lowest in elevation will experience erosion first. Regardless of structure type, the structures begin with an intact upland lacking erosional features and progress towards open water landward of the structure for the entirety of the tidal cycle, and a linear shoreline that is similar to a natural shoreline. Shore-parallel structures may reintroduce a sediment supply as they deteriorate that may help to maintain beaches downdrift. As a naturally functioning beach is reestablished, habitat is created for local fauna that is not present when the upland remains intact.

7.1 Progression of Wood Sheet Pile Bulkheads

There are four distinct stages through which a wood bulkhead will progress if it is not adequately maintained to prevent deterioration or a decrease in freeboard, which causes erosion landward of the structure (Figure 65). In Stage 1, the condition of the structure is good with no gaps or noticeable damage (e.g. Great Kills Site). The fill landward is undisturbed and level with or higher than the bulkhead, and there is no erosion landward.

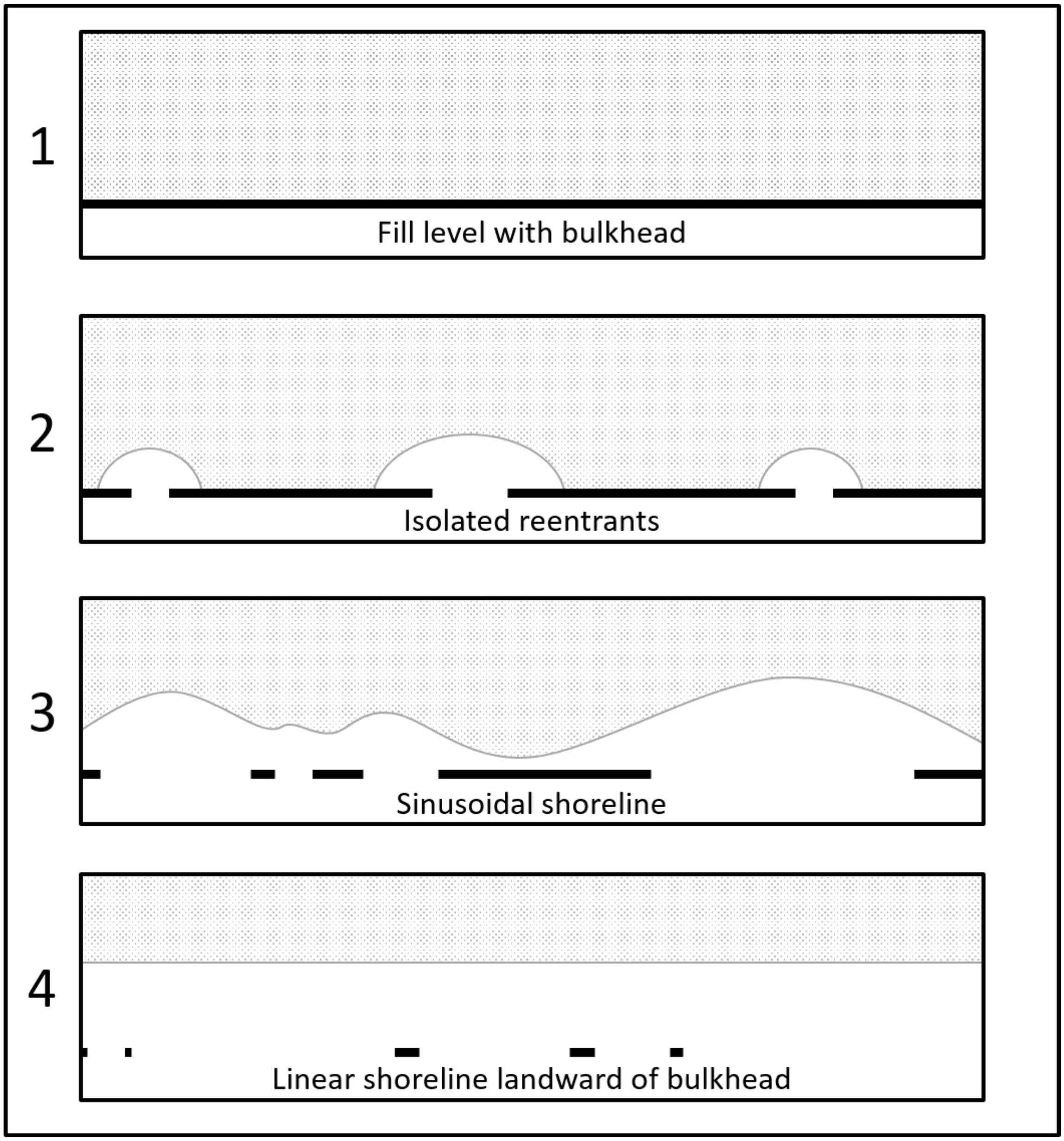

Figure 65. Illustration of the four morphological stages of a wood bulkhead as it transitions from having fill level with the bulkhead (1) to a linear shoreline and open water landward of the bulkhead (4).

In Stage 2, the condition of the bulkhead has degraded to fair and there are small gaps in the structure. These small gaps result in small reentrants landward of the gaps and some reworking of the sediment (e.g. Chapel South site). The small gaps in the bulkhead, like the ones present in the southern portion of Bulkhead 2 (Figure 25), channel some outflow through the structure, which results in localized erosion directly landward of the gaps in the bulkhead. The bulkhead may not have enough freeboard to prevent overtopping, which results in more widespread erosion of the upland and a transition from a level fill area to upper beach. The bulkhead is less of a barrier within the beach environment to water and sediment flow. The beach profile from the bulkhead to the dune at this stage appears similar to a truncated natural beach profile in both width and slope, where the bulkhead is on the mid-foreshore. This is illustrated by the similarities in cross-shore profiles between the Natural Control site and Chapel South site landward of approximately 0.5 m elevation.

The condition of the bulkhead is still fair in the Stage 3, but gaps in the structure are larger or more numerous than in Stage 2. Because the gaps are larger, the reentrants are larger and can merge, resulting in a sinusoidal shoreline landward of the bulkhead (e.g. Chapel North site). Remaining segments of the bulkhead act as nearshore breakwaters, with the horns of the sinusoidal cusps remaining landward of them and bays landward of the gaps. During this stage, there is most likely some standing water landward of the bulkhead during all portions of the tidal cycle.

Stage 4 defines a bulkhead that is in poor condition. As the size and number of gaps in the bulkhead increases over time and the linear extent of the gaps exceeds the intact portions of the bulkhead, the shoreline once again becomes linear and begins to resemble a natural shoreline (e.g. Battery Kingman North site). In this stage, waves break directly on the beach rather than the bulkhead during most, if not all, of the tidal cycle. While pilings will most likely remain offshore for decades (Nordstrom and Jackson 2016) even as the remainder of the sheet pile deteriorates, the beach has already returned to a natural shape and further deterioration will not have additional large-scale effects on the surrounding landscape.

Most bulkheads in the inventory are in poor condition indicating that wooden bulkheads do not remain in Stage 1 for long. Historical imagery at the Chapel North site indicates that once the condition of the structure begins to degrade, deterioration may progress in a matter of decades. It is possible for a bulkhead to progress to a more advanced stage while it remains in good condition, if the bulkhead elevation is not sufficient to prevent overtopping (e.g. Bulkhead 2 at the Chapel South site). A bulkhead in good condition that reaches Stage 4 solely due to overtopping will not exhibit shoreline irregularity or large reentrants

It is proposed that Stage 2 (small gaps and isolated reentrants) is the most critical stage for managers to decide whether a structure will be repaired and maintained or permitted to deteriorate. The cost to repair piles on a bulkhead and backfill small areas of erosion when gaps are few and small is significantly less than in Stage 3. Once in Stage 3, it is likely that the entire bulkhead would need to be replaced and the quantity of backfill needed would be much larger.

7.2 Progression of Stone Riprap Revetments

Four distinct stages can also be used to describe how a riprap revetment will progress if it is not adequately maintained to prevent decreased freeboard due to raveling, dispersion of riprap, or rising water levels. The stage of a revetment is only partly related to its condition. Stage depends on the morphological characteristics of the area landward of the revetment including elevation, and the amount of erosion and reworking of sediment that has taken place. Descriptions of the four stages follow and are illustrated in Figure 66.

Stage 1 is characterized by a lack of erosion (e.g. Battery Kingman South and Officer's Row South sites), if the structure is built to sufficient standards (non-engineered dumped-rubble revetments are common on estuarine beaches). Structures with higher average elevations are characterized by an earlier stage because the higher elevation provides more protection to the area landward from inundation and erosion. The elevation of a revetment in Stage 1 extends above high water, and the elevation landward of the revetment is above high water. Unless developed, the area landward of the structure is covered by vegetation at this stage because the elevation of the structure is higher than that of a natural beach.

Stage 2 is characterized by areas of bare sand and erosion landward of the revetment, as indicated by such features as the scarp at the Officer's Row North site. This stage represents a period where the condition of the revetment may be good but its elevation is not sufficient in places to prevent water from overtopping or passing through the structure to erode the upland.

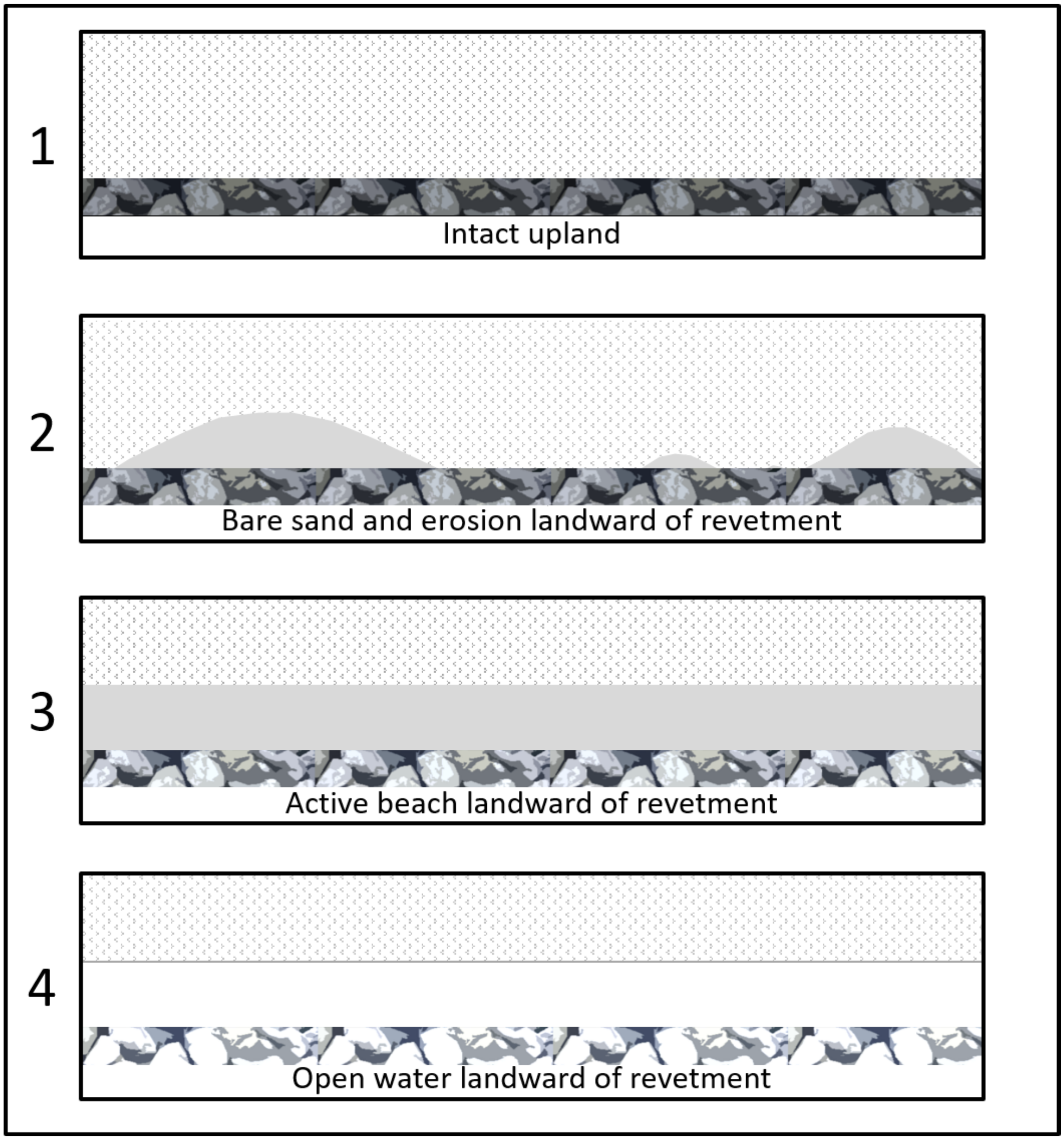

Figure 66. Illustration of the four morphological stages of the landscape surrounding a riprap revetment as it transitions from having intact fill landward of the revetment (1) to open water landward of the revetment (4).

Stage 3 is characterized by an active beach landward of the structure due to insufficient elevation of the structure (e.g. Horseshoe Cove site). Water overtops or penetrates the structure frequently and reworks sediment landward of the revetment. Indications of this stage are bare sand landward of the structure and fan deposits and wrack landward of the structure. The eroding upland may allow for increased sediment delivery to beaches downdrift. The condition of the structure may be good, fair, or poor, because riprap structures rarely fail catastrophically, although a revetment is more likely to progress to Stage 3 if in poor condition.

Stage 4 is characterized by open water landward of the structure (e.g. Chapel North site). At this point, the revetment may be subaerial or submerged for a portion of the tidal cycle, and acts as a breakwater. The beach is linear and appears similar to a natural unarmored beach. As water levels increase after this point, the distance from the revetment to the shoreline will increase, the freeboard of the revetment will decrease, and its effect on minimizing the wave energy reaching the beach will decrease.

Similar to wood bulkheads, Stage 2 is the most critical stage for decision-makers because it indicates that the integrity of the structure is beginning to be compromised. The condition of the structure remains good, but removal of sediment surround the structure due to erosion may cause a decrease in freeboard of the revetment. If the revetment remains in good condition, the site may move to a higher stage with sea level rise, which is likely during the lifetime of the structure given the longevity of stone material in estuarine environments.

7.3 Relationships Among Structure Characteristics

Condition, age, and stage of the structures in all GATE inventories were investigated for potential relationships in addition to understanding landscape features and providing descriptions of characteristics unique to each stage of deterioration.

Most wood bulkheads in the inventory (9 out of 14) are in poor condition (Figure 67). If the bulkhead is in good condition, the structure is in Stage 1. The structures in the Great Kills Area of the Staten Island Unit are in the best condition and lowest stages of all bulkheads in GATE. There is only one bulkhead in fair condition (Bulkhead 8 in STIS), which is in Stage 2. Bulkheads in poor condition are in Stages 2-4. The results indicate that a bulkhead can only be in Stage 1 if it is in good condition.

Stage and condition are related to the age of wood bulkheads. If less than approximately 40 years has passed since a bulkhead was built or last maintained, the bulkhead is in good condition and in Stage 1. If more than approximately 80 years has passed since a bulkhead was built or last maintained, the bulkhead is in poor condition and is in Stage 3 or 4. Between these ages, bulkheads are either in fair or poor condition (Figure 68).

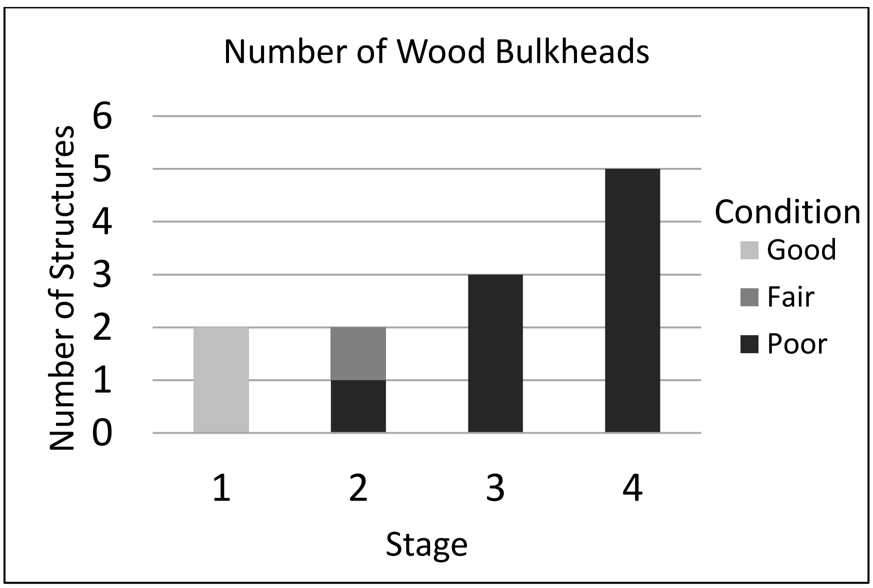

Figure 67. Number of wood bulkheads by Stage in Gateway National Recreation Area.

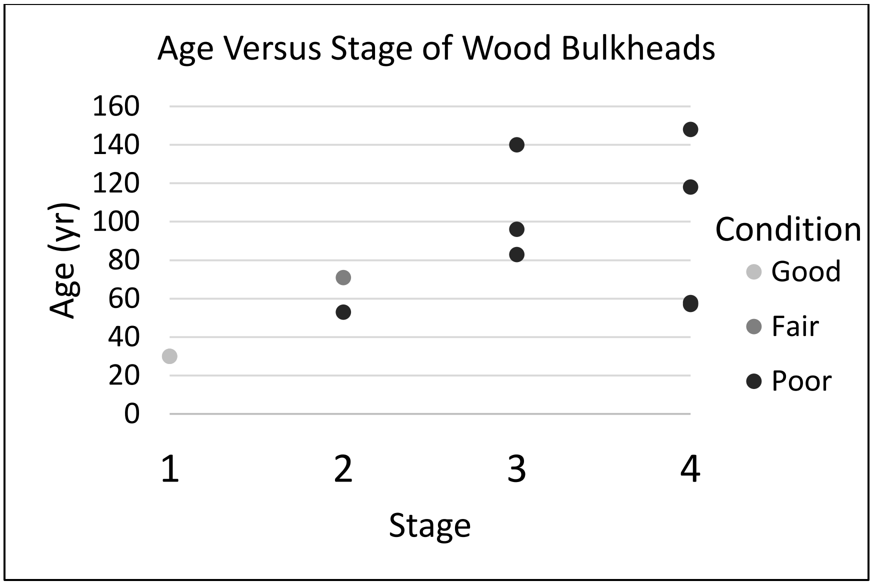

Figure 68. Age versus Stage of wood bulkheads in Gateway National Recreation Area. Bulkheads were excluded if age data were not available.

Most revetments (19 out of 36) are in good condition (Figure 69). The condition of the revetment does not provide an indication of its stage, as revetments in good condition are in Stages 1-3. Six revetments in good condition were categorized as Stage 1; eight were Stage 2; and four were Stage 3. Revetments in poor condition are in Stages 2-4. Similar to wood bulkheads, however, the data indicate a revetment can only be in Stage 1 if it is in good condition.

Condition of revetments appears to be independent of age, where structures less than 20 years old can be in good, fair, or poor condition (Figure 70). Age also does not drive the stage of the revetment. The age of revetments within each stage varied by 24 to 101 years, with the greatest range of ages in Stage 3 structures and the smallest range in Stage 2 structures. This supports the observations that the stage of a revetment is driven by the elevation of the structure and upland area.

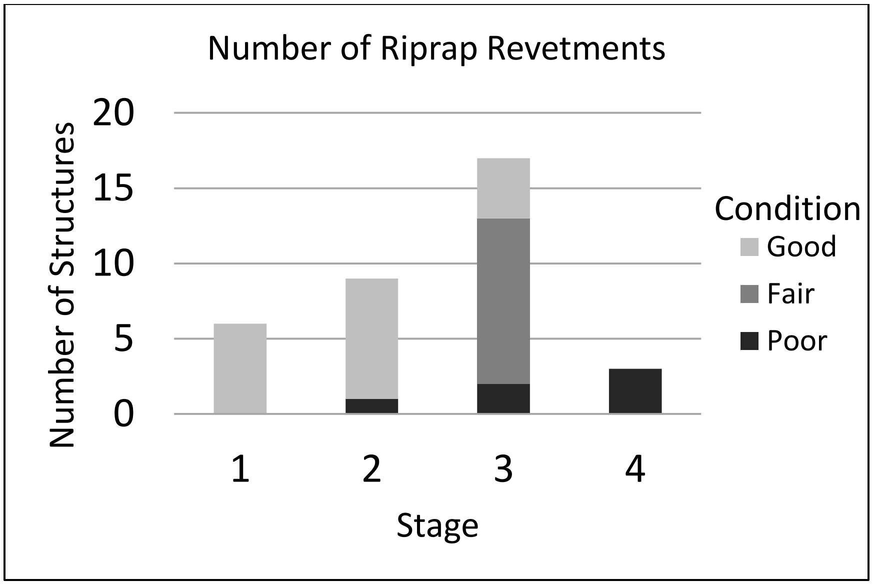

Figure 69. Number of riprap revetments by Stage in Gateway National Recreation Area.

For any given site, the condition of the structure decreases and the stage increases with time if no upgrades, modification, or maintenance occur on the structure. Results show that these changes do not happen at the same rate for all wood bulkheads or riprap revetments, or at similar locations, and may not be easily predictable. The rate of deterioration of a structure and changes in the landscape are a function of both internal influences (such as type and quality of construction material, engineering design, elevation) and external forces (such as wave regime, storm events, shoreline orientation). For example, the revetment at Officer’s Row is more degraded at the north site than the south site, and the revetment that is at the most advanced stage of the case study sites (Horseshoe Cove) is also the youngest.

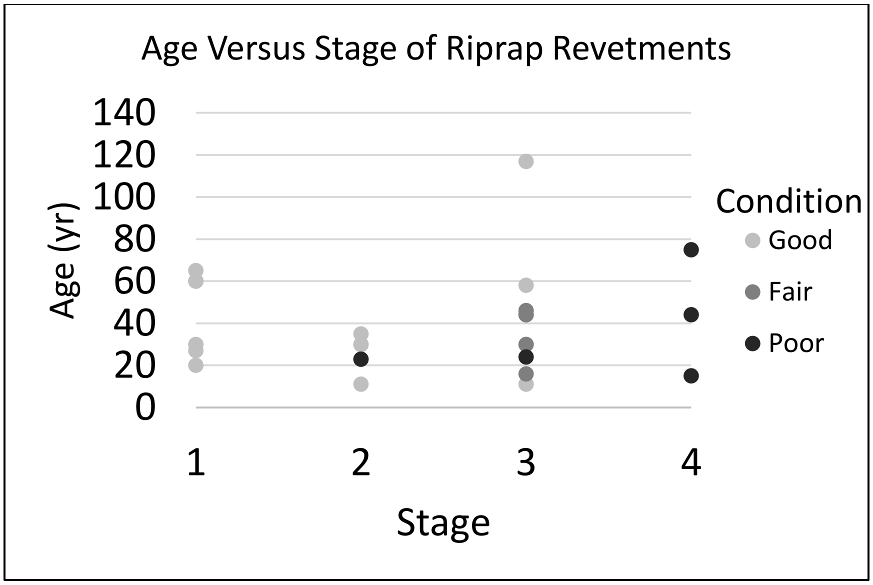

Figure 70. Age and Stage of riprap revetments in Gateway National Recreation Area. Revetments were excluded if age data were not available.

7.4 Summary

Results from this study reveal that 1) the condition or stage of a structure cannot be determined by age, indicating the rate of deterioration is not constant for all structures of the same type and material, 2) the landscape will adjust to a decrease in the effectiveness of a structure in a predictable manner, which is different for wood sheet pile bulkheads and stone riprap revetments, 3) the ability of a structure to have an effect on the beach morphology decreases as the structure deteriorates and beach becomes more similar to a natural one.

A summary of the critical changes in the structure and nearby morphology that take place between Stages 1 and 4 are illustrated in Figure 71. As the condition or effectiveness of a structure decreases over time, the amount of open water or bare sand landward increases along with sediment mobility. Shoreline irregularity peaks in Stage 3 and is greater for bulkheads, but peaks in Stage 2 at a smaller magnitude for revetments. Intact protection structures act as a barrier to water flow and sediment transport (van der

Nat et al. 2016) and the ability for a beach environment to migrate inland when faced with sea level rise (French 2001), often resulting in loss of beach areas (Kraus and Pilkey, 1988; Pilkey and Wright, 1988; Kraus and McDougal, 1996; Fletcher et al., 1997). These barriers are reduced as structures deteriorate and advance to higher stages.

Understanding and identifying the stage of a structure fills in a critical piece of information that should be inserted as a key consideration during the decision-making process, in addition to the present condition of the structure and socio-economic factors. The most critical period to make a decision regarding the future of a structure is in Stage 2, especially if the structure is to be repaired or upgraded to maintain effectiveness. Coastal armoring, which inhibits sediment, nutrient, and biota exchange in the coastal environment, decreases the ability of the ecosystem to absorb natural or human-induced perturbations by reducing variability, complexity, and diversity that provide its ability to adapt (Holling, 1996; Holling and Meffe, 1996; Bengtsson et al., 2003; Elmqvist et al., 2003; Kittinger and Ayers 2010). Further deterioration of structures will result in a tradeoff between the effectiveness of the structure in protecting the upland and resilience of the coastal ecosystem (Berry et al. 2013; Nordstrom and Jackson 2013).

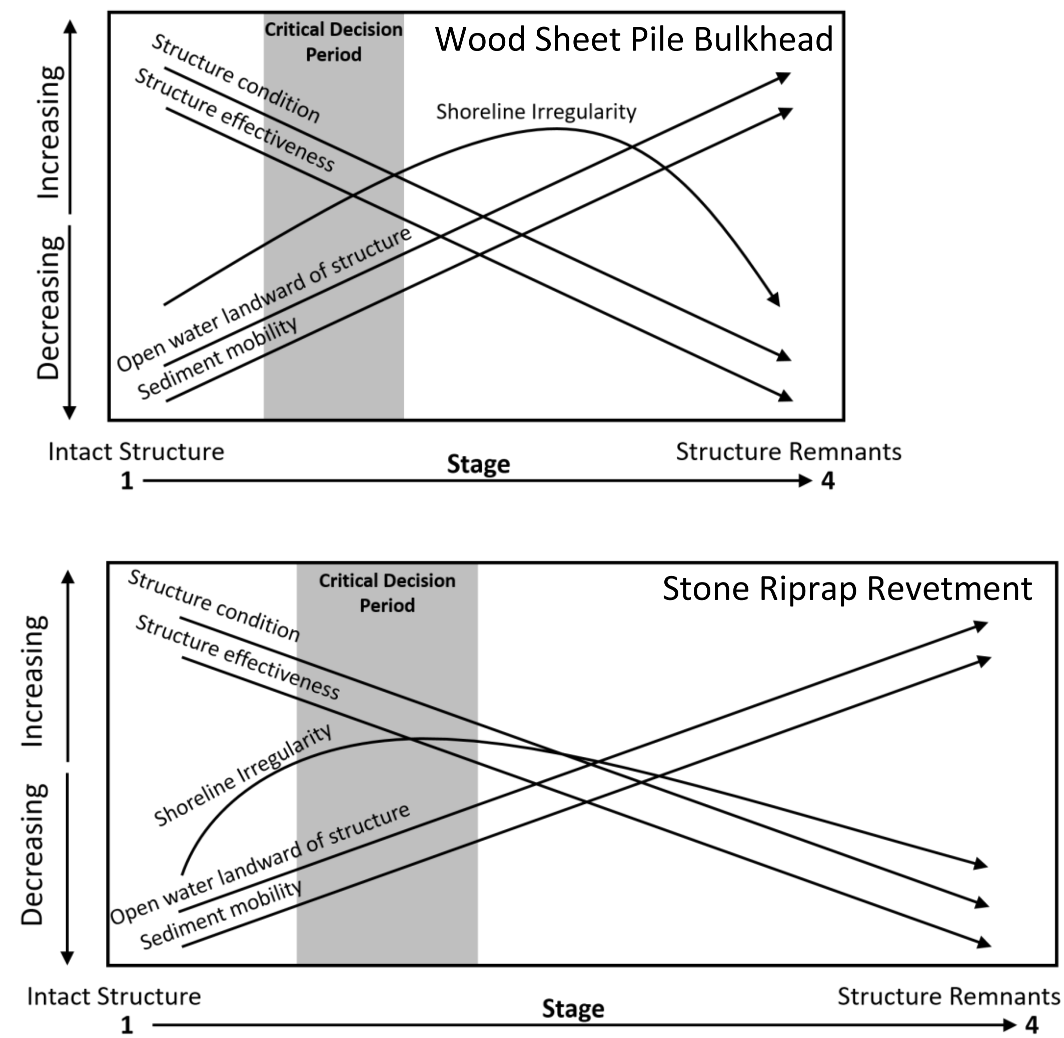

Figure 71. Diagram of the relative changes in protection structures and the surrounding environment that take place over time from Stage 1 to 4.

Chapter 8

Conclusions

8.1 Future Research

There is currently a lack of studies evaluating the processes and changes that existing shore protection structures and the surrounding landscape go through as the functionality of a structure decreases and the structure deteriorates in place. Future studies should increase the dataset surrounding wood bulkheads (e.g. different sizes of pilings, thickness of sheet piles, placement of wales) and riprap revetments (e.g. different sizes and arrangement of armor stone) while expanding on the types and materials of structures on estuarine shorelines, where most degrading structures are likely to be found. This study did not evaluate other materials that are commonly used in coastal armoring, including concrete, steel, and geotextiles, which may experience a different pattern of deterioration and erosion of the upland due to material properties and associated structure types. Future studies that control for structure elevation may aid in separating effects caused by deterioration versus a decrease in freeboard.

The impact of the speed at which the shoreline returns to a natural state is an additional area for study, which can incorporate and compare research focused on removing structures or allowing them to deteriorate. This would help to determine if there is more benefit to allowing for a quick return from an armored beach to a natural state or a more gradual transition by allowing structures to deteriorate. Differences in ecosystem function and resilience in each stage remain unknown, but may affect management decisions regarding removal versus deterioration.

8.2 Concluding Statements

Coastal management strategies are trending away from coastal armoring, but many protection structures remain in the landscape. The life stage model presented provides an indication of what to expect as structures deteriorate and natural processes and dynamism resume. The following statements summarize the implications of this study:

1. An increase in stage for a wood bulkhead is most likely due to deterioration of the structure. Gaps in the bulkhead allow for removal of backfill, which provides the resistant force against wave attack. Conversely, an increase in stage for a riprap revetment is most likely due to changes in freeboard of the structure, which allow overtopping and subsequent erosion of the upland. Successful renovations or improvements on existing structures should consider the primary mode of deterioration during the planning process.

2. The morphology surrounding a structure becomes increasingly similar to a present-day natural beach as the structure deteriorates. This means that allowing a structure to deteriorate may not result in an area that resembles its original state before the structure was built, due to changes in water levels, environmental conditions, or surrounding beach morphology over the same time period. However, the resiliency of the beach ecosystem will still be greater when compared to its armored state, and is a benefit of allowing a structure to deteriorate.

3. The stage of a structure is a critical piece of information that should be considered in the process of deciding the future of a structure. A protection structure life stage model is presented as a tool to aid in the decision-making process. The most critical stage to make

a decision regarding the improvement, repair, removal, or abandonment of a structure is Stage 2, which can be determined by managers via site surveys or remote imagery using the key features described in this study.

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