



Facilitating migration of coastal landforms and habitats by removing shore protection structures

An adaptation strategy for Northeast Region units of the National Park Service

Natural Resource Report NPS/NER/NRR—2016/1240



ON THE COVER

Photograph of seawall and deteriorated bulkhead near Battery Kingman, Sandy Hook Unit, Gateway National Recreation Area.
Photograph by K.F. Nordstrom

Facilitating migration of coastal landforms and habitats by removing shore protection structures

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Natural Resource Report NPS/NER/NRR—2016/1240

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Contents

	Page
Figures.....	vii
Tables.....	xi
Appendices.....	xiii
Executive Summary	xv
Acknowledgments.....	xvii
Introduction.....	1
The global issue.....	1
Potential actions by the National Park Service.....	1
Study sites and policy framework.....	5
Methods.....	9
Relationship of present study to NPS Coastal Engineering Inventories.....	15
The case for coastal erosion.....	17
Beach and dune erosion.....	17
Marsh erosion.....	17
Bluff erosion.....	18
Overview of results	21
Inventory of protection structures	21
Emerging adaptation plans and actions in parks	24
Characteristics at individual parks	27
Acadia National Park.....	27
The situation	27
Options	28
Suggestions for structure removal.....	30
Salem Maritime National Historic Park	31
The situation	31
Options	31
Suggestions for structure removal.....	34
Saugus Iron Works National Historic Site	34

Contents (continued)

	Page
The situation	34
Options	34
Suggestions for structure removal	35
Boston Harbor Islands National Recreation Area	35
The situation	35
Options	37
Case study 1: removal of the wall on the northeast side of Lovells Island	39
Case study 2: removal of protection from the north end of Thompson Island	41
Suggestions for structure removal	42
Cape Cod National Seashore	42
Options	43
Case study: Herring Cove Beach	44
Suggestions for structure removal	44
Fire Island National Seashore	45
The situation	45
Options	46
Suggestions for structure removal	48
Sagamore Hill National Historic Site	48
The situation	48
Options	49
Suggestions for structure removal	49
Gateway National Recreation Area	49
The situation	49
Jamaica Bay Unit of Gateway	51
The situation	51
Options	51
Case Study 1: Removal of Wall 2, Aviation Road, Floyd Bennett Field	53
Case Study 2: Removal of Wall 4, Ranger Road, Floyd Bennett Field	53

Contents (continued)

	Page
Case Study 3: Removal of Wall 28, Fort Tilden	54
Suggestions for structure removal	54
Staten Island Unit of Gateway.....	55
The situation	55
Options	55
Case study 1: Bluff at Battery Hudson	57
Case study 2: Removal of Wall 8.....	58
Suggestions for structure removal	58
Sandy Hook Unit of Gateway.....	59
The situation	59
Options	61
Case Study: removing Walls 14 and 15 (Figure 26)	62
Suggestions for structure removal	63
Assateague Island National Seashore.....	64
The situation	64
Options	65
Case study 1: replacing asphalt with unconsolidated sediment.....	69
Case study 2: modifying Causeway 1	69
Suggestions for structure removal	70
Fort McHenry National Monument.....	70
The situation	70
Options	71
Suggestions for structure removal	71
George Washington Birthplace National Monument.....	72
The situation	72
Options	72
Suggestions for structure removal	73
Colonial National Historical Park	73

Contents (continued)

	Page
The situation	73
Options	77
Case Study 1: removing breakwaters at the Jamestown Island marsh	79
Case Study 2: removing the bulkhead at the Jamestown isthmus	80
Suggestions for structure removal	81
Discussion	82
Overcoming impediments to facilitating landform migration	82
Removing structures versus allowing them to deteriorate	85
Retaining or rebuilding protection structures	86
Removing functional buildings and changing landscaping practices in human-use areas.....	86
Conclusions.....	88
Literature Cited	90

Figures

	Page
Figure 1. Location of coastal parks in the Northeast Region of the National Park Service.....	2
Figure 2. Two views of Herring Cove Beach, Cape Cod, showing effects of removing an asphalt revetment	25
Figure 3. Deteriorated bulkheads at Gateway considered for elimination using post Hurricane Sandy rehabilitation funds	25
Figure 4. Locations of structures at Acadia National Park on Mt. Desert Island and Schoodic Peninsula	28
Figure 5. Setting of structures at Acadia National Park.....	29
Figure 6. Acadia, showing Sand Beach, looking west toward the concrete walkway (left panel) and Wall 16 with angular riprap in the foreground contrasting with the gravel beach in the background (right panel).....	30
Figure 7. Setting of Salem Maritime, Saugus Iron Works and Boston Harbor Islands in eastern Massachusetts	32
Figure 8. Salem Maritime National Historical Park. Left panel shows structures evaluated in text and Appendix A, Table 2.....	33
Figure 9. Saugus Iron Works National Historic Site.....	35
Figure 10. Setting of Boston Harbor Islands. Source: US Fish and Wildlife Service, National Wetlands Inventory Program.	36
Figure 11. Setting of structures at Boston Harbor Islands National Recreation Area.	38
Figure 12. Riprap of Lovells Island Wall 1, protecting the east-central portion of the island (Figure 11C)	39
Figure 13. Thompson Wall 1 (Figure 11E), showing greater erosion on the unprotected bluff on the south (right) side of the wall than on the bluff landward of the wall.	41
Figure 14. Locations of shore protection structures at Cape Cod National Seashore.....	43
Figure 15. Fire Island National Seashore, showing the regional setting and locations of detailed views of shore protection structures portrayed in Figure 16.	45
Figure 16. Structures evaluated at Fire Island National Seashore.....	47
Figure 17. Eroding shore east of Sailors Haven Marina Wall 1b, Figure 16B, showing beach transgressing the marsh (far right) and undermined trees falling onto beach (center background).	48
Figure 18. Sagamore Hill National Historic site, showing the relatively great distance of fixed infrastructure from the shore (left panel) and the lack of erosion of the upland landward of the spit and marsh (right panel).	49

Figures (continued)

	Page
Figure 19. Setting of the units of Gateway National Recreation Area. Rectangles identify panels in Figures 20, 22 and 25.	50
Figure 20. Structures evaluated at the Jamaica Bay Unit, Gateway National Recreation Area.....	52
Figure 21. The evolving beach north of Ranger Road, showing the degraded bulkhead (Wall 4) and rip-rap that are interfering with exchanges of sediment and biota across the intertidal zone.....	53
Figure 22. Structures evaluated at the Staten Island Unit, Gateway National Recreation Area.....	56
Figure 23. Eroding bluff at Battery Hudson, Staten Island Unit, showing protection provided by gravel at the base and delivery of sediment from the bluff face.....	58
Figure 24. Deteriorating bulkhead near center of Wall 8, Great Kills Park area, Staten Island Unit.....	59
Figure 25. Structures evaluated at the Sandy Hook Unit, Gateway National Recreation Area.....	60
Figure 26. Structures and environmental resources at Walls 14 and 15, north of Spermacetti Cove, Sandy Hook Unit (modified from Nordstrom and Jackson (2014).	63
Figure 27. Setting of Assateague Island National Seashore. Rectangles identify panels in Figure 28 depicting sites in the northern section of the park.	64
Figure 28. Structures evaluated at Assateague Island National Seashore.....	67
Figure 29. Causeway 1, High Winds area, Assateague Island, looking west, showing the expanse of water to the south and the parallel ditches created by mining sediment to build up causeway height.	68
Figure 30. Setting (left panel) and structures evaluated (right panel) at Fort McHenry National Monument.	70
Figure 31. Wall 1, near the southern portion of Fort McHenry.	71
Figure 32. Setting (left panel) and visitor center (right panel) at George Washington Birthplace National Monument.....	72
Figure 33. Location of places linked by Colonial Parkway (black dots) and panels (rectangles) identifying structures in Figure 35.	73
Figure 34. Colonial Parkway on the York River side, showing proximity to the water.	74
Figure 35. Locations of shore protection structures at Colonial National Historical Park	76
Figure 36. Bluff at the mouth of College Creek (Figure 35B), revealing the kinds of habitats that would form if static structures were removed from uplands along the shore.....	78

Figures (continued)

	Page
Figure 37. Offshore breakwater fronting marsh in the undeveloped portion of Jamestown Island southwest of Wall 5 (Figure 35A).....	79
Figure 38. Bulkhead (southeast portion of Wall 6) protecting low grassy area landward of causeway to Jamestown Island in a location suitable for future marsh development.	81

Tables

	Page
Table 1. Establishment year, missions and characteristics of coastal parks in the Northeast Region of the National Park Service. ^A	6
Table 2. Definitions of coastal engineering terms used to identify structure type, modified from Allen (1972).	10
Table 3. Decision support criteria for deciding whether to retain protection structures or to consider removing them or letting them degrade.	12
Table 4. Number (N) and length (L) in meters of shore protection structures within Northeast Region coastal parks.	22

Appendices

	Page
Appendix A: Characteristics of shore protection structures evaluated for removal	99
Appendix B. Evaluation of structures at Fort Monroe National Monument.....	137

Executive Summary

Increases in sea level, intensity of storms and coastal erosion are expected in the future in many locations. Removing the barriers that shore protection structures create between coastal and upland habitats would reestablish exchanges of sediment and the ecological functions of the natural ecotone. The potential for removing shore protection structures or allowing them to deteriorate was evaluated in 12 national parks managed by the U.S. National Park Service (NPS). Criteria for potential removal included condition of structures, influence of natural processes following removal, environmental benefits and public safety, access and use.

A total of 407 individual structures provide at least some obstruction to natural reworking of coastal formations by waves and currents in 10 of the 12 parks. Reasons for not suggesting removal of structures were many and varied, but they can be synthesized into six general categories, including (1) threat to a bridge or key park resource (cultural, historical or recreational) that is not easily moved (23.3%); (2) threat to a road that is historic or difficult to relocate (15.5%); (3) threat to features outside park jurisdiction (19.4%); (4) limited potential for new habitat to form because of lack of space landward (22.8%); (5) limited effect on landforms that already exist because the structure is raised (e.g. pier) or is a protection structure of similar rock type to formations landward of the protected infrastructure (13.6%); and (6) potential for pollutant release (landfills) or difficulties obtaining a permit for structures in water (5.3%).

We suggest that 145 structures could be removed or allowed to deteriorate, although we acknowledge that many of these would be initially controversial. Our suggestions are based on a reconnaissance level investigation of all parks and could be different from local managers, operating under existing guidelines and making use of more detailed local knowledge and evolving plans for management. The structures are in Boston Harbor Islands National Recreation Area, Cape Cod National Seashore, Fire Island National Seashore, Gateway National Recreation Area, Assateague Island National Seashore and Colonial National Historical Park. No structures are suggested for removal in Acadia National Seashore, Salem Maritime National Historic Site, Saugus Iron Works National Historic Site, Sagamore Hill National Historic Site, Fort McHenry National Monument and Historic Shrine and George Washington Birthplace National Monument. Reasons for suggesting removal were varied, but synthesized into four general categories, including (1) protecting removable but functional facilities, including roads (14.2%); (2) protecting buildings and infrastructure no longer in active use (37.5%); (3) fronting land with limited facilities (e.g. trails, campsites) and having space and sediment sources favoring ready development of landforms (21.4%); and (4) in locations where the protection structures have no clear value, e.g. backed by other, more effective, protection structures or having no facilities landward (26.8%). Protection structures are in no better than fair condition or are in poor condition in 77% of the locations where removal was suggested.

Adaptation plans can be broadly characterized by three approaches: defend, elevate, or retreat. We highlight three adaptation projects involving retreat that are currently being planned or conducted in coastal parks. These projects show great potential, although they are limited in size. They include (1) moving user facilities farther landward and building them in way that facilitates future relocation; (2)

removing bulkheads to allow beaches to become more self-sustaining; and (3) abandoning roads and building new ones farther landward with erodible, temporary surfaces in anticipation of future retreat.

The number of projects involving actual retreat by removing shore protection structures (rather than allowing them to deteriorate) is limited. Reasons for not taking a more pro-active approach to removing structures include (1) conflicting policy directives; (2) presence of key access roads and critical archaeological and historic sites; (3) lack of data; (4) lack of funds and human resources; (5) reluctance to replace known problems with an unknown set of problems; (6) consideration of visitor desires; and (7) reluctance to allow erosion to occur. Many of the protection structures and the facilities they protect are classified as contributing resources. The importance of a contributing resource may have to be reevaluated in light of policy changes and the increasing difficulty of protecting resources in the coastal zone against future sea level rise. Priorities are changing and will continue to change in the future. Demonstration projects are needed to provide information about adaptation strategies that promote enhancement of ecosystem functions. Projects to remove protection structures are most likely to be viewed as successful if results are specified as a positive product, and the distinction between the concept of loss (erosion of existing landforms and habitats) and the concept of gain (evolution of new landforms and habitats associated with the provision of sediment and space) is made clear.

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Introduction

The global issue

Shore protection structures are ubiquitous on many shores throughout the world. These structures range from small to massive and old to new, and they often reveal a sequence of implementation, with older, smaller structures being replaced by newer, more massive structures. In some cases, older structures are left to deteriorate when changes in land use practice or cost of new structures makes repair or replacement impractical. Many scientists, managers and planners argue that fixed shore protection structures are detrimental to natural resources because they restrict movement of sediment and biota, truncate or eliminate beaches, dunes, bluffs and marshes, decrease resilience of natural systems and restrict future management options (Pilkey and Wright 1988; Defeo et al. 2009; Dugan et al. 2008, 2011). Greater dynamism allows landforms and habitats to undergo cycles of change that retain diversity and complexity and increase resilience (Doody 2001; Larsen et al. 2006; Larsen et al. 2007; Arens et al. 2013; Walker et al. 2013). Accordingly, emplacement of new structures has been restricted in several jurisdictions (Platt et al. 2002; Kelley 2013), and some structures are being removed in others. Removal occurs mostly on low energy coasts to restore natural environments farther landward in managed realignment projects (French 2006; Garbutt et al. 2006; Rupp-Armstrong and Nicholls 2007) or less commonly to create beaches as recreational amenity and spawning sites (Zelo et al. 2000; Hummel et al. 2005; Toft 2013). Increases in sea level, intensity of storms and the potential for accelerated coastal erosion are expected in the future in many locations (Stocker et al. 2013; FitzGerald et al. 2008), placing increased emphasis on finding ways to adapt.

Adaptation to change may be a global and long-term issue, but it is an issue that can best be facilitated by local actions that begin now. Widespread removal of protection structures that still perform their intended purpose is unlikely, but many structures have degraded and can no longer perform their design function (Nordstrom 2014). These structures can include those that (1) were initially well designed but have exceeded their useful lives; (2) were under-designed and quickly failed (Jackson et al. 2006); or (3) became unnecessary due to changes in land management, such as where military bases were converted to park lands (Nordstrom and Jackson 2013). Eliminating the barrier that structures have created between coastal and upland habitats would permit reestablishing the natural ecotone, ecological functions, and exchanges of sediment between these two environments.

Potential actions by the National Park Service

This study is an evaluation of the potential for removing shore protection structures or allowing them to deteriorate in place to allow natural shoreline processes to prevail as part of an adaptation strategy to future sea level rise. The study was conducted in 13 units of the National Park System managed by the U.S. National Park Service (NPS) in their Northeast Region (Figure 1). Fort Monroe National Monument is still in the formation stages, so evaluation of that park took the form of a reconnaissance survey and is reported only in Appendix B. The parks differ in purpose of establishment, physical setting, biological conditions, cultural resources, levels of human development, modes and intensities of access, management focus, and interests of visitors and external stakeholders.

The study procedure included (1) identifying all structures within park boundaries that represent human-caused barriers to sediment exchange and habitat migration associated with landform change; (2) determining the current function of each structure in protecting a natural or cultural resource; (3) identifying opportunities to facilitate migration of landforms and their associated habitats by removing or altering the structures; (4) prioritizing structures that can be removed without threat to critical infrastructure; and (5) evaluating existing adaptation plans. The results are presented in three sections, including (1) an overview of the inventory of structures in all twelve parks; (2) the way adaptation is being addressed in three parks; and (3) detailed evaluation of conditions in each park. The results are then discussed in terms of impediments to adapting by managed retreat, and tradeoffs between removing protection structures and allowing them to deteriorate.

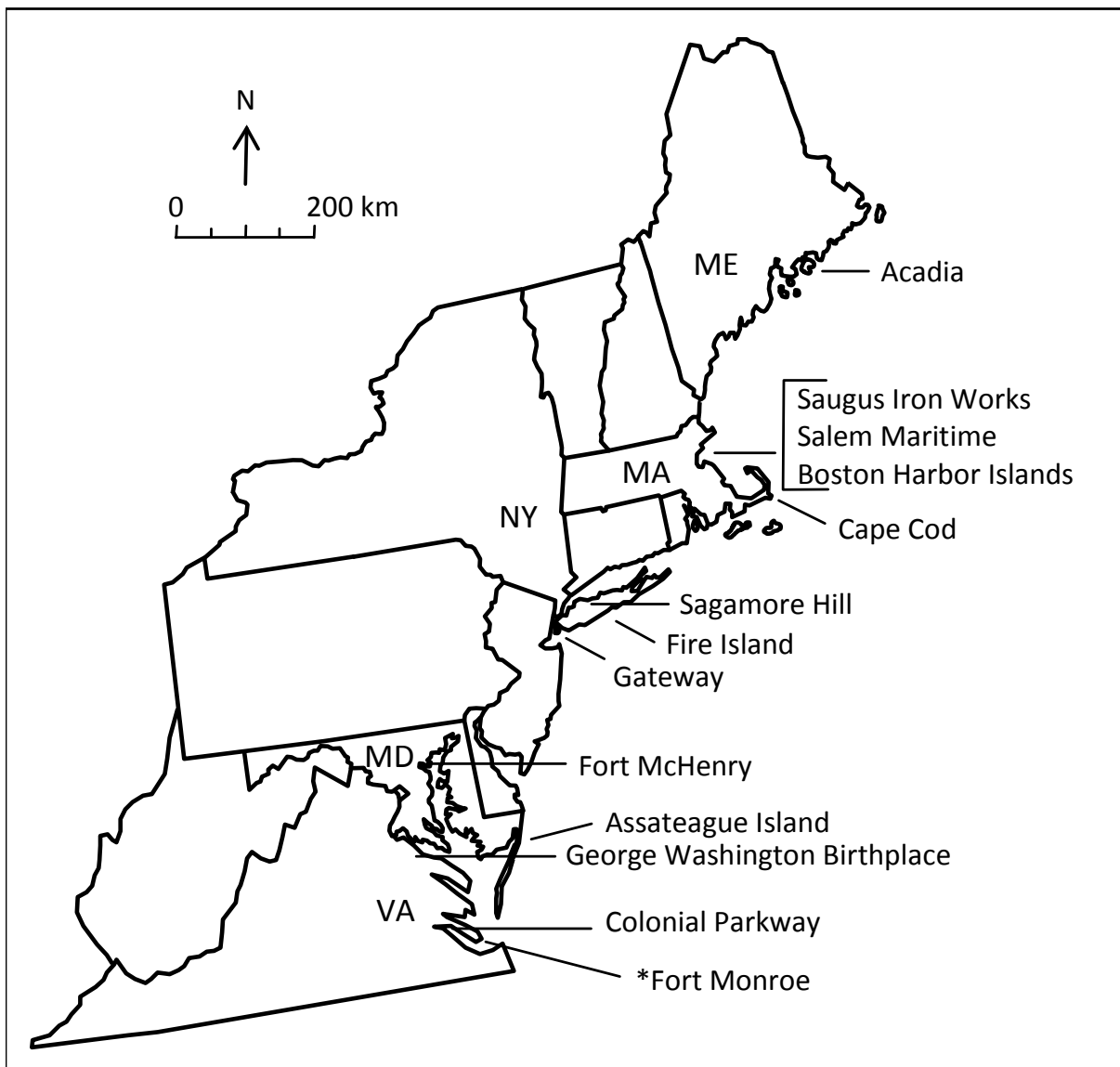


Figure 1. Location of coastal parks in the Northeast Region of the National Park Service. *Fort Monroe National Monument was included after this project began and is discussed only in Appendix B.

Criteria used to identify potential structures for removal were adapted from a pilot study conducted at the Sandy Hook Unit, Gateway National Recreation Area (Nordstrom and Jackson 2013) and include (1) type of natural processes that would influence evolution of landforms and habitats following removal; (2) potential environmental benefits of future migration of habitat that will outweigh detrimental effects; (3) potential effect on adjacent habitats landward and alongshore; (4) natural barriers to migration, such as steep topography; (5) potential public safety benefits or hazards; (6) visitor access and use; and (7) value in demonstrating how the concept of adaptation in response to sea level rise can provide planners with useful information. This study was concerned with only the present and future condition of coastal structures, so the years of construction, maintenance, cost or original reason for the projects were not assessed.

Study sites and policy framework

Coastal parks on the northeast coast of the USA are located near or within urban and suburban lands. The twelve coastal parks have different designations, based on somewhat different missions, and they exhibit great variability in physical characteristics and cultural features (Table 1). Saugus Iron Works, Fort McHenry, George Washington Birthplace and Colonial are totally within estuaries. The other sites have sizeable proportions of their shorelines in estuaries or bays, but all sites differ in their degree of wave exposure. Maximum fetch distance for wave generation at Saugus Iron Works is just over 300 m but over 20 km within the estuaries at Colonial and Gateway. Portions of Acadia, Boston Harbor Islands, Cape Cod, Fire Island, Gateway and Assateague Island have shoreline segments that are directly exposed to ocean waves and currents.

Erosion rates can be up to or greater than 2 m yr^{-1} in portions of parks, including Cape Cod, Fire Island, Gateway and Assateague Island (Hammar-Klose et al. 2003; Pendleton et al. 2004a, b, 2005). Relative rates of sea level rise in the recent past are $3.88 \pm 0.15 \text{ mm yr}^{-1}$ at Sandy Hook in Gateway (Pendleton et al. 2005), $2.65 \pm 0.10 \text{ mm yr}^{-1}$ in Boston Harbor (Hammar-Klose et al. 2003), and at least $3.16 \pm 0.16 \text{ mm yr}^{-1}$ and $2.58 \pm 0.19 \text{ mm yr}^{-1}$ at stations near Assateague Island and Fire Island (Pendleton et al. 2004 a, b). Rates of rise on the northeast coast of the USA are projected to increase in the future (Boon 2012).

Resources in the parks that received protection in the past include cultural features (historic buildings, forts and bunkers, archeological sites) and infrastructure for visitor services (roads, visitor centers, parking and picnic areas). Threats to existing resources vary in scale and importance, from erosion of earthen access paths and picnic areas that can be easily relocated, to erosion of large scale water treatment facilities (Harbor Islands and Gateway) and private homes adjacent to park boundaries. Levels of human development vary from isolated visitor facilities occupying only a small proportion of a park (Acadia, Cape Cod, Fire Island and Assateague Island) to nearly complete conversion to a human-modified landscape in small parks in urban areas (Salem Maritime, Fort McHenry). Many past modifications were made to enhance access, including construction of roads accompanied by diversion of stream flows and filling of marshes to facilitate construction. Access roads are common near the shore in most parks and are designated as key cultural/historical resources in their own right at Acadia (carriage roads) and Colonial (the Parkway). Boston Harbor Islands and Gateway have many military structures that no longer serve their original purpose and are in disrepair, although many are valued historic resources. Other former military structures in these parks and at Fort McHenry are well used by park visitors. Shore protection structures in Boston Harbor Islands and Gateway were emplaced as early as the 19th Century (Coburn et al. 2010; FitzGerald et al. 2010; Dallas et al. 2013b). Naturally-functioning shoreline without shore protection structures does not exist at Fort McHenry and consists of only a 50 m segment of beach at Salem Maritime. In contrast, Assateague Island and Fire Island have ocean shorelines extending more than 60 km without shore protection structures.

Table 1. Establishment year, missions and characteristics of coastal parks in the Northeast Region of the National Park Service.^A

Park and Date	Abbreviated mission statement	Setting	Defining cultural resources in park
Acadia National (Natl.) Park (1919)	Protect and preserve outstanding scenic, natural, scientific and cultural values.	Rocky islands with steep slopes and varying exposures to ocean waves; gravel beaches, one sand beach.	Shorefront road providing access and scenic views.
Salem Maritime Natl. Historic Site (1938)	Promote maritime history and preserve part of the historic waterfront in Salem.	Low upland adjacent to urban harbor with houses and roads immediately adjacent.	Historic buildings and wharfs near urban development.
Saugus Iron Works Natl. Historic Site (1968)	Preserve the first sustained integrated iron works in the thirteen colonies.	Upland with tidal creek within suburban development; wave energy minimal.	Historic buildings near suburban development.
Boston Harbor Islands Natl. Recreation Area (1996)	Preserve lands and waters; improve access by water transport; increase appreciation of natural and cultural resources.	Drumlins and bedrock islands with spits in an embayment exposed to ocean and locally-generated bay waves; gravel/sandy beaches.	Former military structures with historic value, but many presently unused; lighthouses; many piers used for access to islands.
Cape Cod Natl. Seashore (1971)	Preserve seashore; restrict incompatible visitor conveniences; provide for public use and understanding.	Eroding glacial and glacio-fluvial deposits, with accompanying sandy beaches and dunes.	Parking lots and bathhouse.
Fire Island Natl. Seashore (1964)	Conserve and preserve beaches, dunes, and other natural features near urban area.	Sandy barrier island, with naturally functioning segments separated by numerous developed enclaves.	Marinas for boat access; bulkheads at marinas and adjacent developed enclaves.
Sagamore Hill Natl. Historic Site (1963)	Preserve the Theodore Roosevelt home and interpret his life and accomplishments.	Upland composed of glacial deposits adjacent to narrow bay.	Historic structures, not threatened by coastal processes.
Gateway Natl. Recreation Area (1972)	Preserve and protect an area possessing outstanding natural and recreational features.	Sandy barrier, upland (often artificial fill) with variable exposure to ocean and bay waves and urbanization.	Many historic buildings and fortifications; intensive recreation near urban development.
Fort McHenry Natl. Monument and Historic Shrine (1925 ^B)	Preserve natural and cultural resources and foster appreciation of events surrounding the national anthem and flag.	Landscaped upland adjacent to urbanized harbor.	Historic fort near urban development.
Assateague Island Natl. Seashore (1965)	Protect and develop Assateague Island and adjacent waters for outdoor recreation use.	Sandy barrier island, largely undeveloped.	Parking lots, campgrounds, remnant human-created causeways.
Geo. Washington Birthplace Natl. Monument (1930)	Preserve and interpret the history and resources associated with George Washington.	Upland adjacent to Potomac River and a tributary forming a small embayment.	Historic structures and grounds not threatened by coastal processes.
Colonial Natl. Historical Park (1930)	Preserve the historical structures and remains for the benefit and enjoyment of the people.	Eroding low upland and marsh adjacent to wide tidal streams.	Shorefront road providing access and scenic views; archaeological and historic sites of national interest.

^A Sources: US Code; park management plans and administrative histories.

^B Transferred to the Park Service under Executive Order 6166, signed 10 June 1933. (Source: New South Associates, 2013.)

NPS management policies (NPS 2006) acknowledge the tradeoffs involved in allowing natural processes to prevail where erosion or flooding threatens cultural resources. Natural shoreline processes will be allowed to continue without interference, and measures to protect cultural resources may be approved only after an analysis of the effect on natural processes and resources is made. New developments cannot be placed in areas subject to active shoreline processes unless the development is required by law, essential to meet the park purposes, can survive without needing erosion control measures and minimum harm will occur to property and natural resources. Intervention against natural processes is permitted in emergencies that threaten human life or property or if there is no other feasible way to protect natural resources, park facilities or historic properties. Archeological resources are to be managed *in situ* unless removal is justified for their preservation. These resources should be stabilized using the least intrusive and destructive methods that will protect natural processes and resources. Historic structures of less-than-national significance may be moved, providing that efforts are made to reestablish their historic orientation, immediate setting and general relationship to their environment. Data that would be lost as a result of uncontrollable degradation is to be preserved in park museum collections. Significant physical attributes are to be preserved if they contribute to historical significance (NPS 2006).

Future outcomes of climate change have the potential to cause an increased magnitude of change in natural and cultural resources that will lead to greater complexity in conflicts among resources and choices of solutions. Adaptation to climate change has been promoted as a management strategy to increase ecosystem resilience (NPS 2010), and memoranda on climate change have been introduced recently by the NPS Director (NPS 2012, 2014a, 2015) to better define the agency role in adaptation.

Methods

Structures restricting shoreline change and characteristics of natural and cultural resources landward of them were identified and measured using existing aerial photos. Each park was then visited to verify data from photos and to interview managers about plans to remove protection structures or build new ones and about attitudes about adapting to sea level rise. Inventories of engineering projects were conducted in Boston Harbor Islands National Recreation Area, Fire Island National Seashore, Gateway National Recreation Area, Colonial National Historical Park and Assateague Island National Seashore in previous inventories of coastal engineering projects (Coburn et al. 2010; Dallas et al. 2013a,b; Schupp and Coburn 2015). Our study (here called the Migration of Habitats Study) makes use of some of the data from those studies, especially Dallas et al. (2013a,b). The Assateague Island study (Schupp and Coburn 2015) was completed after our assessments were made. The structures identified by Dallas et al. (2013a,b) are reported using their numbering system (preceded by the letters CEI) as well as our system in Tables 7,8,9 and 12 in Appendix A.

ESRI ArcMap 10.2.2 computer software and data sources were used to digitize structures for each park within the digital park boundary shapefiles downloaded from the National Park Service Integration of Resource Management Applications (NPS IRMA) and georeferenced digital orthophoto imagery (ESRI ArcGIS basemap, 2011 Bing Maps layer). Bing Maps Aerial was chosen because it is readily available to everyone with access to ArcGIS. Google Earth imagery was used to aid in the identification of structures or habitats. Only hard shore protection structures, buildings, roads and causeways within park boundaries were identified. Bridges were excluded because they are elevated above the water and do not greatly interfere with the natural movement of water or sediment. The NPS Facilities Management Software System and Archaeological Sites Management Information System were not used for identifying information, so the data and analysis could be independent of existing systems. These databases will be internally important for cultural resource and facility management staff within the NPS.

The presence of a structure was identified on maps, GIS files or photos using the overall shape, color, and location of the structure as cues. Only intact structures above the water surface and not covered by vegetation or sediment were identified. Structures were designated as distinct if they had dissimilar impacts on shoreline processes and sediment transport. Examples include revetments separated by gaps or a groin attached to a revetment. Conversely, a revetment composed of rocks or concrete blocks (riprap) fronting a cement seawall was designated as one structure because the combined wall protects the same length of shoreline and decisions for removal would include all components. Groins and breakwaters built as a series of structures were identified as groin fields and breakwater series rather than as individual structures.

Attributes of each structure include location, type, construction material, length, orientation relative to the shoreline, condition, landuse within 50 m of the structure, priority for removal, landform characteristics and rationale for removal priority. The type of structure was classified as wall, dike, groin, jetty, breakwater, pier, causeway, wharf or ramp (Table 2). Shore-parallel structures separating land and water were collectively termed “walls” because intact walls have a similar effect

on the landscape landward of them. The effects of deteriorated walls vary, so a distinction between wooden and steel bulkheads and rock and concrete seawalls and revetments was made for selected sites where removal was an option. In a few places, coastal erosion has exposed buildings and roads that now interfere with waves and currents and thus function as shore protection structures. These structures are identified as walls because of their present function. Causeways protected by walls are identified as walls. This designation corresponds to the terminology in the inventories used by Dallas et al. (2013a,b), which focused on the shore protection structures rather than the facilities they protect. Causeways built of earth and not protected by hard structures are identified as causeways.

Orientation to the shoreline was easily determined for breakwaters, jetties, groins, and walls. The orientation of dikes and causeways that were more oblique to the shore, and piers composed of shore-parallel and shore-perpendicular segments was sometimes more difficult and was based on whether the longest dimension was oriented alongshore or across the shore. Condition of each structure was described as good, fair, or poor. Good means the structure appears complete with no apparent gaps or holes or that rip-rap is coherent with no stray boulders. Fair means mostly intact, but with small gaps or holes in bulkheads or stray boulders surrounding rip-rap structures. Poor means many gaps and holes or little left of the original structure.

Table 2. Definitions of coastal engineering terms used to identify structure type, modified from Allen (1972).

Term	Definition
Wall	Shore-parallel structure (seawall, revetment, bulkhead) separating land and water, and designed to protect a shore from erosion.
Groin	Shore-perpendicular structure built to trap littoral drift.
Breakwater	Shore-parallel structure that protects a shore by reducing wave energy.
Dike	Wall or mound built around a low-lying area to prevent flooding.
Jetty	Structure extending into a body of water, designed to prevent shoaling of a channel by littoral materials and to direct and confine the tidal flow.
Causeway	Raised road that prevents flows across wet or marshy ground or between water bodies.
Pier	Structure, usually on pilings, extending into the water to serve as a landing place or recreational facility.
Wharf/ramp	Structure, usually not on pilings, extending into the water or alongshore to serve as a landing place.

Many judgment calls are required in the process of identifying what to call a structure or how to determine its length (especially after its original function has changed). A bulkhead remnant that functions as a sill at the new low-water line can be defined by its initial design or its current function. Our inventory was more concerned with current function than the specific terminology used for the initial design. The length of a deteriorated seawall can include the entire length as originally built or the length that still functions as designed. The length associated with structures built in a series

alongshore (e.g. groins and breakwaters) can be measured in terms of the individual or cumulative length of the structures themselves or in terms of the total length of shoreline that falls within the longshore limits of the series of structures. Dallas et al. (2013a,b) identify the length of each structure, whereas we use the length of shoreline that extends along the series of structures. Our rationale is that if decisions are made to remove structures, the decision should normally be applied along the entire segment.

Some structures have deteriorated to the extent that they may be invisible on aerial photographs or even inconspicuous during the site investigations. These structures are not included in our assessment. Managers in each park will be aware of small, buried or submerged structures that are not included in the inventory presented here, but the concepts for addressing future actions at the structures that are included in this report should help inform management decisions for structures that are not included.

Visits to parks provided information on (1) manager attitudes about removing structures, given the mission of each park and the concerns of local stakeholders; (2) insight to local conditions for structures that looked like the strongest candidates for removal based on analysis of aerial photos; and (3) evidence of erosion in presently unprotected areas that could threaten fixed facilities in the future and thus result in demands to employ new protection structures. Meetings were held with NPS representatives in each park (the chief resource management specialist in large parks) and whomever that person suggested, including park superintendents, GIS specialists and maintenance personnel. Sites in large parks were visited by vehicle; sites in smaller parks were evaluated on foot; visits to selected structures on the Boston Harbor Islands were conducted by boat. Visits were made to Acadia National Park 20-21 November 2013; Boston Harbor Islands 12 July 2013 and 7 August 2014; Saugus Iron Works National Historic Site and Salem Maritime National Historic Park on 18 March 2013; Cape Cod National Seashore on 1 August 2013; Fire Island National Seashore on 9 July 2013; Sagamore Hill National Historic Site 18 September 2014; Gateway National Recreation Area on selected days in January, May and June 2011, July 2013, and September 2014; Assateague Island National Seashore 12 February 2014; Fort McHenry National Monument 11 November 2012 and 25 March 2015; George Washington Birthplace National Monument 10 November 2012 and 26 March 2015; and Colonial National Historical Park 8-9 November 2012 and 28-31 May 2013. Site visits could not be made to every structure in all parks, so structures that appeared to be the most likely candidates for removal were targeted.

Priority for removal of a shore protection structure is described as low, medium, or high based on current condition, effect on flow of water or sediment, feasibility of removal, and presence of culturally important features landward. Culturally important features include paved access roads and buildings currently in use and historically important buildings or remnants. We make reference to historic value or interest, but we do not tie the structures discussed with the historic districts, or to their nominations or what is listed as a contributing resource (i.e. a building, site, structure or object adding to the historic significance of a property). The potential to create new natural habitat after removal of a protection structure was also considered. If a known culturally important feature is located within 50 m of a protection structure, the priority was considered “low” regardless of the

potential for new habitat creation. In many cases, the structures had deteriorated to the point where they did not interfere with natural processes although construction materials remained on site. In these cases, the removal priority was identified as “low” but the suggestion was “let deteriorate,” i.e. allow to degrade. Inevitably, removing a structure or allowing it to deteriorate could have similar effects on reestablishing coastal landforms, although aesthetics and safety issues could differ.

Information on building identification and current usage was gained from the National Park Service website and/or NPS IRMA whenever possible. Assigning priority for removal required collaboration with park personnel from all disciplines (e.g., natural and cultural resources, facilities and facilities maintenance). Comments by NPS personnel about stakeholder interests outside the park units were also included. Prioritization was a complex process, but was assisted by a framework developed to provide consistent decision-making criteria (Table 3). The decision-making criteria are meant to be generic, not specific and definitive. For example, the application of these criteria is based on the information and technical expertise available. Decisions about structures and the consequences of removing them represent a consensus of the two authors of this report. The emphasis of the study was on evolution of landforms and habitats after removal of structures. Potential scenarios of change are based on informed opinion, rather than intensive modeling, given the need to inventory hundreds of structures at reasonable cost. Suggestions of the authors on this reconnaissance level investigation of all parks could be different from local managers, operating under existing guidelines and making use of more detailed local knowledge and evolving plans for management.

Table 3. Decision support criteria for deciding whether to retain protection structures or to consider removing them or letting them degrade.

Factor	Not favoring removal	Favoring removal/degradation
Buildings/infrastructure landward that are presently in use.	Buildings/infrastructure are outside parks or not easily movable and are place- or water-dependent; space for new habitat is limited.	Buildings/infrastructure movable; space available for relocation; opportunity for successful restoration of natural habitat.
Buildings/infrastructure landward are not in use.	Structure has clear historic value; permits for removal difficult to obtain.	Habitat or historic value unknown or unclear or not constrained by site-specific location.
Availability of space landward.	Little space for new habitat or its ability to migrate through time.	Space for restoration or evolution of water-dependent habitat is available.
Nature of coastal formations.	Toxic fill that is difficult to remove; steep slopes or bedrock that limit evolution of landforms; erodible substrate fronting key infrastructure.	Low land with space and unconsolidated sediment sources favoring ready development of new landforms and habitats.
Construction material of protection structure.	Environmentally-benign chemically; not a safety hazard; massive structure that is difficult to move or porous structure that does not restrict water/sediment flows (e.g. pier).	Material toxic to flora/fauna or favored by invasive species; safety hazard for humans; material is of high quality and can be reused elsewhere.
Significance of existing landforms and habitats.	Existing landforms and habitats are similar to what would occur if structure is removed.	Existing landforms and habitats are truncated, unable to migrate or not native.
Ease of obtaining permission and removing structures.	Economic cost high; environmental assessment challenging.	Small, easily moved components; clearly demonstrated environmental advantages.

Table 3 (continued). Decision support criteria for deciding whether to retain protection structures or to consider removing them or letting them degrade.

Factor	Not favoring removal	Favoring removal/degradation
Stakeholder concerns.	Stakeholders have commercial/legal interests that would be threatened and could not be compensated; visitor access not threatened.	Concerns not based on commercial or legal interests or water-dependent uses; concerns are based on convenience or past precedent and not on current/future needs.

Relationship of present study to NPS Coastal Engineering Inventories

Overlap occurs between the methods used in this project and the Coastal Engineering Inventories conducted in Colonial National Historical Park and Gateway National Recreation Area presented in Dallas et al. (2013a,b) and in Boston Harbor Islands, Fire Island and other parks outside the northeast presented in Coburn et al. (2010). Similar data sources and ArcMap computer software are used, with ArcMap 10.2.2 version used to complete this study. The data include digital park boundary shapefiles downloaded from the National Park Service Integration of Resource Management Applications (NPS IRMA) and georeferenced digital orthophoto imagery (ESRI ArcGIS basemap, 2011 Bing Maps layer). The underlying goals of the projects are not identical. One major difference is the inclusion of dune building and dredge and fill projects in the other inventories. Dallas et al. (2013a,b) provided background related to the structures, including year of construction, year(s) of maintenance, initial reason for project, cost of construction and construction agency. Their numbering system for structures is included in our report (with the letters CEI before the numbers). Coburn et al. (2010) also identify years of construction and cost. The focus of our study is not the data base as an end in itself but as a basis for making suggestions about what should be done with the protection structures in the future in terms of implications for the use of land now protected by the structures. Thus, buildings, roads, cultural features, landforms, land use and vegetation within 50 m landward of the structure are identified here as well as rationale and priority for removal. Our emphasis on future management actions and their potential consequences required a more theoretical, prospective approach than in the previous engineering inventories, aided by reference to the social science literature and conceptual models of coastal change from the geomorphic and ecological literature.

Only visible remaining portions of structures are identified in the present project, whereas Dallas et al. (2013a,b) mapped the extent of the structures at the time of their initial emplacement. Structures were designated as being distinct in their project if there was a physical separation between them (e.g. individual groins or portions of the same bulkhead separated by gaps). Separated units of the same structure are often treated as one structure in our study because the management suggestions apply to the entire reach that is protected. For example individual groins are grouped as a groin field because of the need to consider the regional sediment budget in management decisions. We did not include structures that front shores managed by entities other than NPS, such as the structures on Coast Guard land at Sandy Hook that are included in the inventories in Dallas et al. (2013a,b) and the numerous bulkheads in the communities on Fire Island in Coburn et al. (2010).

The terminology for some protection structures may differ in the projects because the differences between a seawall and revetment are blurred, especially in non-engineered or deteriorated features, and the distinction between sills and breakwaters is often subject to interpretation. The tables for structures in Gateway National Recreation Area and Colonial National Historical Park in this report use the identification numbers in both inventories to facilitate comparison between data sets, but the numbers and dimensions of structures may differ because of the differences identified in the paragraph above.

Projects in lands adjacent to parks are not assessed in the present project, because removal of these structures is out of the direct control of NPS. Structures outside park boundaries can have significant effect on resources inside parks. For example, about 18% of the 67.3 km-long bay shore of Fire Island is protected by 43 bulkhead segments (Nordstrom et al. 2009), but only 7 structures are directly in front of portions of the shore managed directly by NPS. Removal or deterioration of these other structures would have important effect on NPS resources, but their removal is unlikely and conclusions about their effect would be too speculative.

The case for coastal erosion

Shore protection structures in coastal parks managed by NPS are most commonly deployed in estuaries, where they have severed linkages between beaches and the dunes, marshes and coastal bluffs landward of them. Availability of sediment and space are key elements in sustaining landforms and habitats (Orford and Pethick, 2006; Cooper and McKenna 2008). Shore protection structures truncate the beach profile and interfere with sediment exchanges. Shoreline retreat and availability of sediment are highly correlated, placing emphasis on the importance of accommodating erosion. Adoption of any system of working with natural processes will thus require a change in attitude from the prevailing view of coastal erosion as a problem (Cooper and McKenna 2008). Vast amounts of sediment are needed in many locations for restoration of beaches and wetlands under present conditions, and the need will only increase with acceleration of sea level rise (Orford and Pethick, 2006; Morris, 2012; Williams et al., 2012). Supply of sediment under natural conditions occurs through erosion of landforms, and the need for erosion should be highlighted.

Beach and dune erosion

The changes associated with coastal storms are often cyclic, with offshore transport of sediment during storms followed by subsequent onshore transport that replenishes the backshore (Davis et al. 1972). Short-term cycles associated with small storms are so common that the erosion phase is rarely misinterpreted as a permanent loss by shorefront managers. The cycles related to intense storms are more problematic because reestablishment of landscape features would normally occur farther landward, where human facilities are often placed.

Dune erosion by storm waves supplies sediment to the beach and nearshore to partially replenish losses from those environments. Recovery of the backshore after storms provides a source for wind-blown sand for dune building and creates a wider buffer against erosion of incipient dunes by small storms, allowing dunes to grow in their new locations. Beaches and dunes are part of the same sediment exchange system, and dune erosion and rebuilding are cyclic. This cycling of sediment is not associated with shoreline retreat as a result of small storms. Waves from intense storms deliver the sand farther landward, but the sand remains within the coastal system to form new dunes farther inland (Godfrey et al. 1979). This process can occur if accommodation space exists landward and human efforts do not prevent it. Human attempts to restrict overwash by building oversized dunes (essentially dune dikes) using earth moving equipment, vegetation plantings or sand fences and building walls have reduced the likelihood of new washover habitat forming (Elias et al. 2000). Washover habitat has become rare in developed areas, resulting in increased threats to species that make use of it, such as piping plovers (Maslo et al. 2011; Schupp et al. 2013). Walls also restrict beach width, reducing available habitat types and abundance of macroinvertebrates that, in turn, result in habitat loss and reduced prey availability for shorebirds (Dugan et al. 2008).

Marsh erosion

The survivability of marshes depends on their ability to maintain their elevation in the tidal frame and their ability to survive wave attack or re-form afterward. Periodic flooding is required to prevent invasion of upland species and to provide sediment to maintain marsh elevation to allow it to keep

pace with sea level rise. Sediment can come from sources outside the region and be transported by rivers or the sediment can come from local sources, such as overwash, tidal flow through inlets, longshore transport from eroding uplands within estuaries or erosion of the shoreline of the marsh itself. The amount of suspended sediment contributing to marsh buildup under present conditions can be considerably less than in periods of deforestation during earlier settlement stages (Kirwan et al. 2011), increasing the value of present day sediment sources for marsh maintenance.

Wave attack plays a key role in erosion of a marsh margin and the subsequent impact on the sediment budget (Francalanci et al., 2013). Erosion of marsh margins is assumed to be the main mechanism leading to marsh loss in some estuaries (Marani et al. 2011), but this erosion is only one phase of an erosion-progradation cycle that can contribute to relative stability of marshes over the long term. Cycles of erosion and accretion of the marsh edge have been documented in many studies (identified in van der Wal et al. 2008). Vertical scarps and slump blocks in depositional landforms are commonly seen as diagnostic evidence of erosion, but this is often only one stage in a cycle. Sediment can accumulate in the depressions landward of slump blocks fronting marshes. This sediment and the vegetation that subsequently grows on it are protected from wave erosion by the slump block (Gabet 1998). Eroding marshes can have conspicuously greater sediment entrainment rates than expanding marshes (Callaghan et al. 2010), and remobilization of marsh fronts by wave erosion can contribute sediment that can then aid vertical growth of marshes, thereby helping marshes keep pace with relative sea level rise (Rizzetto and Tosi 2011; Xie et al. 2013).

A marsh system can be considered a volume of sedimentary material and not simply a surface of accumulation (van Proosdij et al. 2006; Friess et al. 2012). The case is rarely made for allowing marsh fronts to erode, despite the value of the released sediment. Structures can be built to restrict marsh erosion, such as the breakwaters and sills on the east end of Jamestown Island (discussed later), but structures are not a substitute for sediment, and a policy of defending marshes against the natural processes that created them is questionable. At issue is whether preventing tens of meters of erosion of marsh fringe by wave attack over the next several decades causes a larger area of marsh to be lost through inundation due to sea level rise.

Bluff erosion

Eroding bluffs are important habitat types that are frequently prevented from evolving by protection structures, except for a few isolated places. These landforms were almost certainly ubiquitous throughout Boston Harbor Islands and Colonial National Historical Park and portions of Gateway, often far earlier than their establishment, including locations where shore protection structures are now considered critical.

Bluffs are not created by coastal depositional processes like beaches, dunes and marshes, but they maintain their unique value as a result of active coastal processes. Erosion of coastal bluffs can be a source of sediment to beaches and nearshores fronting them and downdrift of them (Carter et al. 1990; Dawson et al. 2009; Brooks and Spencer 2010). Eroding bluffs in estuaries supply sediment that can eventually be transported to marshes to build up their surfaces. The sand and gravel that erodes from bluffs creates sand spits that are good intertidal habitat for birds, mussels, and other organisms (Bell et al. 2004), and allow new salt marsh habitat to form behind them (Nordstrom and

Jackson 2013). Recognition of the value of eroding bluffs as sediment sources has increased interest in abandoning protection structures or providing only partial defense and coping with effects of bluff erosion (Brampton 1998; Nordstrom et al. 2007). Bluff erosion may not be a major source of sand in some locations (e.g. Runyan and Griggs 2003), but eroding bluffs still have ecological and aesthetic benefits (Brampton 1998), making them worthy of conservation. Shore protection structures that reduce rates of bluff erosion contribute to establishment of vegetation on bluff faces. This may seem like a positive value, but shore-parallel protection structures decouple beaches from their sediment sources and, as in other coastal locations, place a physical barrier between what would otherwise be two mutually evolving natural habitats.

Coastal bluffs can provide a unique habitat for plants that are tolerant of physical stresses such as salt spray, poor soil and strong winds. Bluffs are a source of groundwater, nutrients, and organic debris and provide critical roosting and nesting habitat for seabirds and cavity- and ledge-dwelling birds (National Research Council 2007). Eroding bluffs often reveal a diverse mosaic of microhabitats in close proximity to each other. Bare surfaces exist in the vertical scarps created by slope failures and the fresh cones of debris below these scarps. The portions of the bluff that remain stable for several seasons can establish a vegetation cover, contributing to surface variety. The vegetation cover and root mass at the top of the bluff can create an overhanging canopy that provides shelter to the upper portion of the bluff and allows access to roots and subsurface characteristics that would not be exposed otherwise. Water table outcrops in the bluff face provide sources of ground water that would otherwise not be available. Digging by fauna creates excavations that provide local patches of moist surface juxtaposed against adjacent dry surfaces.

The texture and color of the patchy microhabitats give eroding bluffs great aesthetic appeal. Risk to upland habitats should be viewed in terms of loss of the naturally functioning ecotone and natural scenic beauty due to placement of a structure at the beach/upland boundary and not just in terms of loss of area of upland that is the traditional rationale for shore protection. It is doubtful that most bluff tops have habitat that is as rare as the eroding face of the bluff itself. The first step in deciding whether to stabilize a bluff should be to determine the potential for moving threatened infrastructure.

Overview of results

Inventory of protection structures

The inventory of protection structures is summarized in Table 4. A more detailed description of the structures is provided in Appendix A, and the rationale for removal of many of these structures is elaborated in the sections devoted to characteristics at individual parks. These data, and maps for parks, are all available online in GIS format at <http://Irma.nps.gov>.

A total of 407 individual structures provide at least some obstruction to natural reworking of coastal formations by waves and currents in 10 of the 12 parks. Boston Harbor Islands and Gateway are both within urban environments and have the greatest number of deteriorated structures. Most of the deteriorated structures in these two parks remain from the period when the parks were managed by the military and considerable time has elapsed since they were constructed. The most common structures are walls (Table 4). These walls are mostly rock riprap or wooden bulkheads, with fitted quarry stone in some of the oldest walls. The greatest length of walls is used to protect roads (especially at Acadia and Colonial) and historic military facilities (at Boston Harbor Islands and Gateway). Groins are common at Gateway. Offshore breakwaters are common at Colonial. This park differs from the other parks in that many breakwaters were built to protect eroding shores that have archaeological resources but no built infrastructure landward.

Most of the structures are in good condition (69.5% of the total); 14.0% are in fair condition; and 16.5% are in poor condition. Many protection structures are in good condition because of the use of stone riprap, which does not degrade rapidly. Some walls protect buildings that are no longer used for their original function, although the buildings may have historical importance. Some walls (e.g. Boston Harbor Islands, Gateway) front artificially filled land that contains waste material that may be toxic. Some deteriorated shore protection structures no longer perform their design purpose but still interfere with wave processes and habitat structure and function across the foreshore. Reasons for not suggesting removal of structures were many and varied, but they can be synthesized into six general categories, including (1) threat to a bridge or key park resource (cultural, historical or recreational) that is not easily moved because of its size or linkage to existing infrastructure (23.3%); (2) threat to a road that is historic or difficult to relocate because of terrain or lack of space (15.5%); (3) threat to features outside park jurisdiction (19.4%); (4) limited potential for new habitat to form following removal because of lack of space, usually caused by an immovable structure landward (22.8%); (5) limited effect on landforms that already exist because the structure is raised (e.g. pier) or it is a protection structure that is of similar rock type to formations landward of the infrastructure being protected (13.6%); and (6) potential for pollutant release (landfills) or difficulties obtaining a permit for structures in water (5.3%).

Table 4. Number (N) and length (L) in meters of shore protection structures within Northeast Region coastal parks. Sagamore Hill and George Washington's Birthplace have no structures affecting shoreline change.

Park Unit Name	Wall ^A		Groin ^B		Breakwater / sill		Pier ^C		Jetty		Causeway / Levee/dike		Structures in fair-poor condition ^D		Structures to remove or deteriorate ^E	
	N	L (m)	N	L (m)	N	L (m)	N	L (m)	N	L (m)	N	L (m)	N	L (m)	N	L (m)
Acadia	17	4201	0	0	0	0	2	118	0	0	0	0	0	0	0	0
Salem	2	1689	0	0	0	0	3	73	0	0	0	0	0	0	0	0
Saugus	3	117	0	0	0	0	1	11	0	0	0	0	0	0	0	0
Boston Harbor Islands	33	17,971	8	1046	1	37	15	1988	0	0	0	0	16	10,016	9	7606
Cape Cod	5	1103	3	87	0	0	0	0	0	0	2	2715	5	687	4	663
Fire Island	3	1502	0	0	1	61	3	259	0	0	0	0	4	220	4	220
Gateway	62	32,187	105	6201	4	582	25	3130	2	1295	0	0	90	14,210	76	8723
Assateague	2	680	0	0	3	165	6	347	1	741	1	837	5	284	5	1096
Fort McHenry	1	1154	0	0	0	0	1	47	0	0	0	0	0	0	0	0
Colonial	17	13,014	0	0	64	3110	11	1525	0	0	0	0	4	3353	47	4943
All Parks	145	73,618	116	7334	73	3955	67	7498	3	2036	3	3552	124	28,770	145	23,251

^A Shore-perpendicular structures at streams that function more as toe protection than traps for alongshore transport are termed walls, not jetties.

^B Groin length and breakwater/sill lengths are cumulative lengths of the structures exclusive of shoreline lengths between structures.

^C Pier length refers to the major portion of the pier, not all perpendicular extensions for individual boats.

^D The entire length of a structure with any portion in fair/poor conditions is suggested for removal because decisions affecting deteriorating portions should be applied to the other portions.

^E Structures suggested for removal include categories of "high or medium priority" or "let deteriorate."

We suggest that 145 protection structures out of the total of 407 could be removed or allowed to deteriorate (Table 4), although we acknowledge that many of these would be initially controversial. Reasons for suggesting removal were also varied, but synthesized into four general categories, including (1) protecting easily removable but functional facilities, including roads (14.2%); (2) protecting buildings and infrastructure no longer in active use (37.5%); (3) fronting land with limited facilities (e.g. trails, campsites) and having space and sediment sources favoring ready development of landforms (21.4%); and (4) in locations where the structures have no clear value, e.g. backed by other, more effective, protection structures or having no facilities landward (26.8%). Protection structures are in fair or poor condition in 77% of the locations where removal was suggested. Removal of structures in good condition (23%) was primarily suggested for locations where the structures interfered with sediment supply or had little effect (e.g. groins in sediment starved areas). Many of the shore protection structures are more than 50 years old and therefore have historic value. We suggested removal of the deteriorated protection structures that have lost their protective function and visual image of their original historical context but not intact structures that protected infrastructure of similar age.

The total length of the structures suggested for removal is over 23 km, and they extend along nearly 26 km of shore (including the lengths of gaps between breakwaters and groins). Shorelines in George Washington Birthplace and Sagamore Hill are unaffected by protection structures. Protection structures in three other historic sites, Saugus Iron Works, Salem Maritime and Fort McHenry, protect cultural features that are the basis for establishment of these parks, and removal is not a consideration. No structures protecting roads were suggested for removal at Acadia National Park and Colonial because the parks were established, in part, to provide longshore access for scenic coastal views. Protection structures are suggested for removal where roads are not required for visitor access, emergency use, or where the roads can be readily relocated inland. Bedrock foundations and steep slopes in portions of Acadia make construction of new roads difficult. Relocation of threatened coastal roads is easier in coastal parks on low-lying sandy formations, although issues of terrestrial and wetland habitat alteration associated with the relocated road must receive careful consideration.

Some structures, such as the dikes crossing salt marshes at Cape Cod have altered wetland conditions. Partial removal of the dikes and installation of water control structures has been determined as the most appropriate approach to restore marsh hydrology and ecological functions of the diked salt marshes (Roman et al. 1995; Portnoy 2012). Complete removal of the dikes would impede the marsh restoration process and threaten infrastructure outside the park with flooding. Removal of some but not all protection structures in a series does not necessarily mean that the landward shore will function naturally (e.g. removing old groins between newer stone groins or removing groins fronting seawalls).

The only relatively new and intact protection structures identified for possible removal are at the Jamestown Island marsh in Colonial (discussed in greater detail below). This portion of the island is undeveloped, but presence or potential presence of Native American archeological sites in some portions of the island led to construction of a series of detached offshore breakwaters and sills as recently as 2002. The breakwaters may reduce erosion rates but also reduce sediment inputs from the

eroding formations. A policy of defending marshes against the natural process of sediment transport contributing to marsh elevation growth and sustainability is questionable. Removal of breakwaters fronting marshes that do not have known archaeological resources landward of them can be given high priority if the breakwaters do not protect park infrastructure, cultural landscapes, or historic structures, and they have changed the scenic character of the coastal landscape.

Bluffs composed of unconsolidated sediment, occurring at Boston Harbor Islands, Gateway and Colonial, have been protected from wave attack by riprap or fitted quarry stone. Eroding bluff faces often reveal a diverse mosaic of microhabitats, with bare partially-cohesive scarps juxtaposed against vegetated remnants on the bluff faces and unconsolidated debris cones at the base (e.g., Himmelstoss et al. 2006). The top of an eroding bluff may have a historic or contemporary structure, roadway, or archaeological site worthy of protection, so the first step in deciding whether to stabilize the bluff should be to determine if there are acceptable alternatives for moving, abandoning, or otherwise addressing the threatened infrastructure and cultural resources.

Emerging adaptation plans and actions in parks

Adaptation plans can be broadly characterized by three approaches: defend, elevate, or retreat. Defense can take the form of hard engineering structures or nature-based solutions such as beach nourishment and dune building that can provide compatible habitat if properly managed (Nordstrom et al. 2011). Elevating facilities can accomplish the dual purpose of protecting them from wave and flood damage, while allowing nature to evolve beneath them, if that is an intended outcome. Retreat can remove structures from coastal hazards, while also providing the space for nature to evolve. This report concentrates attention on the retreat option, which holds promise for future management of coastal parks but is less well studied than the other approaches.

Adaptation by retreat can occur in urban parks as well as in less developed areas. Managers in some parks are already addressing strategies for adaptation by retreating from the shoreline, removing structures inherited from past practices and using more flexible construction methods. A wall and the road it protects are being removed at Herring Cove Beach on Cape Cod (Figure 2). A new parking lot is being designed 38 m farther landward and at a higher elevation than formerly to account for expected sea level rise, continental subsidence and the level predicted for a 1 in 100 year flood event (National Park Service 2013). The 38 m distance represents 50 years of mean shoreline retreat at the site. A bath house has already been rebuilt farther landward and constructed in a way that is easy to break down in anticipation of having to reconstruct it even farther landward in the future. The new bathhouse replaced a 70-year-old structure at the high water line and four riprap groins that protected it. The new structure was built to be more sustainable with regard to materials and energy consumption, and an old septic system was removed and connected to a municipal wastewater treatment system that will enable future relocation. The project is a compromise that attempts to maintain traditional recreational uses while providing restoration of natural processes. The relatively short distance was, in part, a response to public opposition to moving farther landward. Although the re-aligned infrastructure will remain at the dynamic coastal boundary, its life expectancy has been increased. The infrastructure was moved to protect it from storm damage, but the return to natural processes is a welcome side effect that is worth mentioning in educational programs.



Figure 2. Two views of Herring Cove Beach, Cape Cod, showing effects of removing an asphalt revetment. The left panel shows the old road used as a parking lot and protected by the asphalt revetment (Wall 1, Table 5, Appendix A). The right panel shows the naturally-evolving shore where structures were removed.

NPS is considering eliminating two deteriorated bulkheads at Gateway using post-storm rehabilitation funds following Hurricane Sandy in 2012 (Figure 3). In this case, the rehabilitation objective is the natural habitat not the bulkheads or the infrastructure they were initially designed to protect. Removal of the bulkheads and infrastructure landward would allow the beaches to become self-sustaining and more valuable for horseshoe crab spawning and bird foraging. The bulkheads could be allowed to deteriorate rather than being removed, but the intact remnants would remain as intrusive barriers between the nearshore and new upper foreshore and create safety hazards. One of the bulkheads considered for removal is on the exposed ocean side (Figure 3, right panel). Examples of managed retreat sites in estuaries exist, but demonstration sites that document the value of the approach on ocean beaches are lacking (Nordstrom et al. 2015), and removal of the ocean side bulkhead would have great pedagogic value.



Figure 3. Deteriorated bulkheads at Gateway considered for elimination using post Hurricane Sandy rehabilitation funds. Left panel is Wall 2 at Aviation Rd. and right panel is Wall 28 at Ft. Tilden (Figure 20, Table 7, Appendix A).

Plans for managing Assateague Island recognize its dynamic nature and provide examples of ways to accommodate future barrier island migration (NPS 2011; Schupp et al. 2015). Managers have already abandoned one threatened shorefront road and built a new road landward, using shell and clay as construction material. Other roads and parking areas will be moved in the future and will be built with erodible, temporary surfaces in anticipation of future retreat. Use of shell, gravel and clay instead of asphalt can reduce cost of construction, facilitate the decision to abandon or relocate roads when threatened, and eliminate problems of exotic debris or costs of removal when they are damaged. Portable bath-house facilities have also been installed at Assateague; they are removed from the barrier island prior to major storm events, providing an excellent template for other parks to follow.

Characteristics at individual parks

Acadia National Park

The situation

Key geologic aspects of Acadia National Park (Figure 4) include its high local relief and exposure of wave-planed and glacially-scoured igneous and metamorphic rocks (granite, schist). The human imprint is less conspicuous than in many coastal parks, except near the shoreline, where access roads provide vistas of the water. The high local relief results in great local diversity of habitats. These habitats transition from maritime to mountain summit within only a few kilometers (Harris et al. 2012). The complexity of the shoreline and presence of offshore islands result in great local differences in exposure to ocean and locally-generated waves. Some sites protected by structures are fully exposed to ocean waves; other sites are in bays where fetch distances are less than 1 km (Figure 5). The large amount of bedrock in the coastal formations results in creation of gravel beaches in some locations and bedrock outcrops at the waterline in others. Sandy beaches are confined to small isolated pockets, except at Sand Beach (Figure 6, left panel). Most of the protection structures in the park (Appendix A, Table 1) were built to protect roadways that are still used, in contrast to many coastal parks, where remnant structures protect infrastructure that does not perform its original function. Loop roads on the southeast side of Mount Desert Island and the southern portion of Schoodic Peninsula are close to the shoreline and low, resulting in a threat from wave overwash, with deposition of boulders and cobbles on their surfaces during storms. Some of the roads function as barriers to landward migration of the gravel beaches seaward of them (background of Figure 6 right panel).

Many protection structures appear to be non-engineered dumped rip-rap. This rip-rap has a chemical composition similar to the naturally-forming gravel beaches, but the blocks are larger, more angular, with less sand and pebbles within the boulder/cobble matrix (Figure 6 right panel). Engineered walls, with fitted quarry rock, occur where roads on bridges or filled causeways cross bays. The rock used to build protection structures in the park is less intrusive visually and environmentally than the rip-rap used to protect sandy environments in most other coastal parks. Some of the roads and rip-rap placed across bays prevent tidal exchanges between ocean and bay; other protected roads have culverts that allow for tidal exchanges but at restricted rates of flow. Most of the bays are small and steep-sided, so the areas of existing and potential saltwater wetland that would be affected by removal of protection structures are small. Some bays are relatively large, such as at the road at the Natural Seawall site (Figure 4).

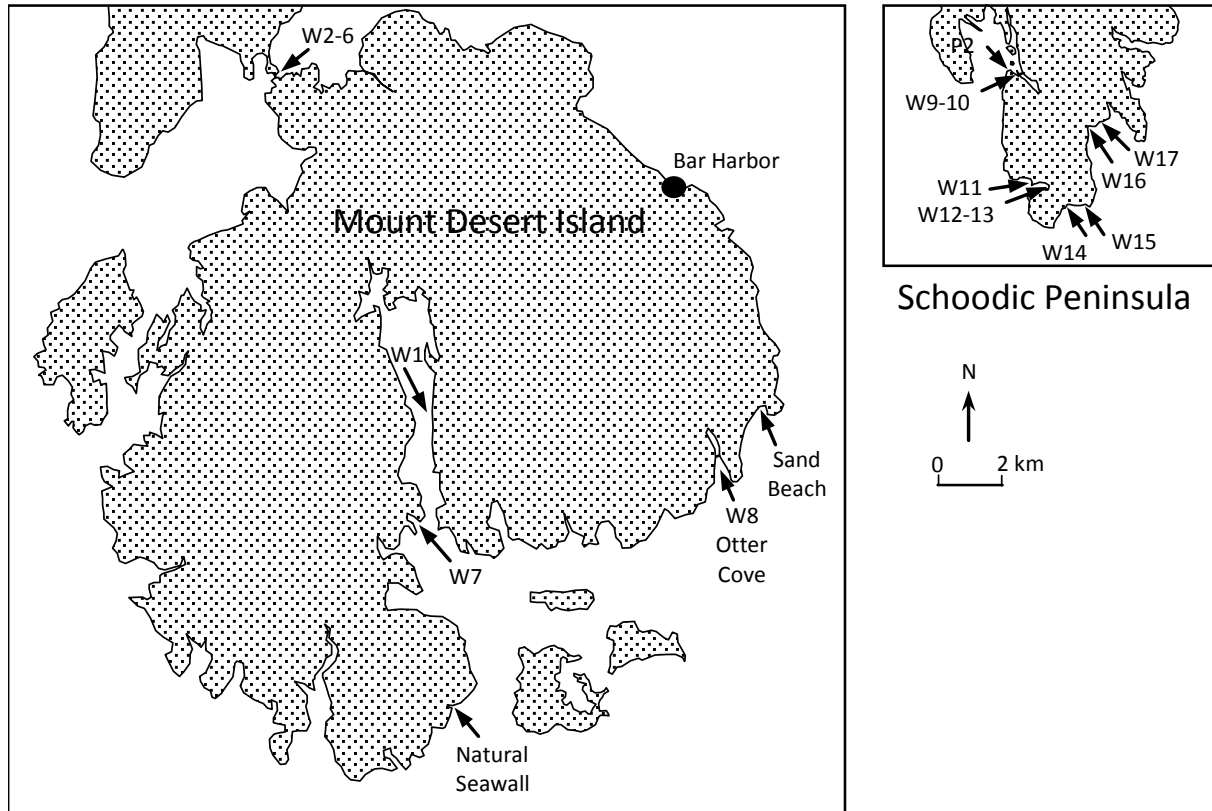


Figure 4. Locations of structures at Acadia National Park on Mt. Desert Island and Schoodic Peninsula. Pier 1, on Isle Au Haut, is not depicted. Structures are identified in detail in Figure 5.

Options

Rising sea levels will increase the potential for onshore migration of gravel beaches, erosion of unconsolidated (e.g. soil covered) portions of the upland, and flooding of locations formerly above the influence of the sea. If no new rip-rap is emplaced, sediment in gravel barriers will be transported across the roads, and the substrate of the roads will be eroded by storm waves, resulting in undermining and structural failure. The steeply sloping coast and bedrock foundation will limit the area affected by shoreline retreat but make construction of new roads difficult. Relocation of threatened coastal roads is not as easy to accomplish as in coastal parks that are on low-lying sandy formations. Protecting the roads by traditional structural methods would require placing new rip-rap where it has not been needed before and increasing the height of rip-rap where it already exists. This would keep the sediment that is in the gravel beaches seaward of the rip-rap rather than being transported across roads.

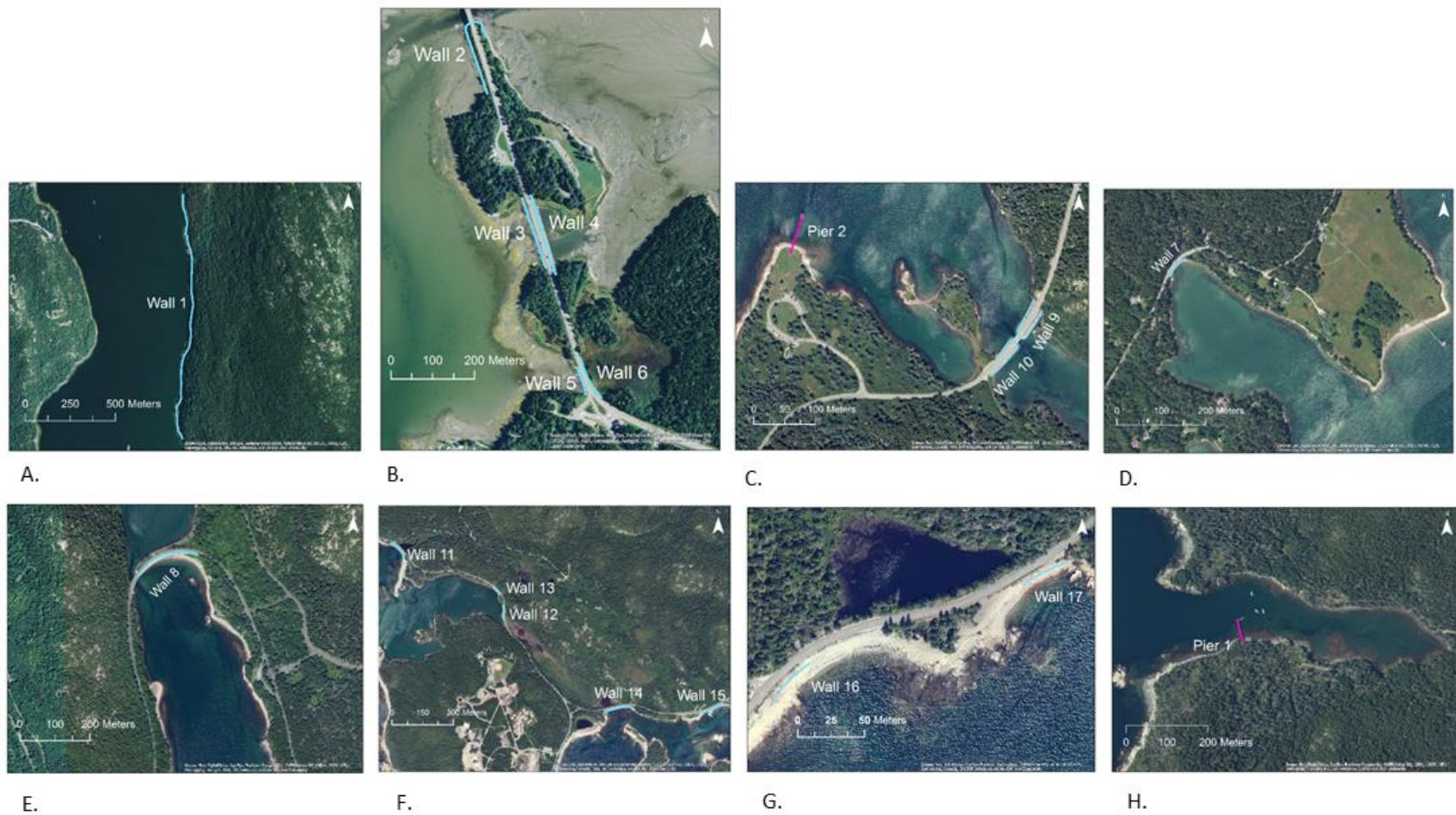


Figure 5. Setting of structures at Acadia National Park.



Figure 6. Acadia, showing Sand Beach, looking west toward the concrete walkway (left panel) and Wall 16 with angular riprap in the foreground contrasting with the gravel beach in the background (right panel).

Alternatively, the rip-rap could be removed or allowed to erode in place to allow natural processes to prevail. Gravel beaches would migrate onshore and eliminate the cultural barrier between coastal and upland habitat, reestablishing the natural ecotone and exchanges of sediment, nutrients and biota between these two environments. Most of the existing and potential future natural beaches have short lengths alongshore and are in pockets isolated by adjacent headlands. Thus sediment delivery alongshore and issues associated with habitat changes resulting from sediment gains and losses would be of less concern than in parks on sandy shores. Removal of rip-rap does not seem as productive in locations without beaches and where resistant bedrock subject to wave attack would differ little from the rip-rap in value of habitat.

Fresh water wetlands that are now separated from the ocean side by roads could be allowed to evolve as salt marsh. Most of the existing salt marsh areas that would be inundated by future sea level rise do not have a significant amount of land at elevations that would become new salt marsh (Nielsen and Dudley 2013). Conversion of fresh water wetlands would increase the inventory of salt marsh. Removal of roads would prevent through traffic, so access roads that are now one-way may have to be designated as two-way to allow visitors to reach the site and return back to their origin rather than continuing the loop. Traffic is already an issue at Acadia, and alternative transport systems, such as use of busses (Hallo and Manning 2009), may be required. Raising roads and constructing culverts to allow flows would establish connections between the open coast and landward bays, but it is not clear whether water flow or sediment supply through the culverts would be sufficient to maintain marsh surfaces and marsh species.

Suggestions for structure removal

No structures are suggested for removal, but any new facilities should be placed farther landward than has been customary in the past and should be readily removable or expendable.

Salem Maritime National Historic Park

The situation

The park occupies a small parcel of land within the town of Salem and on the shore of Salem Harbor (Figures 7, 8). The park is subject to flooding from storm surges generated in the Atlantic Ocean, ocean-generated waves entering the harbor from the northeast, and waves generated within the harbor across fetch distances up to 1.9 km. The park consists of several historic buildings, three wharfs, intervening land between the historic buildings and wharfs that is landscaped using lawn grass, and a beach located on the bayward side of the largest extent of lawn. The wharfs and the short length of upland between them are protected by bulkheads. The longest wharf, Derby Wharf (Figure 8), extends 505 m into the harbor. The bulkhead segments along the wharf (Appendix A, Table 2) are constructed alternatively of wood or rectangular uniformly placed rocks. The center of Derby Wharf is managed as a walkway. Wave splash over the bulkhead on Derby Wharf has eroded portions of the fill along much of its length (Figure 8, right panel) and, in the bayward portions, the pedestrian pathway on top of the fill.

Derby Wharf is the oldest extant historic resource in the park. The wharf is a fundamental landscape element of the park and provides access to the bay for views of the harbor as well as protection to private holdings to the west outside park boundaries (Figure 8). The only portion of park shoreline not protected by a bulkhead is occupied by the 50 m long beach. This beach is the only landform or habitat in the park that is allowed to evolve by natural coastal processes unconstrained by shore protection structures. Beaches in urbanized estuaries are opportunistic landforms that occur in areas of remaining unconsolidated upland formations or where shore perpendicular structures trap the limited amounts of sediment moving alongshore. These two conditions have contributed to maintenance of the beach here. The beach sediments are poorly sorted and poorly graded across the shore, which are diagnostic characteristics of low wave energy. The accumulation of angular quarry gravel that has fallen from the fill within the wharf gives the beach an unnatural appearance. This quarry gravel and the poor grading and sorting of the rest of the beach sediment reduce the aesthetic value of the beach. Nevertheless, the beach is evolving by natural processes, including overwash onto the grassy area landward. Beaches like this were common locations for boat launching in the past, so the beach has cultural relevance as well as natural value.

Options

Allowing the park to evolve by natural processes under a no-action scenario given sea level rise would result in more frequent wave overtopping of existing walls, accelerated erosion of the fill and pathway along the wharfs, onshore migration of the beach, more frequent flooding of the grassy area between the wharfs and beach and Derby Street with the potential for conversion to wetland vegetation, and more frequent inundation of the town road network and adjacent properties. Transgression of the beach across the grassy area could slow through time as the beach becomes more sheltered from waves from the northeast. The transgressing beach would retain its natural value, and any newly evolving wetland landward of it would have greater natural value than the existing grassland.

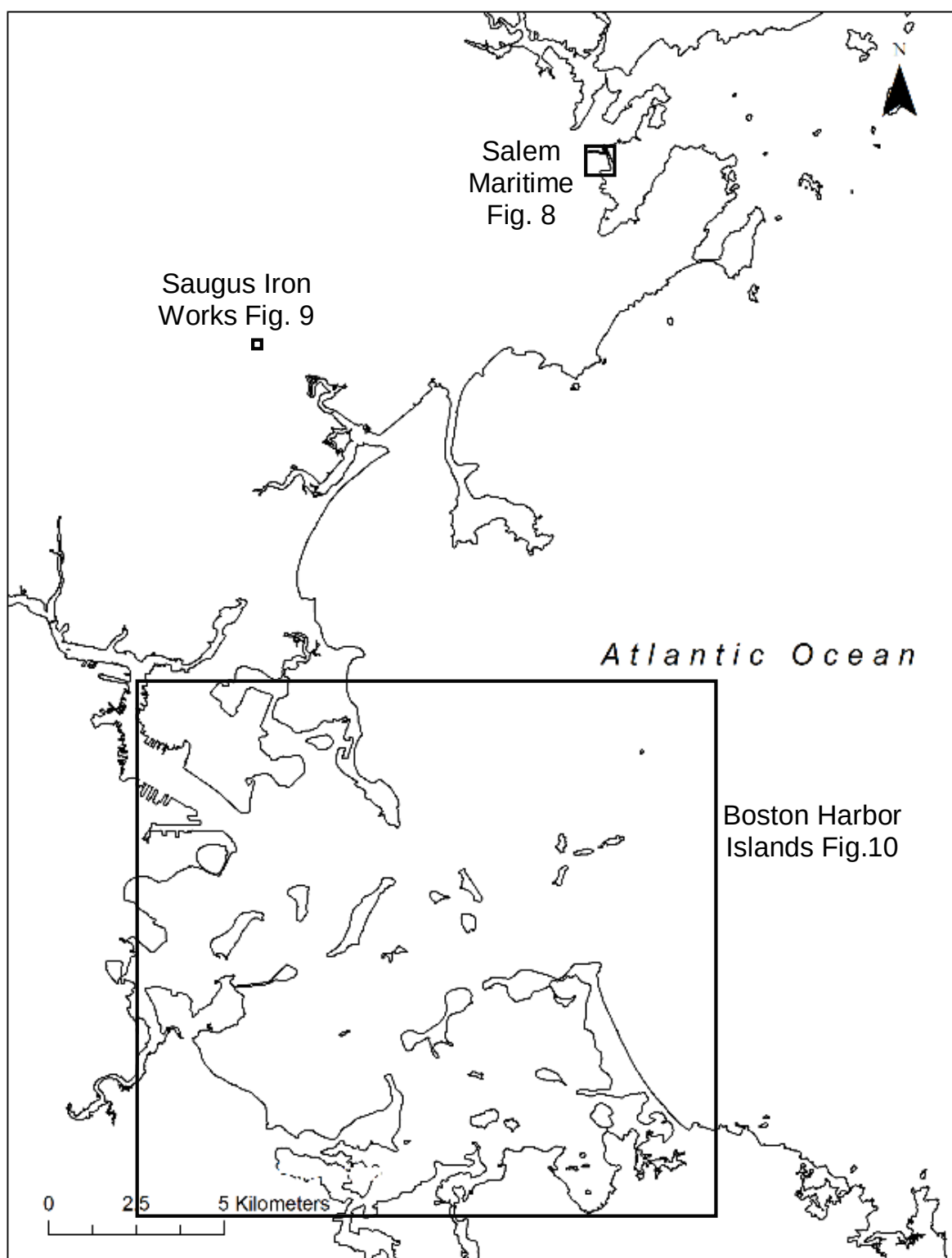


Figure 7. Setting of Salem Maritime, Saugus Iron Works and Boston Harbor Islands in eastern Massachusetts. Rectangles indicate areas depicted in detail in subsequent figures.

Removing the wall around Derby Wharf would have little value in creating natural habitat because the fill landward of it is artificial and of limited volume. As an intertidal feature, it would not mimic any natural feature that would have occurred there in the past. Removal of the wall would eventually allow waves to break on the wall fronting the private developments to the west (Figure 8, left panel). Leaving the wall in place, allowing more of the fill to erode from within, would retain the historical context of the wharf but restrict or prevent its present use as a pedestrian walkway. The walls around the remnant wharfs would be visible most tidal stages and could be marked to identify their locations during high water levels. The NPS will likely consider bolstering the wharf to protect the landscape and visitor use and provide a more sustainable walking path, because of the overriding historic and protective value.

The low elevation of the infrastructure and private property outside the park will complicate decisions that would allow natural evolution of landforms and habitats. Concerns may be expressed by local stakeholders about increased flooding. Demands for protection of Derby Street and developed properties outside the park from flooding may lead to construction of a wall to protect against encroaching bay water. A new wall could be placed next to Derby Street and extended perpendicular to the shore from Derby Street to Wall 1. A wall placed parallel to the shore across the gap between Wall 1 and Derby Wharf would extend the area protected from flooding seaward but would only be practical if the walls around both wharfs were also raised. This alternative would not allow the beach or grassy area to evolve by natural processes.

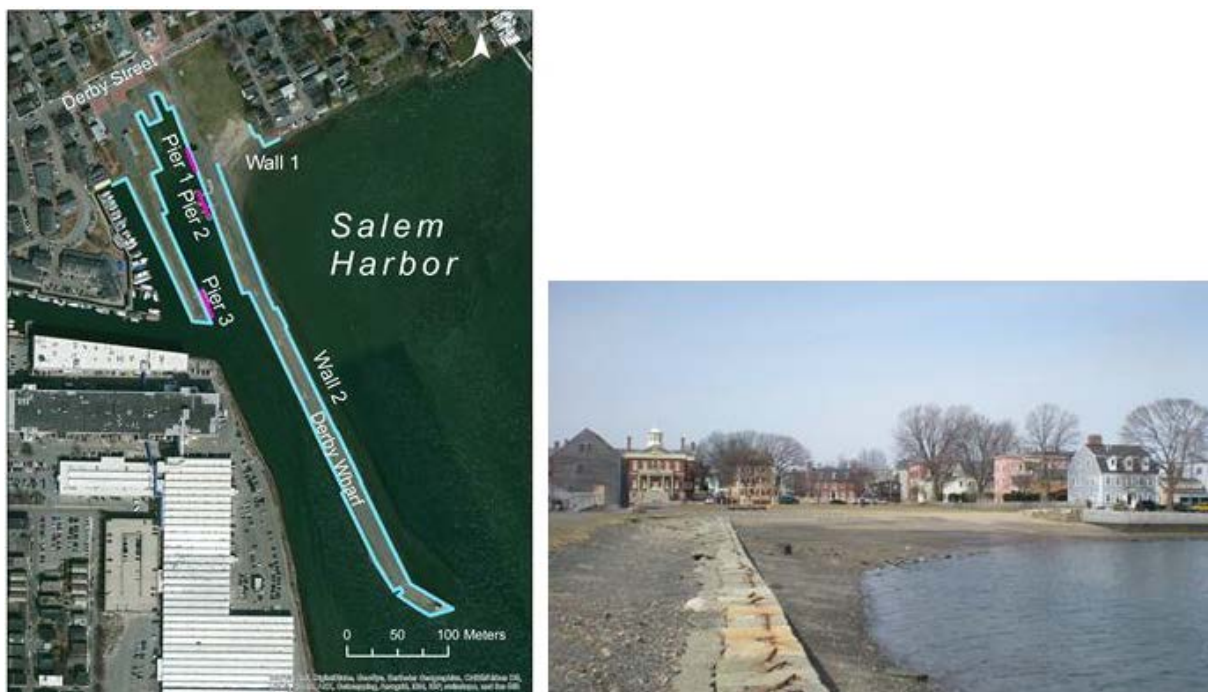


Figure 8. Salem Maritime National Historical Park. Left panel shows structures evaluated in text and Appendix A, Table 2. Right panel shows Derby Wharf (on the left side) and the beach and historic buildings in the background.

Suggestions for structure removal

No structures are suggested for removal to enhance coastal landforms and habitats because of the limited extent of naturally-functioning land that would result and the potential for increased hazard to park historic resources and properties outside the park.

Saugus Iron Works National Historic Site

The situation

The park (Figure 9) is on the margin of Saugus River and surrounded by suburban development. Most of the buildings in the park are close to the water. Several are above flood levels likely to occur in the next few decades, but two (Waterfront Warehouse and Blacksmith Shop, Figure 9) are presently flooded at their bases during extreme events, as are portions of the grassy area, walkways, bridges and pier. These locations are protected from wave erosion by low walls (Appendix A, Table 3). The fetch distance for wave generation across the river basin to the south is only 310 m even when the basin is flooded, and the shallow bottom would restrict wave generation. In 2007-08 a major waterfront and river corridor restoration project was implemented that re-established the open water “turning basin” south of Pier 1 (Figure 9) and tidal mudflats. Wave energies are too low to prevent colonization of the unprotected shore of the basin by vegetation. Wave erosion may not be a critical issue where vegetation protects the banks in the basin, but the expected higher flood levels associated with sea level rise, combined with stream currents, have the potential for inundating and scouring a narrow portion of the grassy margin of the developed area, particularly at the base of the upland where the Saugus River empties into the wider basin. The bar there (Figure 9 left panel) directs the current toward the east bank. The rock retaining wall emplaced there prevents critical bank erosion, but susceptibility to future erosion is evident in scour of the surface of the upland just landward of the wall. Farther south, the flat intertidal gradient and vegetation growth on the margin of the basin indicate that the upland is not subject to erosion away from the channel. Trees growing in low portions of the slope landward of the tidal flat and marsh may become increasingly inundated with future increased water levels, converting portions of the woods into marsh, but the steep upland will confine the marsh to a narrow fringe. Sea level rise should not markedly change the dimensions of the basin due to steep slopes. Thus, the energy of locally generated waves is not expected to increase appreciably in the next several decades. Raised water levels and increases in rainfall and stream discharge may increase the susceptibility of the lower buildings to inundation.

Options

The three bridges along the path over the Saugus River and the pier are low and are likely to be inundated by higher water levels in the future. Structural damage to the bridges by waves is not likely but ice damage is possible. Consideration could be given to relocating the path, the bridges and the Waterfront Warehouse and Blacksmith Shop. Protecting the structures with higher walls is incompatible with natural accommodation strategies, although the minimal amount of natural habitat that would be created by reverting to natural processes may justify protecting the structures in place. The absence of erosion scarps at the beach/upland contact within most of the basin implies that shoreline retreat is not presently critical.



Figure 9. Saugus Iron Works National Historic Site. Ground view, looking east, shows the high ground to the north (left) and the low elevations at the river outfall, Iron Warehouse, Blacksmith Shop, paths and bridges in the right background.

The slag pile (Figure 9, left panel) is protected at the base by a ring of cobbles. It is susceptible to leaching during rain and may be susceptible to sloughing above the line of cobbles when inundated by sea level rise. The pile is known to contain priority pollutant metals (PPM) and polycyclic aromatic hydrocarbons (PAH), and the Massachusetts Department of Environmental Protection has placed an Activity and Use Limitation on the property, which prohibits public access as well as any digging. The slag pile is also a key remaining archaeological feature, so removal may not be a viable option. The substrate would not make suitable habitat if allowed to erode, because of pollutant levels within it. It is likely that these cultural byproducts were left to interact with shore processes in the distant past, but modern practice would argue against allowing this traditional practice to occur in the future, and increasing the size of the wall around the slag pile in the future may be appropriate.

Suggestions for structure removal

No shore protection structures are suggested for removal to enhance coastal landforms and habitats because of the limited extent of naturally-functioning land that would result.

Boston Harbor Islands National Recreation Area

The situation

An overview of the physical processes and landforms in Boston Harbor (Figure 10) is provided in (FitzGerald et al. 2010). A previous inventory of engineering projects is presented in Coburn et al. (2010). Mean tidal range in the harbor is 2.9 m; spring tidal range is 3.4 m. Prevailing winds blow from the north and northwest during fall and winter and from the southerly quadrants during spring and summer. The strongest winds are from the northeast and are associated with extratropical storms that have the greatest frequency in fall and winter. Most islands are at least partially exposed to ocean waves but have sheltered portions primarily influenced by locally-generated waves. Thus fetch distances can vary from virtually unlimited to a few km. Although fetch distances within the harbor can be short (e.g. 3-6 km), eroding bluffs and scarped marsh fronts on the west and south sides of the islands attest to the ability of the locally generated waves to rework the unconsolidated coastal formations. The cores of the islands are drumlins or bedrock, overlain by glaciomarine muds, with

depositional spits, bars, tombolos and salients, providing extensions of beach into the bay or connections between separate drumlins (FitzGerald et al. 2010). Beach deposits consist of sediment eroded from the glacial material in the coastal bluffs. Under natural conditions, the volume and characteristics of sediment delivered to the beaches differs depending on whether the bluff materials are till (characterized by considerable amounts of sediment finer than sand) or glacio-fluvial or reworked beach deposits (primarily sand and gravel). Most of the high bluffs are till, and the fine-grained materials (silts and clays) can help maintain a vertical scarp when the bluffs are exposed to erosion. Fine-grained materials delivered to exposed shores during erosional episodes are removed by wave action, leaving sand and gravel on the beach. These materials can accumulate on sheltered shores. A total of 13 discrete intertidal substrate types occur ranging from bedrock and boulders to mud (Bell et al. 2005).

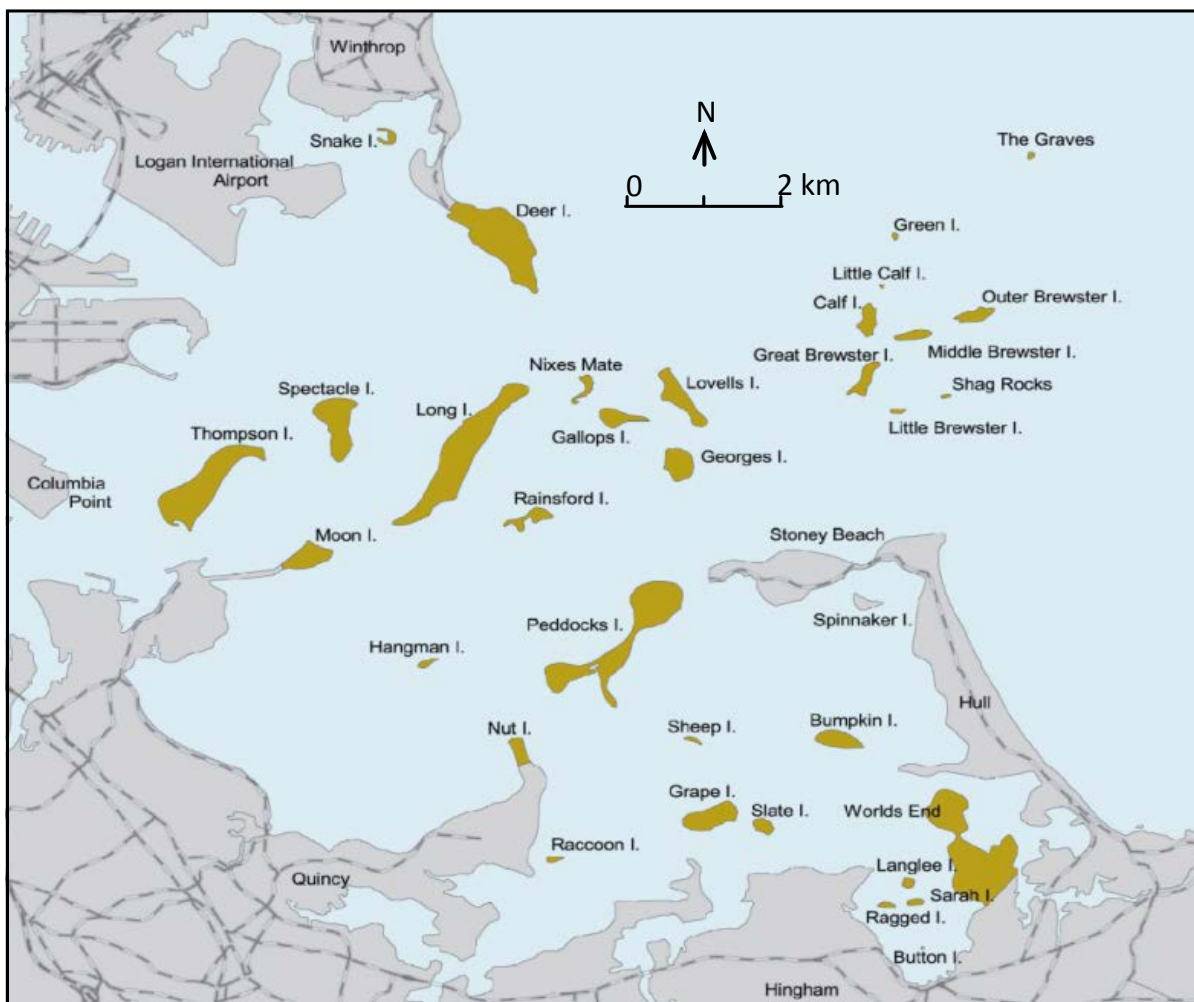


Figure 10. Setting of Boston Harbor Islands. Source: US Fish and Wildlife Service, National Wetlands Inventory Program.

The first seawall on the Harbor Islands was built in 1825, and many structures were emplaced in the 19th Century (Coburn et al. 2010). Others were built when the islands were fortified during WWI and WWII (FitzGerald et al. 2010). Riprap has been added above and at the base of many of the shore protection structures to retain their protective function through time, but many structures are old and often deteriorated, and the uses of many of the facilities they were built to protect have changed. Most of the protection structures located along the shores of the islands (Appendix A, Table 4) are seawalls and revetments, collectively termed walls. Most shore protection structures are constructed of quarry rock and were emplaced to protect human facilities landward of them or help maintain predictable navigable depths in the harbor by restricting sediment transfers (Coburn et al. 2010). The protection structures have reduced rates of bluff erosion, contributing to establishment of vegetation on bluff faces, but stabilization has also decoupled beaches from their sediment sources. Till bluffs that are protected from wave attack at their bases still can erode in places due to rainfall and runoff (Himmelstoss 2003), but this erosional process does not create the vertical scarps or contribute the volumes of sediment to the beach that would occur from wave action.

Options

The purpose of the park is to preserve and protect the drumlin island system in Boston Harbor and the natural and cultural resources of the islands, while enhancing public understanding of the system and providing public access. As in many parks established for multiple purposes, attempting to resolve these often-conflicting missions creates many management dilemmas. The walls themselves have historic value. Removal of some of the walls would help reestablish natural connections between the beach and upland and allow the shores to evolve by natural coastal processes. Some walls protect critical infrastructure that is still in use, such as the wall around much of Deer Island (Figure 11). Some walls protect buildings that are no longer used for their original function but appear to have overriding historical importance and structural integrity, such as Fort Warren on Georges Island. Some walls front land that has waste or hazardous material (Spectacle, Gallops). Some buildings that are located landward of seawalls (e.g. Lovells Island) have deteriorated to the point where their original purpose is obscured and their structural integrity is compromised. Some of these buildings have been overgrown by vegetation. Protecting buildings that have no current use value by building new protection structures may not be feasible, given increased vulnerability in the future, the cost of providing protection, and the desirability of restoring naturally functioning coastal habitat. In some locations, shore protection structures have deteriorated to the point where they have little effect on reducing rates of erosion to their lee, but still interfere with wave processes and faunal movement across the foreshore. Case study sites on Lovells Island and Thompson Island have been selected to illustrate problems and opportunities involved in removing protective structures where the rationale for their construction has changed.



A. Brewster Island Group



B. Deer Island



C. Lovells, Gallops and Georges Islands



D. Long and Rainsford Islands



E. Thompson, Spectacle and Moon Islands



F. Paddocks Island



G. Nut Island



H. Grape Island, Bumpkin Island and Worlds' End

Figure 11. Setting of structures at Boston Harbor Islands National Recreation Area.

Case study 1: removal of the wall on the northeast side of Lovells Island

Lovells Island is exposed to relatively high wave energies at the mouth of the harbor, but it also provides partial shelter to several islands within the bay (Figure 11). The island is now managed, in part, to protect natural resources, such as a Least Tern nest colony, although the characteristics of the shore and its evolution are not natural. The wall on the central ocean-facing portion of the island (Lovells Island Wall 1 Appendix A, Table 4) protects Fort Standish, an abandoned fort built about 1900 and now unused and overgrown (Figure 12, left panel). The portion of the same wall just north of Fort Standish (Figure 12, right panel) now functions as a barrier to wave uprush during small storms but not high surges. Removal of the wall here on the eastern shore of the island would result in increased wave attack of the base of the central bluff, with delivery of more sediment to the beach. The structures at Fort Standish would eventually be exposed on the beach and function as a temporary groin and then as a short revetment until the shoreline migrated landward of it. More frequent overwash would occur into the marsh on the northwest side of the island (landward of the beach in Figure 12 right panel). These changes would occur even if the wall were not removed, although at a much slower rate since the wall would remain as a sill, initially embedded within the landward migrating foreshore and eventually ending in the nearshore.

Re-use of the quarried stone riprap from the former seawall would provide a side benefit that could make removal of the wall more practical. The goal to provide increased protection to some high-priority facilities and the goal to allow other locations to evolve naturally provides the opportunity to remove stone from places where it is becoming ineffective and place it where it will be needed. Re-use of stone would reduce the combined cost of removal and re-acquisition of new stone. Using the stone to increase the level of protection on nearby Georges Island (where the low wall on the north side has resulted in bluff failure), would be a creative re-use of the material. Another option for the stone would be to use it to protect an eroding cemetery site on nearby Gallops Island.

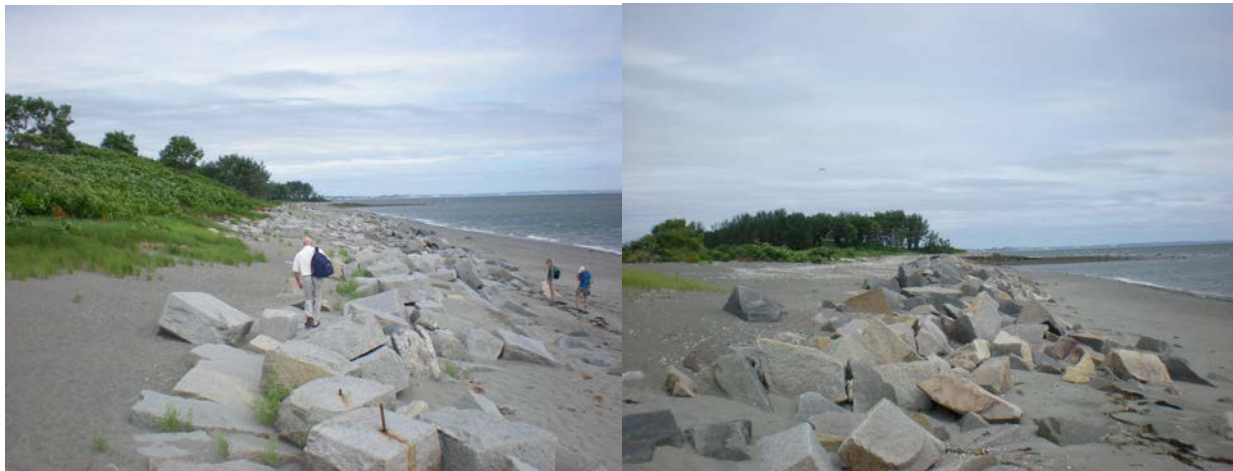


Figure 12. Riprap of Lovells Island Wall 1, protecting the east-central portion of the island (Figure 11C). Fort Standish is buried behind the high ground to the left on the left panel. The right panel shows the portion of wall north of Fort Standish. The wall here separates the foreshore from the storm beach and restricts overwash landward.

Case study 2: removal of protection from the north end of Thompson Island

The wall at the north end of Thompson Island (Thompson Wall 1, Appendix A, Table 4) is now on the foreshore and functions more as a beach sill than a revetment (Figure 13). Rates of bluff retreat monitored by FitzGerald et al. (2010) over a 4 year period revealed an average rate of bluff retreat of 0.51 m yr^{-1} at the more exposed north end of the island. The greater amount of bare ground on the surface of the bluff just south of the south end of the wall (Figure 13) implies that removal of the wall would increase rates of bluff retreat. The top of the wall is about 0.8 m above the elevation of the foreshore fronting it. The wall now functions as a barrier to swash action, and it restricts movement of fauna. Removal of the wall would reestablish full connectivity between the upper and lower foreshores. The northeast side of Thompson Island is a spit/foreland/marsh complex built by sediment eroded from past erosion of the bluffs. Allowing greater erosion of the bluff, through removal of the wall, should contribute more sand and gravel to these types of depositional environments, but it is not clear where these environments would form or how large they would be. The north end of the island is designated as a conservation area. The shore is less geomorphically-complex than the east side of Lovells Island and has no historic structures close to the shore. Stakeholders may be willing to consider adapting current uses as a ropes course and recreational field to allow for natural processes to occur, especially if monitoring were incorporated into ongoing place-based educational programming.



Figure 13. Thompson Wall 1 (Figure 11E), showing greater erosion on the unprotected bluff on the south (right) side of the wall than on the bluff landward of the wall.

Suggestions for structure removal

Removal of walls at Lovells and Thompson Islands represent different points along a spectrum in terms of the potential for major changes to historical features and recreational uses and therefore the potential to generate concern by stakeholders. Many other locations fall between these extremes. Walls could be removed to create beach habitat at several other locations, but creation of more naturally-functioning habitat in many of these locations is already occurring because of deterioration of the protection structures (e.g. north end of Gallops Island and the east side of Great Brewster Island). Monitoring these locations may be more productive and less controversial than removing fully functioning protection structures. There seems to be little reason to build or repair walls to protect the overgrown structures that now have no user value. Deterioration and destruction of seawalls and erosion of concrete military structures have educational value in illustrating the temporary nature of structures in the coastal zone, including massive fortifications.

Cape Cod National Seashore

The situation - Cape Cod (Figure 14) has beaches consisting of sediment eroded from glacial moraines, glacio-fluvial sediments or dunes. The vast quantities of sand and gravel and high levels of exposure to waves and winds on Cape Cod result in a highly mobile shore environment. Beach erosion rates are high and dunes are susceptible to formation of blowouts and migration into forests and human facilities. Barriers to natural shoreline evolution include protection structures (Figure 14B,C,D) and several parking lots that are now located within the beach and foredune environments or soon will be. The parking lots themselves provide little interference with wave overwash and aeolian transport, although remnants of their paved surfaces following wave damage are intrusions into the natural landscape. Walls emplaced to protect parking lots and roads from wave damage, in contrast, resist wave attack and can prevent natural shoreline evolution. Use of gravel instead of asphalt for surfaces of roads and parking areas can reduce their cost of construction, facilitate their abandonment or relocation when threatened and eliminate problems of exotic debris or costs of removal when they are damaged.

Shore protection structures that restrict the interaction between the beach, dune and upland or water flow between two portions of the same wetland (Appendix A, Table 5) include a causeway, dikes, revetments (here termed walls) and groins. Walls built to control erosion include asphalt armoring of the bayward side of the road at Herring Cove (Wall 1, Figure 14B and Figure 2 left panel) and two walls that protect private holdings in Salt Pond Bay (Walls 2 and 3, Figure 14C) in addition to the walls that provide armoring to the two sides of the causeway across Herring River (Figure 14D).

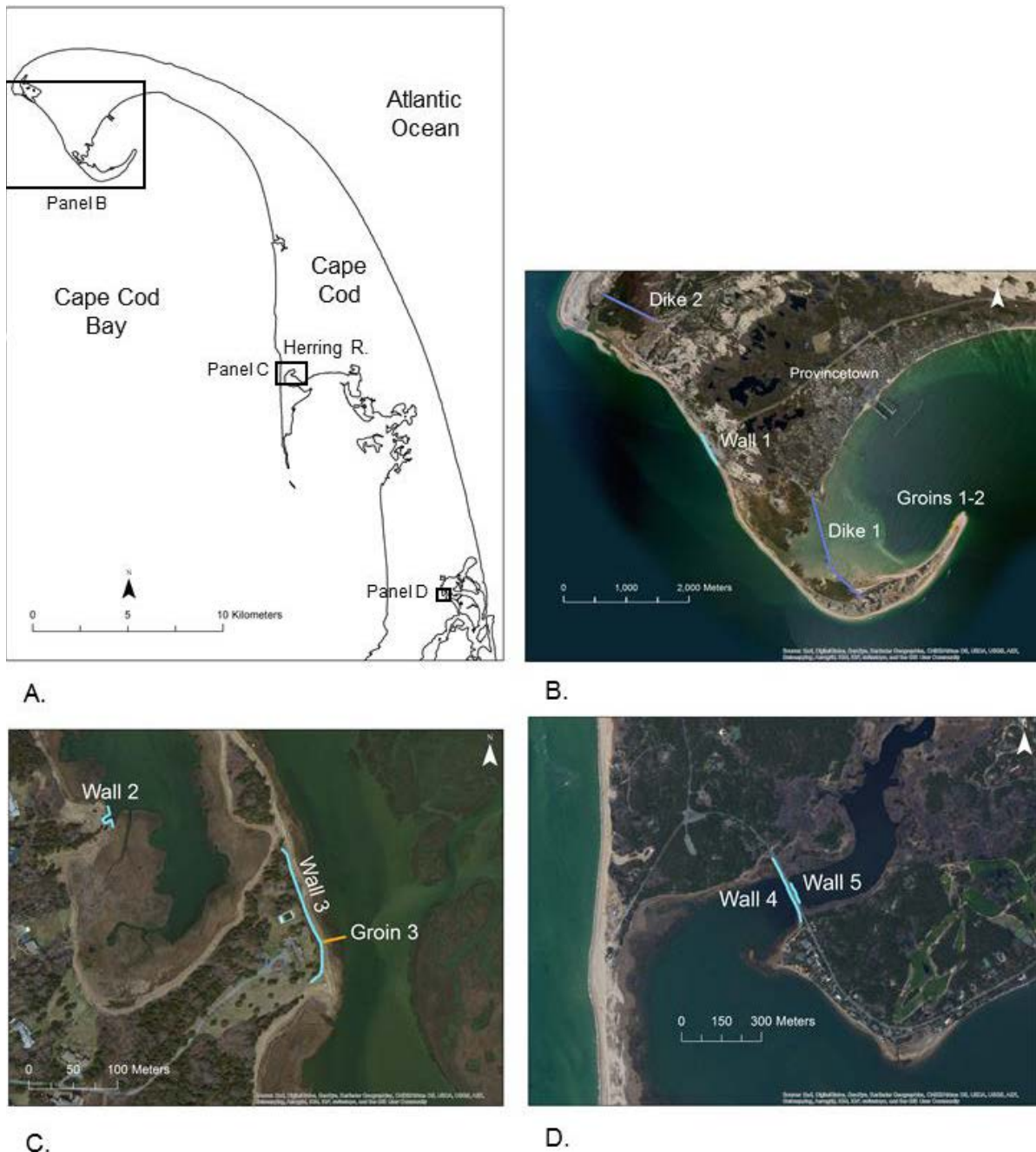


Figure 14. Locations of shore protection structures at Cape Cod National Seashore.

Options

Dikes 1 and 2 and the causeway/dike across Herring River that is protected by Walls 4 and 5 have altered adjacent landscapes to the point where it is debatable whether removing these structures will allow the adjacent landscapes to revert successfully to naturally functioning environments. Predicting future changes at these locations would be difficult, and many different stakeholders would be affected by these changes, including an airport landward of Dike 2 and a golf course and private lots landward of the causeway across Herring River (Roman et al. 1995; Smith et al. 2009). Thus, these

locations would not be good demonstration areas to substantiate the advantages of removing structures to allow natural processes to prevail. Accordingly, removal of Dikes 1 and 2 and the walls protecting the road across Herring River (Walls 4 and 5) has low priority.

Wall 3 and Groin 3 protect private property that is not managed as a natural site, so little would be gained by removing these structures, even if the owner agreed. Removal of the riprap forming Groin 1 would have no appreciable impact on morphologic changes to the tip of the spit on which it was placed. The advantages of retaining the rocky habitat provided by shore protection structures on an otherwise sandy shore are debatable, and still unresolved. Species richness can be increased (Moschella et al. 2005), but it is not clear whether rocky habitat should be considered a positive attribute if it did not exist before the structure was built (Nordstrom 2014). Groin 2 has deteriorated to the point where the geomorphic and ecologic effects appear to be minimal, and there is little reason to eliminate the remnants other than for boating safety.

Case study: Herring Cove Beach

The site holding the greatest promise as a demonstration area for accommodating sea level rise in the park is Herring Cove Beach (discussed earlier in the context of Figure 2), where the bathhouse has been rebuilt farther landward and Wall 1 and the road it protects are being removed. The result is a wider backshore that has allowed for natural wrack accumulation (with its habitat value) and increasing space for recreation, while also presenting a better image of nature (Figure 2, right panel). The dune provides a trap for wind-blown sand and restricts inundation of the parking lot by aeolian transport and overwash. The plan includes periodic re-vegetation and maintenance of the dune to maintain visual access, and boardwalks and accessibility mats to continue to support pedestrian access. The new bathhouse is closer to the shore than it need be, given the potential for inundation by blowing sand and dune migration and considering that the presumed purpose of visits is for active recreation and appreciation of nature. Maintenance of the dune to provide views of the sea from the parking lot is likely to prevent natural processes from creating an equilibrium dune configuration, and the 38 m landward relocation is probably too narrow to allow a fully developed dune to maintain an appropriate width over the calculated 50 year time period. The attempt to accommodate erosion and sea level rise is a good idea, but greater consideration should be given to placing facilities farther back from the shoreline than the minimum. Extra space would ensure that natural processes can create a full suite of active landforms and habitats between the shoreline and infrastructure and would convey a better impression of how far back human facilities should be located to allow these natural features to occur through time.

Suggestions for structure removal

No protection structures are suggested for removal at present, but infrastructure that is threatened in the future should be removed or at least moved landward at greater distances than has been common in the past.

Fire Island National Seashore

The situation

Fire Island (Figure 15) is a 67.3 km-long barrier island. The east end of the island is managed by Smith Point County Park but is included within the boundary of Fire Island National Seashore. The west end of the island is managed by Robert Moses State Park. The portion of the island managed by NPS is comprised of naturally functioning environments separated by numerous residential communities that remain as developed enclaves within the park. The only protection structures on the ocean side of the island are stone jetties at the east and west ends and 2 stone groins fronting one of the developed communities. Many bulkheads have been built along the shoreline in the developed enclaves in Great South Bay. Nordstrom et al. (2009) indicate that about 18% of the shoreline is protected by 43 bulkhead segments. Coburn et al. (2010) state that the length of bulkheads is about 23,475 m. Most bulkheads are sheet-pile structures. The jetties, groins and most of the bulkheads are not in the units managed by NPS, although they influence shoreline change within the park. Only 7 structures are directly within the units managed by NPS (Figure 16, Appendix A, Table 6), and all are along the bay shoreline.

Great South Bay is a narrow basin where fetch distances for generation of waves are usually less than 15 km in the direction of the dominant northeasterly and northwesterly winds. Water depths in the bay are often less than 1.0 m within 1 km of the shoreline. Wave heights are lower and wave periods are shorter than in many estuaries because of the short fetch distances and shallow depths, but erosion rates are relatively great and can be up to 3.3 m yr^{-1} in a given year (Nordstrom et al. 2009). Erosional scarps and fallen trees resulting from this erosion are common along the bayshore. Erosion problems are exacerbated by the lack of sediment input from the ocean side of the barrier island via migrating dunes, overwash and inlets. Human attempts to stabilize the ocean shore by beach nourishment and dune building programs restrict the likelihood of sediment inputs to the bay. Overwash during Hurricane Sandy delivered sediment to the bay in the wilderness area in the eastern portion of the island and one location near the middle of the park, but the extent to which overwash will occur in the future in the developed portion of the island is unknown.

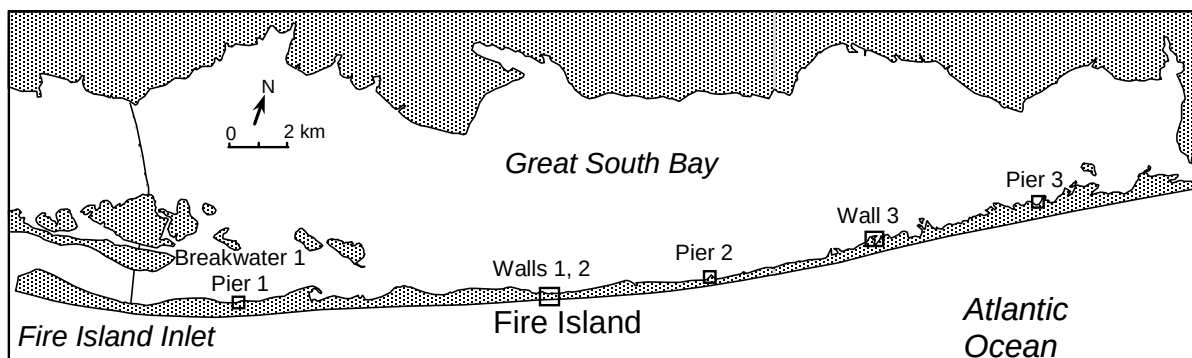


Figure 15. Fire Island National Seashore, showing the regional setting and locations of detailed views of shore protection structures portrayed in Figure 16.

Options

Road access to Fire Island is limited to two bridges near the east and west ends of the island, while access to the center of the island is limited to all-wheel drive vehicles or by boat. The lack of a surfaced road along most of Fire Island makes access by boat crucial. The more intensively used NPS holdings require facilities to handle boat traffic, with maintenance dredging to maintain channel depths. At issue is how the effects of these facilities and dredging activities on landforms and habitats can be minimized while accommodating visitors.

The marina at Sailors Haven (Wall 1a, b) is the most intrusive of the docking facilities that are built into the bay, projecting about 115 m relative to the adjacent shorelines and 260 m alongshore (370 m measured along the perimeter). The bulkhead protecting the marina functions as a barrier between beaches to the east (Figure 17) and west. The bulkhead protecting the marina at Watch Hill (Wall 3) is recessed within a basin dredged landward of the shoreline, but channel dredging and riprap placed at the entrance to the marina interfere with sediment transfers along the exposed bayshore. The two marinas may be oversized for the boats needed for daily use in the bay, but altering fully functioning marinas would provide little benefit for the effort.

The advantages of diminishing the environmental footprint of marinas are apparent at Talisman. The pier there (Pier 2, Figure 16C) is a replacement for a former marina that projected 125 m into the bay and was protected by a bulkhead that created a barrier to longshore transport. The new pier is on pilings and allows for alongshore sediment transport on the beach. The bulkhead at the old marina extended 90 m alongshore. The sediment that was sequestered landward of it has been allowed to erode since construction of the new pier, and has moved alongshore to partially nourish adjacent beaches. The pier is more compatible with natural dynamics than a marina protected by a bulkhead and provides a good example of a way of accommodating natural processes while maintaining access. Piers do not eliminate the need for dredging to maintain depths for deep-draft vessels, so their use for accommodating large boats is not totally benign. Provision of a pier may also lead to demands for provision of support facilities. Piers are not necessary to accommodate use of small boats.

If marinas cannot be rebuilt to be more compatible with sediment transfers alongshore, mitigating action can be taken by using material dredged from the navigation channels to nourish adjacent beaches. The project to establish a feeder upland at Sailors Haven Marina (Nordstrom et al. 2010) is an example of a way to compensate for marina construction while helping overcome the bayside sediment deficit caused by human actions on the ocean side.



A. Lighthouse area



B. Sailors Haven



C. Talisman



D. Watch Hill



E. Otis Pike Wilderness

Figure 16. Structures evaluated at Fire Island National Seashore.



Figure 17. Eroding shore east of Sailors Haven Marina Wall 1b, Figure 16B, showing beach transgressing the marsh (far right) and undermined trees falling onto beach (center background).

Suggestions for structure removal

Other than the two marinas and piers identified above, the only structures along the shoreline within units managed by the park are two deteriorated piers (Piers 1 and 3, Figure 16A,E), a deteriorated riprap structure that now is on the low tide terrace (Breakwater 1) and a concrete walkway that is now exposed along a portion of its length (Wall 1). Removal of the piers and Breakwater 1 (Figure 16A) would alter the bay bottom and could be left to deteriorate. The concrete walkway is suggested for removal because it can be more readily removed without significantly altering the bay bottom. Other portions of the walkway that are farther landward should be removed before they are within the active swash zone. The park already has designated a route farther inland for longshore access.

Sagamore Hill National Historic Site

The situation - The shoreline of the park is within Cold Spring Harbor off Long Island Sound. No buildings are near the shore, and there are no shore protection structures in the park (Figure 18). The fetch distance for wave generation across Cold Spring Harbor is less than 4 km. The longest fetch distance is to the north, across Long Island Sound (15 km). This direction is nearly alongshore, which helps diminish wave generation potential from the north but still favors sediment transport to the south. Southerly transport of sand and gravel has created a 35-70 m-wide spit on the east side of the park (Figure 18 left panel). A 65-140 m-wide marsh separates the upland from the spit. The only structure near the water is a boardwalk over the marsh. Wave energies within Cold Spring Harbor are low, and the spit and marsh provide adequate protection against erosion of the upland. The energy of locally generated waves is not expected to increase appreciably in the next several decades. Increased inundation of the marsh may occur in the future.

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Figure 18. Sagamore Hill National Historic site, showing the relatively great distance of fixed infrastructure from the shore (left panel) and the lack of erosion of the upland landward of the spit and marsh (right panel).

Options

The lack of evidence of active erosion of the shore landward of the marsh (Figure 18 right panel) implies that there is no immediate threat from shoreline retreat during small storms. Periodic flooding during high intensity storms would not penetrate more than a few meters into the steep upland. The visitor center and other buildings are at least 450 m from the seaward edge of the spit and are located on high land. They are not threatened by erosion or flooding in the near or distant future. The boardwalk is on pilings. This method of construction allows for passage of water and sediment and thus does not interfere with evolution of the marsh. The lack of historical infrastructure or visitor facilities other than the boardwalk implies that there is no need for structural protection if future sea level rise or interference with the longshore sediment budget by human actions to the north result in beach retreat.

Suggestions for structure removal

No action is suggested at Sagamore Hill National Historic Site. Natural processes are not presently restricted by protection structures, and no facilities are threatened by natural processes.

Gateway National Recreation Area

The situation

Gateway National Recreation Area (Figure 19) was established to protect and preserve scarce or unique natural, cultural and recreational resources within and adjacent to a dense coastal urban population (Boger et al. 2012). The park consists of two management units in New York (Jamaica

Bay and Staten Island) and one in New Jersey (Sandy Hook). The shores facing the ocean are characterized by wide sandy beaches and foredunes. Estuarine shores (e.g. in Jamaica Bay and Raritan Bay) have narrow sandy beaches, with marshes fronting shores in the smallest bays and tidal creeks. Despite the relatively low wave energies in the estuaries, erosion rates can be relatively high due to the limited amounts of sediment in the beaches. Net longshore sediment transport along the ocean shores is from east to west along the Long Island shore and south to north along the ocean shore of Sandy Hook. Net transport along most of the Staten Island shore and bayshore of Sandy Hook is generally north to south. Transport direction in the northernmost portion of the Staten Island shore is to the north.

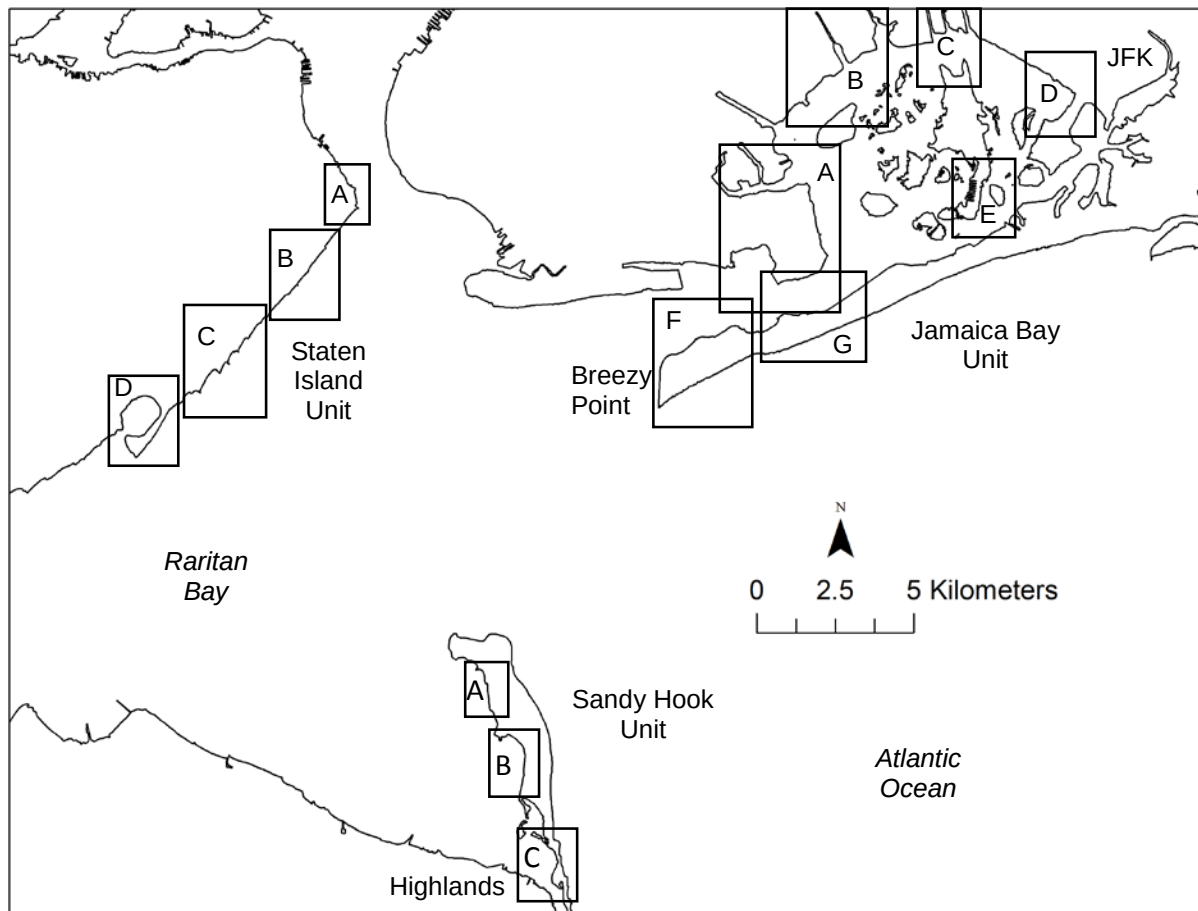


Figure 19. Setting of the units of Gateway National Recreation Area. Rectangles identify panels in Figures 20, 22 and 25.

The location of the park units within one of the most densely populated urban areas in the USA has resulted in considerable modification of the natural shoreline. Inspection of nautical charts dating back to the end of the 19th century reveal that dredge and fill projects have modified the shorelines throughout the units of the park. Jamaica Bay has been extensively modified. By 1950, filling of the margins of Jamaica Bay had reduced the surface area of the bay by nearly 50% (NYCDEP 2007, cited in Dallas et al. 2013b). Many of the shore protection structures were built when the region was used by the US Army for defense of the New York Harbor region. The military facilities are no

longer needed for their original use. Many of the structures have historical value and are listed as contributing resources to the historic districts but are in a deteriorated state. Many protection structures were used to protect artificially-filled areas. Deterioration of many of these structures has allowed the fill to be reworked by waves and currents.

The report for Gateway by Dallas et al. (2013b) identifies 254 individual structures in and adjacent to all of the units of Gateway. Our report focuses only on the structures within park boundaries. We have divided Gateway into the three units and grouped similar structures in Figure 20 to facilitate discussion. The way these structures are grouped relative to the individual structures in Dallas et al. (2013a,b) is identified in Appendix A, Tables 7-9.

Jamaica Bay Unit of Gateway

The situation

Jamaica Bay is a saline to brackish estuary and one of the most heavily urbanized bays in the country. The bay is characterized by a complex mosaic of beaches, salt marshes, landfills, parks, residential communities, roadways, the active John F. Kennedy International Airport (JFK) and the formerly active Floyd Bennett Field. The ocean side of Rockaway Peninsula, that separates the bay from the ocean, has wide beaches and dunes. Under natural conditions ocean spits like Rockaway Peninsula are dynamic and subject to considerable changes associated with overwash, breaching and creation and migration of inlets. Implementation of large scale beach nourishment projects updrift (east) of Jacob Riis Park (Figure 20, panel G), combined with construction of numerous groins, bulkheads and a jetty at Breezy Point at the terminus of the spit have greatly restricted long-term shoreline change. The US Army Corps of Engineers has an active project to provide protection to Rockaway Peninsula, which must be considered in plans to adapt to sea level rise on the ocean side of the spit.

Options

Many protection structures are deteriorating and could be allowed to deteriorate further or removed to allow the shoreline to evolve under natural processes (Appendix A, Table 7). Removal of some structures would further expose historic resources, including buildings or roads (which may also be in a deteriorated state) and cause them to directly alter shore processes. An additional issue is that the quality of sediments in many fill areas is unknown, and allowing the shoreline to retreat in those locations may deliver pollutants to the water. Definitive statements about the feasibility of removing many structures would require more detailed site-specific assessments than can be done here, but three sites (two in Jamaica Bay and one on the ocean side) are singled out for case study to provide perspective on the issues involved.



Figure 20. Structures evaluated at the Jamaica Bay Unit, Gateway National Recreation Area. Sites identified and drawn based on Dallas et al. (2013b) but number designations of structures and type of structures may differ (see Appendix A, Table 7 for differences).

Case Study 1: Removal of Wall 2, Aviation Road, Floyd Bennett Field

The steel bulkhead protecting the facilities at Aviation Road, Floyd Bennett Field (Figure 3 left panel) has deteriorated, contributing to the erosion of the low upland landward of it and destruction of parts of the road, concrete pads and fence that formerly ran parallel to the bulkhead. The bulkhead now has little effect on storm waves or aeolian transport. The shore-perpendicular Marine Corps ramp (Ramp 1, Appendix A, Table 7) to the east (background of Figure 3, right panel) helps to hold beach sediment in the compartment, and the beach fronting the bulkhead is relatively wide for an estuarine beach. The beach is not high enough to provide protection against wave attack and flooding of the upland by the larger coastal storms of a given year. Given continued sea level rise, and the lack of available sediment sources in the region, the beach is not likely to survive without the ability to migrate inland and be replenished by the new sediment source that would be made available by erosion of the upland. Rebuilding the bulkhead would provide protection against erosion of the upland, but the value of the fixed infrastructure landward would likely not justify the expense, and the beach and much of the recreational value of the area would eventually be eliminated. NPS has proposed to cut the bulkhead down below the existing surface. Removal of the influence of the bulkhead and removal of the fixed infrastructure would allow the beach and upland to become a self-sustaining, naturally-evolving habitat. The bulkhead could be allowed to deteriorate further and accomplish many of the goals of removing it, but the site is used by visitors and the deteriorated steel is a safety hazard.

Case Study 2: Removal of Wall 4, Ranger Road, Floyd Bennett Field

The bulkhead and rip-rap placed north of Ranger Road have deteriorated and have had little effect in protecting against erosion of the upland and inland migration of the beach (Figure 21). The lack of user facilities in the upland implies that there is no need to rebuild the bulkhead. Natural evolution would be an appropriate solution. The pilings and strewn riprap in the intertidal zone are an intrusive barrier between the nearshore and upper foreshore. The site can be made safer and more valuable as natural habitat (e.g. for horseshoe crab spawning and bird foraging) and more appealing for recreational use by eliminating the remnants of the structure.



Figure 21. The evolving beach north of Ranger Road, showing the degraded bulkhead (Wall 4) and rip-rap that are interfering with exchanges of sediment and biota across the intertidal zone.

Case Study 3: Removal of Wall 28, Fort Tilden

Previous attempts to stabilize the ocean shore at Fort Tilden included construction of a wooden bulkhead to protect against wave erosion and groins to slow down the rate of longshore transport. The groins were built in two phases, including smaller wooden structures, which have deteriorated or become buried, and newer, larger rip-rap structures that are still effective in trapping sand. The wooden bulkhead (Figure 3, right panel) has deteriorated to the point where it cannot protect against overwash from storm waves or aeolian transport from the beach. Dunes occurred landward of the bulkhead along most of its length prior to Hurricane Sandy. Waves from the storm washed over and through the deteriorated bulkhead, eliminating portions of the dunes that had formed just landward of it. Waves also washed over the shore-parallel road at the eastern end of the Fort Tilden segment and eliminated the road along the western end. Aeolian transport continues to occur across the bulkhead (foreground of Figure 3, right panel). The fence in the figure was placed at the site to prevent visitation because the bulkhead was considered a safety hazard.

Removal of the bulkhead, the road and the unserviceable buildings at Fort Tilden would allow the shore to evolve and function naturally. The lack of important infrastructure within hundreds of meters of the shoreline and the great width of this portion of Rockaway Peninsula (Figure 20) indicate that there is little need to construct a new bulkhead to prevent erosion or flooding. The road landward of the shoreline is at about the position that a foredune would evolve under natural conditions. There appears to be little need for a road near the ocean, when one exists on the bay side. If there is need for this kind of structure as a bike path, the path would be better placed landward of the dune than seaward of it or within it. The fence that is now used to control visitors could be replaced by a symbolic fence. Wooden-slat fences are sand-trapping structures that can create landforms in unnatural positions and shapes and interfere with movement of fauna. Sand-trapping fences may have use in building or repairing dunes, but they are best deployed in locations where the dune would form under natural conditions (in this case farther landward of their present location).

Many of the comments about the site depicted in Figure 3 apply along the west end of the Fort Tilden shore. A former coast defense battery there may require local protection, but there appears to be little reason to build a new bulkhead along the entire Fort Tilden shore to protect site-specific structures. The beach to the east of Riis Park is artificially nourished, but vagaries associated with future projects make assessments of the long-term sediment budget speculative. If the shoreline migrates landward through time, the stone groins along the Fort Tilden shore could eventually be flanked, allowing sediment to pass through the system at an increased rate. Given the net westerly drift in the region, the bypassing of sediment along the Fort Tilden shore may have a positive impact on the sediment budget in the developed portion of the shore between Fort Tilden and Breezy Point.

Suggestions for structure removal

NPS has already given consideration to removing the bulkheads at Aviation Road and Fort Tilden using post-Sandy rehabilitation funds, so these sites are suggested as prototype studies. The projects would provide considerable insight into the issues that will be faced in many other locations. Conditions at Aviation Road are similar to many deteriorating bulkheads landward of urban estuarine beaches, so the results would have widespread application beyond parks administered by NPS. The

precedent of converting a stabilized ocean shore into an evolving coastal landscape would also be of great national and international scientific and management interest.

Staten Island Unit of Gateway

The situation

The eastern shoreline of Staten Island consists of high protected and unprotected bluffs in the north (Fort Wadsworth section), an artificially nourished beach and bulldozed dune dike in the central zone and a lowland fronted by low beach ridges in the south. The southern section has large portions of filled land (Dallas et al. 2013b). The Staten Island shore is exposed to ocean waves entering the opening between Sandy Hook and Breezy Point. Net longshore transport is from northeast to southwest along most of the shoreline. Details of protection structures are presented in Appendix A, Table 8. Construction of groins in the southern part of the shore has resulted in a series sediment-starved beach compartments that are offset ever-farther west, proceeding north to south. Erosion south of these offsets has resulted in the need to place additional structures (hard and soft engineering) in the local erosion zones (e.g. Wall 5 and the sand bags and dune dike recently placed south of the groin at Miller Field (Figure 22C). Flooding is an issue in the low-lying land south of the southern groins in Groin Field 3. Considerable damage occurred to the houses here during Superstorm Sandy.

Options

Structures in the northeast portion of the park, facing New York Bay, have infrastructure close to the shore, making removal of questionable value. One unprotected segment at Battery Hudson is less critical and is identified in Case Study 1 below. Wall 4 and Groin 1 protect land that is vacant, highly disturbed, of little value as natural habitat and of no apparent use for recreation. Removal of the concrete rubble revetment at the southwest end of Wall 4 would allow the beach/upland contact to evolve. Groin Field 1 (not depicted on Figure 22) consists of two deteriorating structures that have little effect on the upland and could be allowed to degrade in place.

The middle segment, extending along Boardwalk 1 and Groin Field 2 (Figure 22B), has a wide beach with less severe offsets than occur downdrift of the groins in the southern segment. This segment is also protected by a new artificially constructed dune dike. Most of the facilities behind the beach are managed by City Parks. Several groins in this segment are deteriorating wood structures that have little effect on trapping and could be removed or allowed to degrade with little impact on shoreline change. Some relatively new, intact groins have little effect because they are located where the beach is especially wide. Removal would be costly and of little value because the need to maintain the dune dike to provide flood protection to landward infrastructure would conflict with allowing a natural shore environment to evolve. The new groins in Groin Field 2 may be needed in the future, given vagaries of future nourishment operations and the need for protection of the landward developed areas.



A. Fort Wadsworth, Battery Hudson



B. Between Fort Wadsworth and Miller Field



C. Miller Field area



D. Great Kills Park

Figure 22. Structures evaluated at the Staten Island Unit, Gateway National Recreation Area. Sites identified and drawn based on Dallas et al. (2013b) but number designations of structures and type of structures may differ (see Appendix A, Table 8 for differences).

Removal of groins that have contributed to the offsets in Groin Field 3 (Figure 22C) could help nourish downdrift beaches, but the proximity of houses, parking areas and park buildings to some of the groins makes the removal of some of the structures problematic due to cascading effects alongshore. Removal of the groins that have trapped sand in front of the buildings at Miller Field and the shorefront houses south of there would simply transfer erosion problems from one location to another.

Natural landforms are already beginning to become reestablished landward of weak points at Wall 6 (Figure 22C). Wall 7, which extends the effect of Wall 6 southward, would have little use if Wall 6 degrades further. Removal of these structures is not suggested because of the proximity of the Oakwood Beach Wastewater Treatment Plant landward of them. Allowing these two walls to remain while they deteriorate would provide some erosion protection, even as the shoreline evolves to more natural conditions. The bulkhead at Wall 8 (Figure 22D) could be removed because there are no key features landward of it. This site and a site on the eroding bluff shoreline in the northern portion of the park (at Battery Hudson) are singled out as case studies to provide perspective on the issues involved in restricting the future use of structures or removing structures in the Staten Island unit.

Case study 1: Bluff at Battery Hudson

The bluff under the Verazanno Narrows Bridge was undercut during Hurricane Sandy, resulting in reactivation of the bluff face (Figure 23). The bluff was protected from wave attack by rip-rap and cobbles at the base, but the water levels associated with the storm were so high that undercutting took place above the level of the rip-rap. Subsequent slope failures created an un-vegetated bluff face and delivered sediment to the top of the rip-rap (Figure 23). At issue is whether the bluff will naturally revegetate and restrict future bluff failure. Recently-eroded bluffs convey an image of instability and environmental degradation, but bluffs may be more stable than they appear. If a bluff was stabilized by vegetation prior to a major storm, it is likely to become re-vegetated afterwards despite some initial slope failures. Water level elevations associated with Sandy were considerably higher than most storms in the New York City area, so it is not surprising that the base of the bluff above the rip-rap and gravel was exceeded. The apparent lack of wave attack at this elevation in the years prior to Sandy indicates that this is a relatively rare occurrence. The question is whether to increase the elevation of the rip-rap and artificially stabilize the slope or allow the bluff to evolve.

Increasing the elevation of the rip-rap (and increasing its protective value using coarser grade rip-rap) seems to be an extreme measure, given the past stability of the slope, the extreme water levels associated with Hurricane Sandy and the success of the rocks in protecting the base. A case can also be made for retention (at least temporarily) of the bare active bluff face as a source of sediment for beaches and for ecological and aesthetic benefits. This issue is elaborated in the discussion section of this report under the subheading bluff erosion. Visitors could be kept away from the top of the bluff using signs and fences. Falling rocks at the bottom of the slope does not appear to be a safety issue, given the lack of any large caliber rocks at the base of the slope (Figure 23). Climbing the unvegetated face of the bluff is likely to be more appealing than climbing the previously vegetated face, so some consideration may have to be given to that safety issue.



Figure 23. Eroding bluff at Battery Hudson, Staten Island Unit, showing protection provided by gravel at the base and delivery of sediment from the bluff face.

Case study 2: Removal of Wall 8

The east end of this wall is a new bulkhead protecting a paved access path. The central and west end (Figure 24) is a deteriorating wooden bulkhead holding fill sediment in place and preventing erosion of a portion of low-energy shore. The bulkhead is 10-12 m from a paved road near the center of the segment. No facilities are near the bulkhead farther west. The bulkhead is too low to be an effective barrier against storm surge, and the road (which at the time of this report was closed to visitors) does not appear to have an important use. Removal of the deteriorated portion of the bulkhead and road would allow a 690 m segment of the shore to evolve naturally and connect the aquatic habitat with terrestrial habitat. This location is identified as having been filled in 1944-1948 using nearly 11 million m³ (15 million yd³) of refuse material from the boroughs of New York City, converting the pre-existing wetland habitat into upland (Dallas et al. 2013b). Contaminants in the fill could be an issue, so testing is suggested before a decision to remove the bulkhead is made.

Suggestions for structure removal

Removal of many structures along the Staten Island shore would seem to be more problematic than in many parks because of the proximity of important infrastructure and private houses and the possibility of pollutants in the fill. However, decisions about these structures will be required in the future, and case studies of potential sites, either at Staten Island or Jamaica Bay, would provide valuable information to facilitate future actions in highly developed areas.

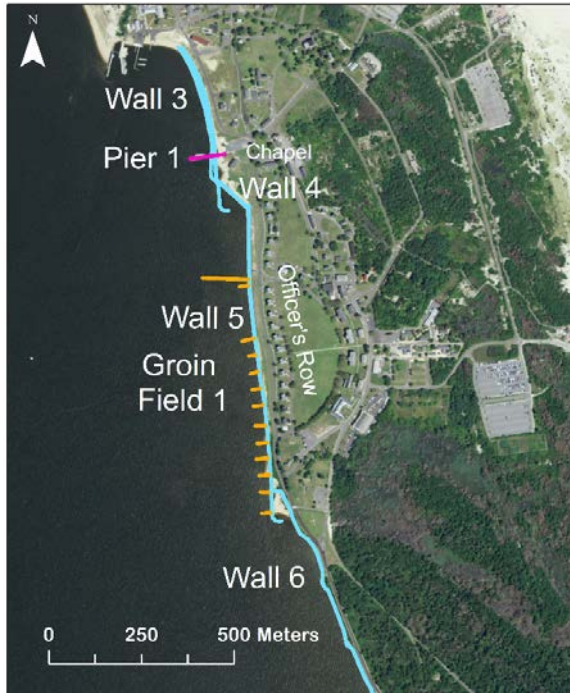


Figure 24. Deteriorating bulkhead near center of Wall 8, Great Kills Park area, Staten Island Unit.

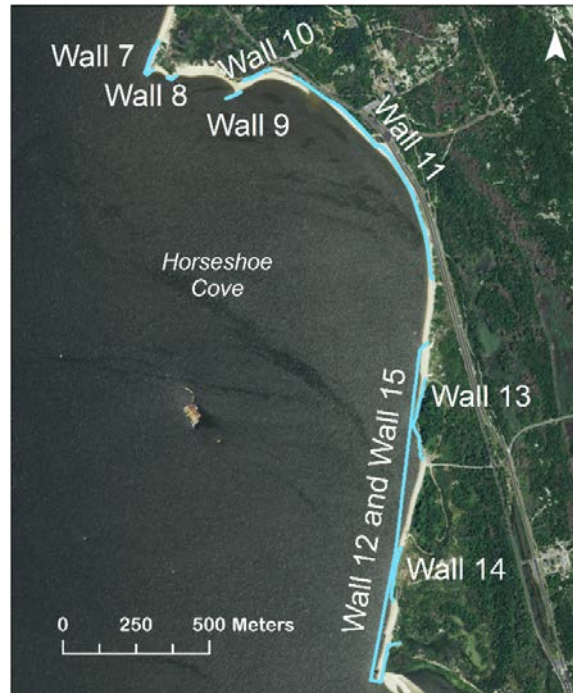
Sandy Hook Unit of Gateway

The situation

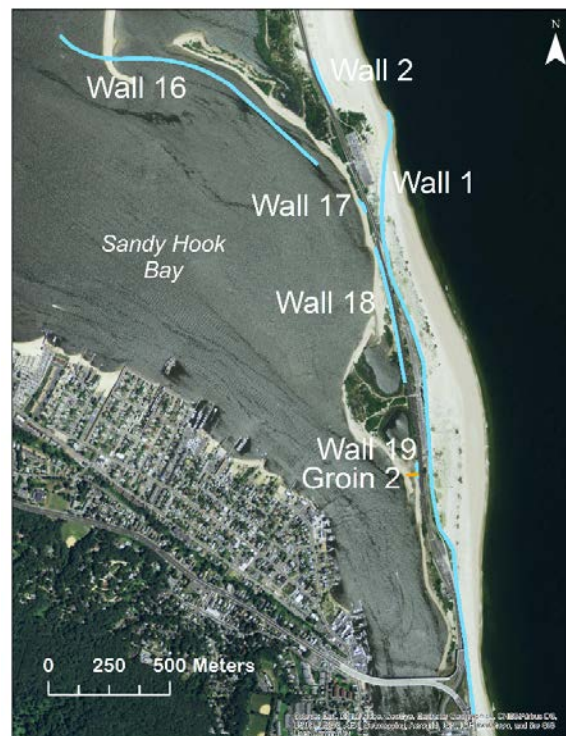
The Sandy Hook Unit was evaluated in greater detail in Nordstrom and Jackson (2013). Prevailing winds are from the westerly quadrants. Wind speed, duration and fetch favor wave generation from the northwest in Raritan Bay (Figure 19). Wave refraction causes the shallow water waves on the ocean-facing beaches to approach from the east-south-east (Fairchild, 1966). The net direction of longshore transport is south to north on the ocean side and north to south on the bay side (Nordstrom, 1980). In the past, Sandy Hook has been an island; it has been attached to the mainland at the town of Highlands; and it has been attached to the barrier to the south, as it presently is (Moss, 1967). Construction of a seawall in the southern portion of the spit (Wall 1, Figure 25C, Appendix A, Table 9) beginning in 1898 has prevented breaching and kept the spit attached to the barrier to the south (Nordstrom et al., 1982). Erosion of the spit just north of Wall 1 caused NPS to implement a program of beach nourishment along it and just north of it. Longshore transport of this sediment and sediment transported from a Corps of Engineers nourishment project in developed communities south of NPS land resulted in considerable beach accretion in the northern portion of the spit. Excepting a short segment of the very northern end of Wall 1 (Figure 25C), none of the shore protection structures built on the ocean side of the spit are now exposed to wave attack. Most of the protection structures on the bay side are exposed to wave attack, as are some of the historic military buildings and support infrastructure.



A. Officer's Row area, Fort Hancock



B. Horseshoe Cove



C. Plum Island area

Figure 25. Structures evaluated at the Sandy Hook Unit, Gateway National Recreation Area. Sites identified and drawn based on Dallas et al. (2013b) but number designations of structures and type of structures may differ (see Appendix A, Table 9 for differences).

Options

Nineteen of the structures in the twenty-two locations on NPS land (Figure 25) are shore-parallel walls. All but two of the walls represent initially well designed structures. Wall 8 (Figure 25B) is a building that eroded in place, with its concrete remnants now functioning as a revetment. Wall 14 is dumped concrete and asphalt rubble. The quarry stone seawalls are in good condition except for a few spots where settling has lowered the top elevation slightly. Most of the seawalls have a top elevation corresponding roughly to the elevation of the land behind them. Five of the six wooden bulkheads on the bay shore have deteriorated and have little present effect on shoreline change, as revealed in formation of beaches or erosion scarps in the upland landward of them. Two locations have groins fronting seawalls. The groins at Groin Field 1 (Figure 25A) have negligible amounts of sand within them. Groin 2 (Figure 25B) is a single structure that acts as a training wall for tidal currents and sediment entering an embayment. Pier 1 (Figure 25A) is elevated on pilings and has negligible impact on shoreline change. Eight more structures (two breakwaters, two walls, three piers and one groin) are located on Coast Guard property on the bay side of the spit north of Pier 1 and are not evaluated here.

Fort Hancock and the Sandy Hook Proving Ground is a National Historic Landmark District and the majority of the buildings are listed as contributing resources. Buildings that are in use or have considerable historical value occur landward of Walls 3, 4, 5, and 13. The portion of Wall 3 that protects the wooden chapel landward of it (Figure 25A) is no longer functioning as designed and could be removed or allowed to deteriorate if the wooden chapel landward of it is moved farther landward. The many relatively large former Army officer quarters landward of Wall 5 (Officers Row on Figure 25A) have considerable historic interest. They are constructed of brick, so they would be costly to move and they would interfere with coastal processes if allowed to deteriorate in place. Accordingly, removing Wall 5 or allowing it to deteriorate is not suggested.

Battery Kingman, landward of Wall 13, is a massive structure and is difficult to remove. It makes little sense to remove Wall 13 and allow the narrow strip of upland to erode if the battery will then act as a barrier to natural processes as has occurred at the structure that now functions as Wall 8 (Figure 25B).

Walls 5, 6, 11, 17, 18 and 19 protect access paths or roads. Little will be gained in removing these protection structures as long as they remain serviceable and visitor access is important. Replacing Wall 10 with a new wall when the old one degrades does not seem appropriate because the trail can be relocated or abandoned. Walls 12 to 15 were built to protect two coast defense batteries (Kingman and Mills), two ammunition bunkers and a service road to them. The bunkers and road landward of Walls 14 and 15 (Figure 26) have been damaged by wave erosion and they have no potential for intensive visitor use. This is the only location where removal of shore protection structures is initially suggested, so it is analyzed in greater detail as a case study.

Case Study: removing Walls 14 and 15 (Figure 26)

This portion of Sandy Hook had been stabilized by a long wooden bulkhead in the past, but the bulkhead has deteriorated and remains as Walls 12 and 15 on Figure 25. The portion of Wall 15 facing the saltmarsh to the east is intact (Figure 26) but the portion facing west has deteriorated, and the beach behind it is now more mobile than in the past. No clearly demarcated public access to the shore exists in the vicinity of Walls 12 to 15. Battery Mills is 25 m from the seaward edge of the eroding headland. No functional shore protection structures are directly bayward of Battery Mills, but a short groin-like extension at the northern end of Wall 14 helps retain sediment bayward of the battery. Wall 14 is dumped concrete and asphalt riprap, placed to protect the service road that provided access between the batteries and the bunkers. The debris is only partially effective in providing protection to the upland landward of it because it is too small to withstand wave attack, and bluff erosion is occurring in places. The asphalt blocks could be removed because they can have potentially adverse effects on biota. The concrete blocks are chemically benign, but they would introduce an exotic habitat in a naturally functioning nearshore.

The two ammunition bunkers in the sand-starved segment south of Wall 14 are no longer protected by the west side of Wall 15 and are exposed on the beach (Figure 26). The eastern intact portion of Wall 15 still prevents overwash from the bay onto the marsh landward of it. Some sediment has passed beyond the south end of the bulkhead, but the volume is not sufficient to prevent onshore migration of the spit that formed there (bottom of Figure 26). The southern portion of the bulkhead now forms a salient that functions as a hinge point in the shore. Eventual natural destruction of the bulkhead will eliminate this stabilizing effect but leave remnants stranded offshore. Pilings remaining as remnants of the deteriorated western portion of Wall 15 are likely to exist in place for decades, as will the concrete in the bunkers. Little reason exists to retain Wall 15 as a structural headland with no historic or human-use value. If removal of the bulkhead and bunkers are desired options, this should be done soon, while vehicular access still exists via the beach (Nordstrom and Jackson 2013).

Removal of Wall 15 would result in overwash into the marsh at its southern end and replace a resistant artificial headland with an eroding headland in other places, contributing to an increase in the amount of sediment delivered to the spit southeast of the present terminus of the wall. The low elevation of the beach landward of Wall 15 indicates that overwash onto the marsh would occur as soon as the wall is removed. The upland just landward of Wall 14 is too high for overwash to occur into the brackish meadow landward of it (Figure 26). The lowland there may experience flooding with sea level rise because the stream that runs through the marsh provides a conduit for bay water. The newly inundated land will be close to existing marsh, facilitating natural colonization by marsh plants. Extension of the marsh inland via stream flooding may partially compensate for loss by inundation of lower portions of the marsh because of sea level rise and burial of bayward portions of the marsh by overwash deposits.

Relatively steep slopes at the margin of the maritime holly forest east of the low-lying land will decrease the likelihood for migration of marsh habitat in that direction. The expected extension of the spit south of Wall 15 may create an environment for marsh growth landward of it, as occurred landward of the pre-existing spit in this location in the 19th century (Nordstrom and Jackson 2013).

This former marsh, and other portions of marsh landward of bayside spits, were eliminated by accelerated erosion of the spits following construction of shore-parallel walls updrift of them. The vulnerability of these sheltered marshes to shoreline transgression reveals the significance of maintaining longshore sediment supplies to retain protective beaches in front of them (Nordstrom and Jackson 2013).

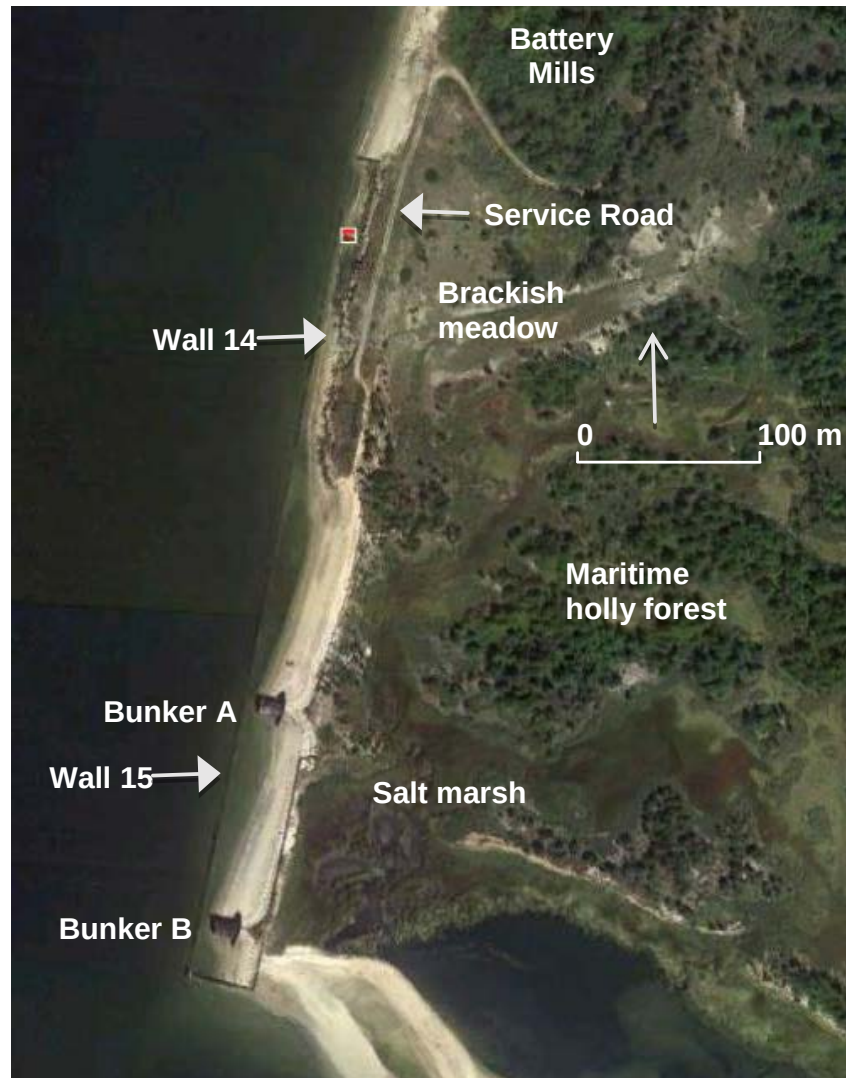


Figure 26. Structures and environmental resources at Walls 14 and 15, north of Spermacetti Cove, Sandy Hook Unit (modified from Nordstrom and Jackson (2014)).

Suggestions for structure removal

Removal of Walls 14 and 15 would reestablish natural processes in a location where there is no longer a need to provide protection, and the protection structures and the facilities they protect have lost their structural integrity. Wall 3, portions of Wall 4, Walls 8, 9, 16) also remain in the landscape but serve no protective function. Removal of any of these walls would provide useful examples of ways natural processes could be accommodated.

Assateague Island National Seashore

The situation

Assateague Island National Seashore (Figure 27) was created to preserve the outstanding coastal resources of the island and adjacent waters as well as the natural processes on which they depend, while providing resource-compatible recreation opportunities (NPS 2011). Prior to establishment of the park, the island was comprised of about 5,800 private lots and several dozen buildings and piers, plus a network of earthen roads, ditches and dikes. These latter structures were sometimes built to convert wetlands into uplands or to bisect portions of wetlands to create ponds to enhance hunting (NPS 2014b). The island is one of the most dynamic coastal units in the National Park system, with past overwash events common (Leatherman 1979). Fewer hard structures exist on the island than in many other coastal parks, but many of the earthen roads and dikes remain. Most of the structures built prior to NPS control have lost their primary function. The dynamic nature of the island and the general lack of hard structures of historical interest make the park an interesting case study area and demonstration site for formulating and following management plans to adapt to coastal change.

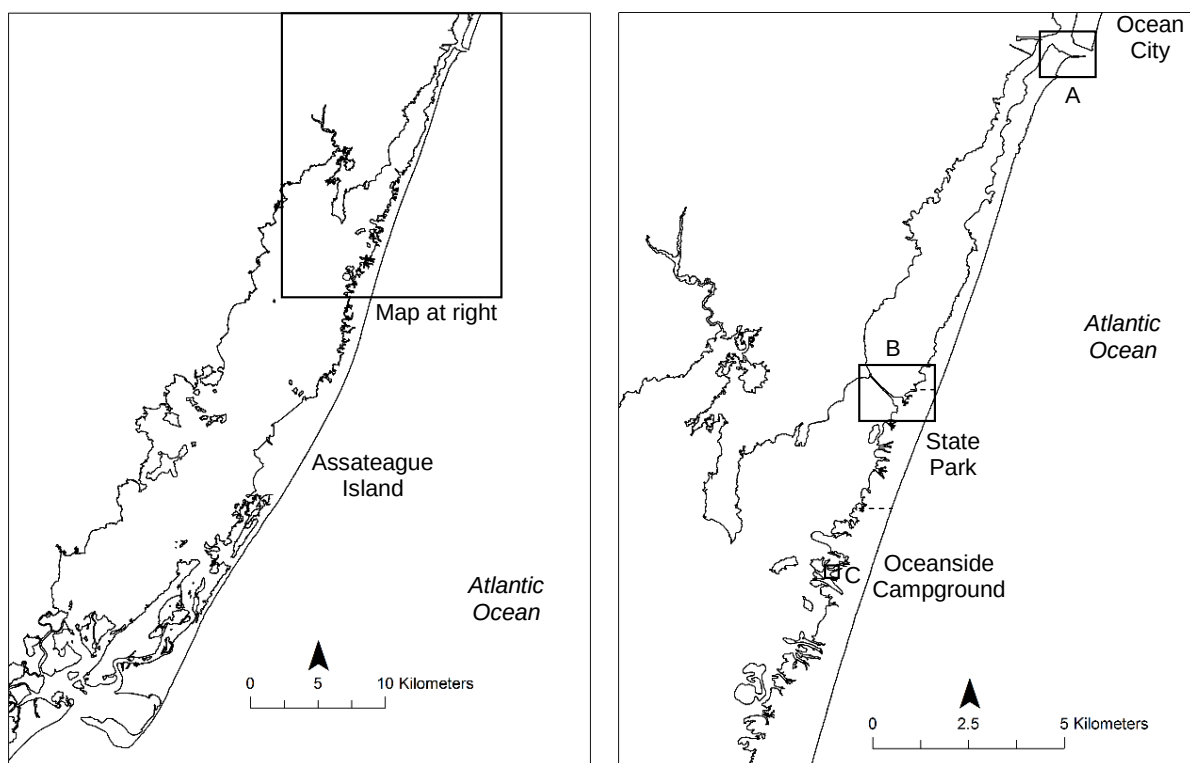


Figure 27. Setting of Assateague Island National Seashore. Rectangles identify panels in Figure 28 depicting sites in the northern section of the park.

The ocean side of the island is just over 60 km long and is managed to accommodate different processes and functions, including (1) a northern tip where Ocean City Inlet is stabilized by a jetty and breakwaters; (2) a naturally-functioning northern portion subject to overwash; (3) a state park managed for recreational use, where dune-building projects have maintained an unnaturally high dune; (4) a developed area that supports recreational beaches, campgrounds and other facilities

managed by NPS with use of sand fences to create a partial barrier to overwash; (5) a naturally evolving segment in the central part of the NPS managed lands; (6) a segment south of the Maryland-Virginia border managed as part of Chincoteague National Wildlife Refuge (and not evaluated in this study); and (7) a recreational beach and former Coast Guard station near the south end that is managed by NPS but part of the refuge. Extensive areas of marsh occur on the bay side of the island. Two bayshore sites in Maryland are developed for recreational use and have paved parking lots associated with them. Dikes and causeways (earthen roads elevated above grade) dissect the island in many locations. These structures were built on the island to restrict tidal inundation of marshes and impound fresh and brackish wetlands or to provide vehicle access to fishing camps. They were built prior to NPS management, but they remain to interfere with natural hydrologic flows and the habitats those flows would create and support.

Beach erosion rates on Assateague Island are high and dunes are susceptible to frequent episodes of erosion, breaching and overwash, especially where the dunes are not built higher artificially. Natural processes predominate throughout the majority of the barrier island landscape, with the exception of the development zone that is managed for high density visitor use. The significant impacts of Ocean City inlet jetty have been successfully mitigated though a long term sediment restoration project with the US Army Corps of Engineers. Other processes are restricted by past human actions (e.g. construction of causeways, dredging in marshes, impounding fresh water wetlands) or present human actions (e.g. using sand fences to trap sand and maintain dunes). Some processes are prevented locally using hard structures (walls and jetties).

Options

Thirteen structures are identified as complete or partial barriers to shoreline migration (Figure 28, Appendix A, Table 10). Jetty 1 and Breakwaters 1 and 2 are important in maintaining Ocean City Inlet (Figure 28A). Wall 1 (Figure 28B) protects the main access road and bridge to the island, and Wall 2 (Figure 28C) protects a parking lot and interpretive facility at Old Ferry Landing. Little appears to be gained by removing these five structures under current conditions. Piers 1-6 (Figure 28E-H) were associated with past uses and have deteriorated. Piers 5-6 are associated with the US Coast Guard Station boathouse in Virginia. This structure is located within an NPS cultural landscape and is eligible for listing on the National Register. Pier 5 serves as a breakwater and clearly has a localized impact to sediment distribution and shoreline position. Pier 1 and 2 and Breakwater 3 remain as safety concerns and non-sandy exotic habitat although they cause little interference with natural processes. They could be removed or allowed to deteriorate further.

Causeway 1 (Figure 29) has been singled out as an example of a commonly-occurring feature on the island. Although not hard structures, causeways function as impediments to surface flow and can separate fresh water and salt water habitat and change both the natural evolution of the island and the proportion of representative environments. The isolation of habitats can occur at small scale and is especially common in the southern third of the island in the Chincoteague National Wildlife Refuge.

Four basic management alternatives have been considered for updating the park General Management Plan (NPS 2011), reflecting intensities of use juxtaposed against potential natural changes. These alternatives represent stages in a spectrum of options corresponding to the degree of

impact of future erosion and sea level rise and thus provide a blueprint for considering future options at other coastal parks. Alternatives include (1) continuation of current management; (2) concentrated traditional beach recreation with human attempts to protect areas of relatively high density use; (3) sustainable recreation and climate change adaptation with minor manipulation of the natural environment to sustain recreational opportunities with alternative means of accessing the island; and (4) natural island evolution and a primitive island experience with support for only day-use recreation. These options are presented for convenience as either-or scenarios in NPS (2011), but the applicability of individual elements within them and the acceptability of the concepts will change through time, implying that adaptive management could be applied to the adoption of any of the elements of these strategies. All four basic alternatives recognize the dynamic nature of the park and the need to move facilities landward as barrier island migration proceeds.



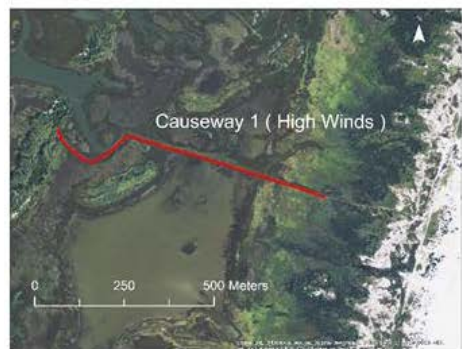
A. Jetty area



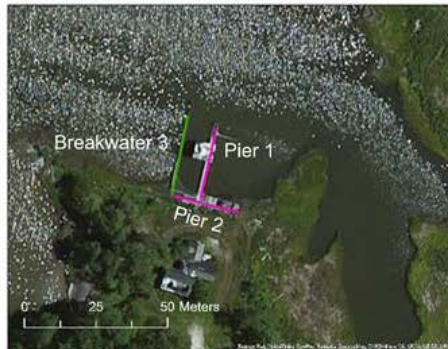
B. Access road, state park area



C. Old Ferry Landing



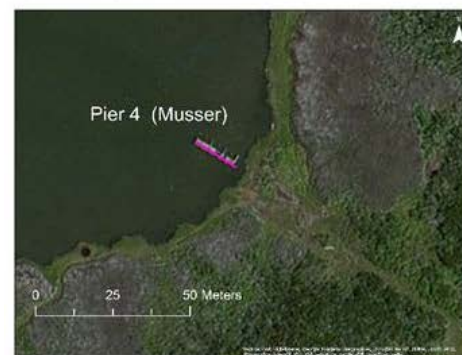
D. High Winds area



E. Jackson's Green Run



F. Clements



G. Musser



H. Coast Guard Station

Figure 28. Structures evaluated at Assateague Island National Seashore.



Figure 29. Causeway 1, High Winds area, Assateague Island, looking west, showing the expanse of water to the south and the parallel ditches created by mining sediment to build up causeway height.

The paved roads, parking lots and campsites are now built at grade and would provide little interference with wave overwash and aeolian transport, except as minor local impediments when they outcrop on the beach due to progressive erosion. Wall 2, Figure 28C, which protects an interpretive facility on the bayside, would resist wave attack directly and prevent natural shoreline change from occurring. Construction of facilities like this is not recommended for the future, but little can be gained in pro-actively removing existing viable protection structures, where removal costs would be high and existing uses would be disrupted at small gains in natural processes and habitats.

Two shore-parallel lines of sand fence are used throughout the development zone to reduce overwash by small storms. The intended strategy is to promote the long term stability of the beach and dune system by allowing some cross-island overwash to occur during future storm events, while minimizing damage to infrastructure by non-storm high tides and wave runup. This use of fences is more compatible with natural barrier island dynamics than the more aggressive dune building projects that occur in the nearby state park. Use of sand fences is a compromise that allows for longer use of existing facilities, but sand fences are a human intrusion that interferes with natural barrier island processes.

Two sites appear to be good demonstration areas for accommodating sea level rise. These are (1) the Oceanside Campground, where retreat can be accommodated with replacement of hard-top surfaces with trafficable but erodible materials and (2) Causeway 1, where the road can be modified to permit flow of water between two basins now largely separated by the structure.

Case study 1: replacing asphalt with unconsolidated sediment

The Oceanside Campground (Figure 27) has a network of asphalt roads and parking sites. Park managers have already considered relocating paved roads and parking areas and using shell or gravel as a surface material in advance of exposure to wave action (Schupp and Coburn 2015). This action is compatible with maintaining human uses while accommodating retreat and promoting resilience in the face of continued erosion and sea level rise. Use of shell or gravel instead of asphalt can reduce cost of construction, facilitate the decision to abandon or relocate infrastructure when threatened, and eliminate problems of exotic debris or costs of removal when damaged. The alternative for addressing erosion at Assateague Island by landward migration of facilities and use of temporary surfaces is thus more compatible with natural processes and less costly than rebuilding fixed buildings and paved parking lots slightly landward (e.g. at Herring Cove Beach in Cape Cod National Seashore). Change in management practice from maintaining stable landscapes and facilities to accommodating natural dynamism is likely to be resisted by some visitors who prefer the status quo. Managers of Assateague State Park may also be reluctant to allow the system to be more dynamic because of recent investments in fixed location facilities and other infrastructure. Good demonstration sites will be valuable for documenting how the retreat option can be accommodated. Implementation of the retreat option outlined in either Alternative 3 or 4 of NPS (2011) would provide a good example for other parks to follow.

Case study 2: modifying Causeway 1

Modification of Causeway 1 (Figure 29) and other similar manmade features along ASIS to re-establish natural flows would provide perspective on actions that can be taken in many locations in NPS and other Department of the Interior lands where earthen roads interfere with coastal dynamics. It will also provide perspective on the effort involved in converting the many locations where impoundments have been artificially built to create or maintain fresh water wetlands immediately landward of estuarine shorelines. Many of those artificially-protected wetlands are now located where their future viability is questionable.

The park has already proposed a project for future funding (NPS 2014b) that is designed to remove abandoned roads and dikes to reestablish natural hydrologic flow patterns and return to natural wetland conditions. Converting dikes and causeways in the park is expected to create new habitats for key species, improve the quality of salt marsh, bay water and habitat for salt marsh fauna and restore the natural wetland zonation governed by tidal influence on the bayside. It is also expected to improve backcountry experience and wildlife viewing for visitors. Project actions include (1) filling the roadside excavation ditches that were formerly used to provide sediment to increase the elevations of the dikes and roads; and (2) lowering the grade, removing or breaching roadbeds to restore more natural tidal flows. Many locations exist where these actions can be applied. Modifications at Causeway 1 would involve some of the biggest changes, so monitoring and documenting the hydrologic and ecological benefits post-restoration would provide a comprehensive picture of the issues involved and demonstrate the improvement in quality of salt marsh habitats. The causeway could be completely eliminated to attempt to reflect conditions that occurred before it was constructed. Alternatively, portions of the causeway could be breached, thus reducing the costs for enhancing flows. Causeways were constructed with local sediments, and reversing the construction

practice could make use of materials already on site. Shrubs that have colonized high ground after driving on them was suspended (Figure 29) would have to be removed, and there would be some temporary adverse impacts from earth-moving vehicles, but restored areas would be expected to re-vegetate by natural recruitment (NPS 2014b).

Suggestions for structure removal

Plans for managing Assateague Island National Seashore recognize and reflect the dynamic nature of the island and provide examples of ways to accommodate future change in light of sea level rise and barrier island migration. The successful implementation of these strategies, which are already planned, will provide good demonstration projects for other coastal parks and conservation areas.

The park should plan for the removal of existing roads and dikes in to mitigate the significant disruption these features have on the natural hydrologic regime. These features have altered the magnitude and spatial extent of tidal flow and natural overwash processes. This corrective action will restore preexisting hydrology and, over time, minimize impacts to the natural evolution of the barrier island.

Fort McHenry National Monument

The situation

The park at Fort McHenry (Figure 30) occupies a small parcel of land at the end of an interfluvial between two branches of the Patapsco River in Baltimore. The river empties into Chesapeake Bay 16 km to the southeast, but maximum fetch distance for generation of storm waves affecting the park is likely to be only about 6.5 km, which is the distance to the Francis Scott Key Bridge and causeway. The portion of the park that is managed for visitor use is high ground that is landscaped using lawn grass and a few specimen trees (Davison and Foulds 2004). The park is protected by a seawall along the shoreline, with riprap toe protection placed in the most exposed portions (Figure 31, Appendix A, Table 11). An asphalt path runs along the perimeter of the park at a distance of about 5 m from the landward edge of the seawall.

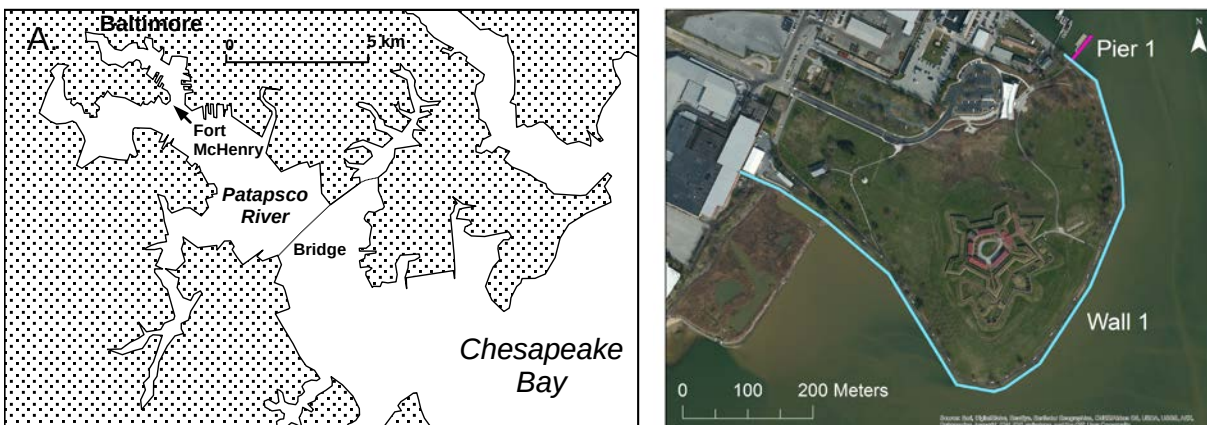


Figure 30. Setting (left panel) and structures evaluated (right panel) at Fort McHenry National Monument.



Figure 31. Wall 1, near the southern portion of Fort McHenry.

Options

Allowing natural shore processes to prevail in the park has limited value. The park is managed as a historic site, so preservation of cultural features would have priority over restoration of natural processes. Fetch distances to the southeast are great enough that erosion of the southeast shore would occur if the seawall were removed. Erosion rates of $0.5\text{--}1.0\text{ m yr}^{-1}$ are common in estuaries with this kind of wave exposure (Nordstrom 1992). A narrow intertidal beach would form, and longshore transport would create shoals or small spits to the northwest and southwest. The fort is about 65 m from the seawall in this area, which implies that it could become subject to damage either from slope failure or direct wave attack in less than 100 years if the wall were removed. Creation of an eroding upland within an intensively developed city environment would provide visitors with an interesting image, but it is questionable whether the habitat would represent the kind of nature that existed in the early 19th century, when the park had its greatest historical significance. Small undeveloped enclaves in urbanized environments are often occupied by exotic flora and by fauna more typical of urban areas (e.g. pigeons and rats) than natural areas (e.g. gulls and rabbits), limiting the value of an undeveloped enclave.

Suggestions for structure removal

Maintaining structural protection for the landscaped and well used park at Fort McHenry appears appropriate.

George Washington Birthplace National Monument

The situation

The shoreline of the park includes a segment of the Potomac River and Popes Creek, one of its tributaries (Figure 32). All of the buildings in the park that are near the shore are in the vicinity of Popes Creek, where the fetch distance for wave generation is less than 1 km. Spits at the mouth of the creek help protect the shore from waves generated in the Potomac by winds from the northeast. Wave energies have been too low to prevent colonization of the shore by vegetation (Figure 32, right panel). This vegetation growth, in turn, makes the shore more resistant to future wave erosion. Sea level rise should not markedly increase the dimensions of the basin within Popes Creek due to the high relief of the surrounding shore. Thus, the energy of locally-generated waves is not expected to increase appreciably in the next several decades. It is not clear if sediment transport along the Potomac shore will be sufficient to maintain the spits across the creek mouth to protect the shore within Popes Creek from waves generated outside the creek basin in the future.

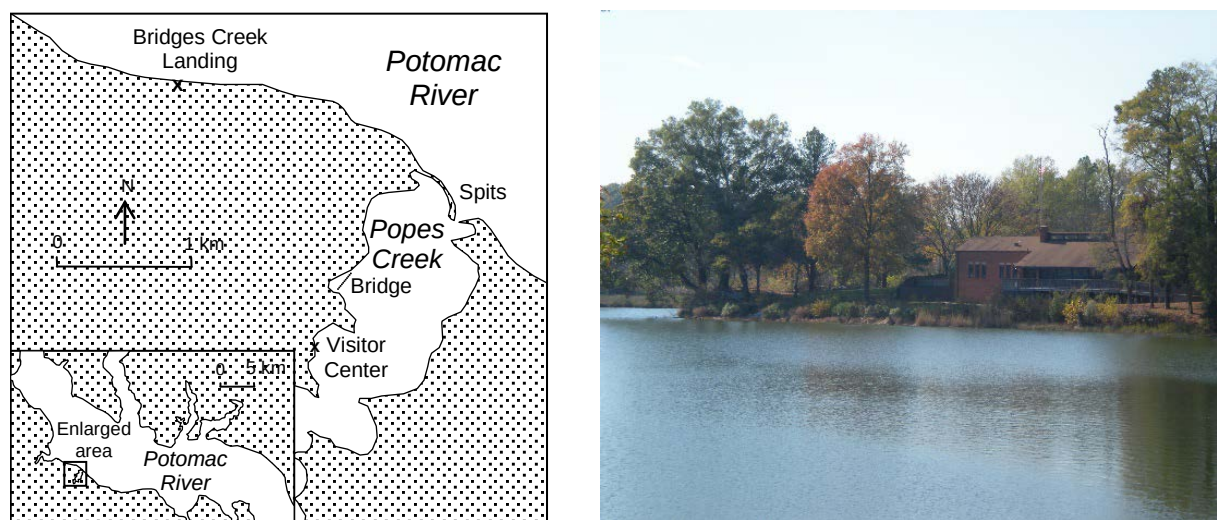


Figure 32. Setting (left panel) and visitor center (right panel) at George Washington Birthplace National Monument.

Options

The visitor center (Figure 32, right panel) is only 10 m from the shoreline. The lack of visual evidence of active erosion of the stream bank implies that there is no immediate threat from shoreline retreat during small storms, but flooding during high intensity storms could be an issue. The potential for flooding will become more of an issue in the future as sea levels rise. A trail along Popes Creek is within a few meters of the edge of the upland bluff and is threatened by slope failures. This need not be a major cause for management concern because the trail is composed of unconsolidated material and can be moved landward with little effort. The single bridge in the park (Figure 32, left panel) is on pilings. This method of construction allows for passage of water and sediment and does not interfere with evolution of the marsh landward of it. The bridge may be inundated by higher water levels in the future, but structural damage to it may be light if waves from the Potomac are dissipated on the spits at the mouth of the creek.

The only structure near the Potomac River is a road end with a small parking area at Bridges Creek Landing. Fetch distance to the east is up to 30 km, resulting in sufficient wave energy to create a relatively wide beach. This beach is supplied by sediment from the eroding bluffs and beach to the east. The parking area is within 30 m of the beach/upland contact, but the lack of an erosion scarp at that contact implies that shoreline retreat is not presently critical. The lack of historical infrastructure or visitor facilities other than the asphalt surface implies that there is little reason to protect the parking area and road terminus if future sea level rise results in an increased rate of erosion of the beach and upland.

Suggestions for structure removal

No action is suggested at George Washington Birthplace. Natural processes are not presently restricted by structures, and no structures are now threatened by natural processes, although there may be calls to protect the visitor center from natural shore processes in the distant future.

Colonial National Historical Park

The situation

Colonial National Historical Park was established to preserve and commemorate the settlement of Jamestown and the battle of Yorktown and link these sites and Williamsburg (Figure 33) with a scenic corridor (parkway) for motorists. Construction of the corridor and the parkway took place between 1931 and 1957 (National Park Service 1997).

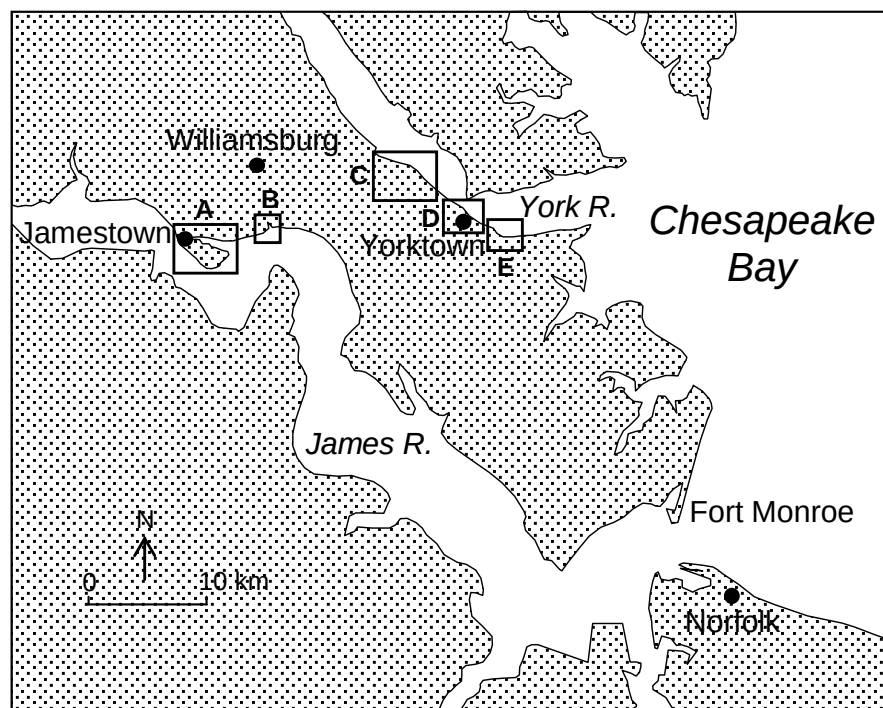


Figure 33. Location of places linked by Colonial Parkway (black dots) and panels (rectangles) identifying structures in Figure 35.

The parkway is a resource listed in the National Register of Historic Places. According to National Park Service (1997), Colonial Parkway is one of the few remaining designated parkways that is considered true to its original design. These kinds of roads were constructed predominantly in the 1930s and 1940s with a design characterized by curving alignments, park-like plantings and limited access points. The shoreline is a key component of the views, vistas, and spatial character, and the parkway retains its intimate relationship to both the York and James River shorelines; changes have occurred in the vistas due to changes in vegetation, but little alteration has occurred in the scenes being viewed (National Park Service 1997).

The shores of the James and York Rivers are fairly typical riverine estuarine environments characterized by intertidal wetlands interspersed with higher bluffs. Dominant waves are generated within the estuarine basins and are relatively low in height with short periods. Like other estuarine shores, erosion rates can be relatively high. Erosion and slope failure is now threatening built structures and archaeological sites close to the shoreline. Erosion is critical because the parkway was intentionally built close to the shoreline (Figure 34). The original Jamestown Island colony was located back from the shoreline when initially settled, but subsequent erosion has caused the shoreline to migrate back toward archeological sites, requiring construction of a seawall.



Figure 34. Colonial Parkway on the York River side, showing proximity to the water.

The shore protection structures at Colonial are primarily riprap revetments and offshore segmented breakwaters (Figure 35, Appendix A, Table 12). Future protection strategies for the York River side include constructing or increasing the dimensions of these structures and building new ones in

selected locations (National Park Service 2012b). The widespread use of shore protection structures along the York and James Rivers within the park has left little of the shore functioning naturally.

The shore protection structures at Colonial are primarily riprap revetments and offshore segmented breakwaters (Figure 35, Appendix A, Table 12). Future protection strategies for the York River side include constructing or increasing the dimensions of these structures and building new ones in selected locations (National Park Service 2012b). The widespread use of shore protection structures along the York and James Rivers within the park has left little of the shore functioning naturally.

Concerns for shore protection along the York River are largely focused on the need to protect the parkway itself. Construction of this road involved partially filling marsh and constricting the openings across streams. Erosion along the Bellfield Strait (along Wall 12, Figure 35C) was recognized as a serious issue as early as 1933, shortly after parkway grading was complete, and protection structures were emplaced even before the parkway opened (National Park Service 2012b).

Most of the protection structures on the York River shoreline were installed between 1930 and 1958 (National Park Service 2012b). A series of recent storms (including Hurricane Isabel in 2003 and Tropical Storm Ernesto and a northeaster in 2006) underscored the vulnerability of the parkway, leading to suggestions to repair and augment existing shore protection structures to protect the parkway and archaeological resources along the bluffs. The road surface of the parkway in the Bellfield Strait segment (Figure 34) is as little as 3 m from the top of the sloping bank of the river (National Park Service 2012b).

Concerns for shore protection along the James River focused on the need to protect the original European colony on the southwest end of Jamestown Island and road access to it as well as archeological sites representing Native American activities on the undeveloped eastern part of the island. Native Americans have occupied the region for over 11,000 years (John Milner Associates, 2006). The European settlement dates from 1607. Shoreline change and sea level rise are also threats to the Civil War earthworks located near College Creek (Figure 35B), and migrating shorelines of creeks that are getting closer to the parkway in places.

Construction of a revetment (Wall 2) on the exposed James River side and a wooden bulkhead (Wall 6) on the landward side of the isthmus has prevented breaching and kept the island attached to the mainland. Longshore transport previously caused growth of a series of easterly-trending beach ridges interspersed with marshes on the southeast portion of the island, but this sediment source for the shoreline has been eliminated with the armoring of the shore (Walls 3 and 4) on the south side of the island. Much of the undeveloped portion of the island is protected by series of detached offshore breakwaters and sills placed along the shoreline.



A. Jamestown Island



B. College Creek area



C. Bellfield Strait



D. Yorktown



E. Yorktown Battlefield area

Figure 35. Locations of shore protection structures at Colonial National Historical Park. Sites identified and drawn based on Dallas et al. (2013a) but number designations of structures and type of structures may differ (see Appendix A, Table 12 for differences).

Options

Most walls throughout the park appear to be in good condition structurally, in part due to the use of stone rip rap, which does not degrade rapidly or become displaced in a low energy environment. Most walls on the developed portion of Jamestown Island have a top elevation corresponding roughly to the elevation of the land immediately behind them when they were built. These elevations are high enough to prevent overtopping at the high ground where historic Jamestown is, but too low to prevent wave overtopping along many portions of the park. Low walls fronting the upland do not prevent wave undercutting and slope failure of the upper portions of the bluffs. Slope failure can also occur independently of wave erosion as a result of the actions of surface runoff, ground water, and freeze-thaw. The low structures will provide less protection from wave overtopping and flooding through time, given the expected rise in sea level.

Many of the walls provide protection for structures with considerable historical value, which argues against removing them. Protecting the parkway in its present location appears to be appropriate due to its historical value, the cost of moving the road, the loss in historical significance if it is moved and the difficulties of securing a right of way for a new road.

In the past, Jamestown Island (Figure 35A) has been attached to the mainland, an island, and re-attached to the mainland by landfill associated with construction of an artificial isthmus.

The parkway is built on an upland. The natural habitats that would be created if protection structures are removed or allowed to deteriorate are eroding bluffs fronted by beaches (similar to the bluff in Figure 36, although often at lesser height). The bluffs have a greatly reduced extent relative to historic conditions. Several locations along the York River have eroding bluffs landward of shore protection structures, but these locations do not retain the full environmental gradient representing the transition from river to beach to bluff.

The historical significance of the location of the original Jamestown and the archaeological value of the artifacts known to be in the ground, limit the potential for allowing portions of that site to revert to natural processes. The breakwaters fronting low upland and marsh on the eastern and southeast portions of Jamestown Island (Figure 35A, 37), in contrast, represent attempts to protect undeveloped land. Some of these locations may have archaeological resources that are worth protecting, but if not, the structures could be removed to allow the shore to function naturally. The reason for constructing the breakwaters and sills in this location is to manage shoreline erosion and protect cultural resources (Hardaway et al. 1999), but not all structures may be needed for these purposes.

Designation as a historical park distinguishes the park somewhat from national seashores and national recreation areas in that no facilities for beach use are provided, and proposed shoreline treatments are not designed to introduce new recreational opportunities either directly or indirectly (National Park Service 2012b). Accordingly, beach nourishment is not considered a principal means of addressing erosion, although small scale fills have been suggested as adjuncts to structural solutions (National Park Service 2012b). The park does face the problem of diminished sediment supply. Creation of new beaches may be undesirable from the standpoint of recreation, but beaches provide natural habitat that is lacking in the park, and longshore transport of sediment to adjacent

eroding areas provides protection against wave attack. These benefits will accrue if bluffs are allowed to erode and supply sediment for wave reworking.



Figure 36. Bluff at the mouth of College Creek (Figure 35B), revealing the kinds of habitats that would form if static structures were removed from uplands along the shore. The beach at this site is narrower than beaches that would be expected to form along the more exposed portions of the York and James Rivers.

Allowing new beaches to form should be encouraged, but active recreational use of beach habitat could be discouraged to allow the habitat to evolve naturally without pedestrian trampling. Eroding bluffs landward of beaches create hazardous conditions, and use could be discouraged for reasons of visitor safety as well maintenance of habitat. Beach recreation in the park has become a serious crowding/parking/traffic issue, leading to installation of fences to control parking outside designated lots. Providing parking near an eroding bluff may have value for interpretive purposes as long as pedestrian use is restricted, but the perimeters of these locations may have to be fenced as well.



Figure 37. Offshore breakwater fronting marsh in the undeveloped portion of Jamestown Island southwest of Wall 5 (Figure 35A).

Case Study 1: removing breakwaters at the Jamestown Island marsh

Use of static structures to protect natural habitats is rare. Breakwaters and sills are being increasingly used to create new marshes in hybrid living shores programs, but not to protect existing marshes. The rationale for the construction of the breakwaters on the southeast end of Jamestown Island (Breakwater Series 1 and 2, Figure 35A, 37) may not be the same rationale that should be used to protect eroding marshes in the future. The existing structures were built in 2002 in a region where historical rates of retreat in the marsh zone were about 0.3 m yr^{-1} (Dallas et al. 2013a). This rate of erosion is not especially high for an exposed estuarine shore. The island has been inventoried for archeological resources and their locations in upland portions are known. There are sites where the shoreline meets upland with resources in the high priority risk category. Marshes were not surveyed because they traditionally have low levels of archeological potential and investigations are difficult to conduct.

The shore southeast of Wall 4 consists of a thin barrier beach fronting a series of northeast-southwest trending former spits that represent accretion from sediments delivered alongshore from the formerly eroding uplands bluffs now protected by Walls 3 and 4. Marshes have formed in the shelter provided by the barrier and spits. The elimination of bluff sediment has contributed to the erosion of the southern and southeastern portion of the island. The installation of breakwaters seaward of the low spits further reduces the amount of sediment delivered to the southeast, reducing the likelihood that a new spit will form to protect the marsh on the southeast end of the island. Several archaeological sites have been identified in the high ground in the barrier and spits (Hardaway et al. 1999), making removal of breakwaters fronting uplands in the western section of Breakwater Series 1 a low priority.

Jamestown Island would make a good test case for issues involved in providing new structural protection for marshes that are threatened by future erosion. Breakwaters restrict erosion but interfere with the sediment recycling system by reducing or preventing sediment inputs from local headlands and marsh fronts directly landward of the structures. Breakwaters fronting portions of the marsh on the southeast end of Jamestown Island could be removed if they do not protect park infrastructure, cultural landscapes, historic structures, or known archaeological resources, but the lack of impact on resources would have to be proved to avoid a potential adverse effect under Section 106 of the National Historic Preservation Act. The breakwaters have changed the processes defining the marsh margin and sustaining the landward portions of the marsh, and they have changed the natural character of the marsh. It is not likely that visitors think of these structures as part of a recreational experience or that they contribute to the aesthetic appeal of the historical landscape. Removal of the breakwaters would increase the erosion rate of marshes landward of them. The erosion rate may increase with future rise in sea level, but this rise would also diminish the effectiveness of the breakwaters if left in place. Breakwater elevations could be increased to retain their current function of protecting erosion of the margin of the marsh, but increases in elevation would not prevent inundation of the surface. If archaeological resources exist in the marsh landward of these structures, they would be inundated as well. An important but undocumented scientific issue is whether preventing tens of meters of erosion of marsh fringe by wave attack over the next several decades causes a larger area of marsh to be lost through inundation.

If the riprap comprising the structures is removed, it could be used locally to increase the elevation of the breakwater protecting Black Point (at the north end of Wall 5, Figure 35A). Black Point is the final destination of a popular path to the easternmost point of the island, and there is a known archaeological site there. The surface elevation is low, and the breakwater fronting it will have diminished value as protection as sea level rise continues. The upland extending south of Black Point has remains of facilities built by the Confederates in the Civil War.

Case Study 2: removing the bulkhead at the Jamestown isthmus

The grassy area landward of the southeastern portion of Wall 6 on the isthmus (Figures 35A, 38) could be allowed to evolve into a natural environment to resemble the habitat just to the northeast of it. Portions of the bulkhead could be removed to allow for inundation during high tides or raised water levels during storms. The wave energies in this fetch-restricted environment would be too low to prevent vegetation from growing along the new shoreline and would likely be too low to erode higher portions of the bank that exist between the low upland and the access road on top of the isthmus. Once a marsh evolved, the vegetation would provide additional protection by dissipating waves moving across the restored surface. The road is high enough that flooding would not be an issue.

The surface of the grassy area could be graded to an elevation corresponding to the present intertidal frame to allow for restoration of marsh under present sea levels, or the present elevation could be retained and the habitat could be allowed to evolve to marsh as water levels rise. Continuation of past precedent in the face of sea level rise would likely result in construction of a new, higher bulkhead,

with continued maintenance of the lawn. That action would likely be more expensive than allowing the location to revert to natural habitat.



Figure 38. Bulkhead (southeast portion of Wall 6) protecting low grassy area landward of causeway to Jamestown Island in a location suitable for future marsh development.

Suggestions for structure removal

Colonial National Historical Park differs from many coastal parks managed by NPS in that (1) many protection structures were built to protect eroding shores with no infrastructure; (2) many of these structures are offshore breakwaters; and (3) there is little interest in creating new beaches as habitat or recreational amenity. The widespread use of shore protection structures along the York and James Rivers has left little of the shore that is functioning naturally.

Plans to increase the effectiveness of revetments protecting the parkway along the York River are consistent with the need to protect the infrastructure, but plans to construct new breakwaters seaward of existing protection structures (National Park Service 2012b) are counter-intuitive, in that they are attempts to advance the shore in the face of the natural trend of coastal retreat. Protecting marshes using structures is of questionable value. Further consideration of allowing remaining bluffs to evolve naturally appears warranted, as is a more careful evaluation of tradeoffs between protecting archaeological resources in place (based on their significance and vulnerability) and allowing natural processes to proceed, given the increasing difficulty of providing protection in the face of sea level rise.

Discussion

Overcoming impediments to facilitating landform migration

Impediments to taking a pro-active approach to adapting to sea level rise by removing structures include (1) conflicting policy directives; (2) presence of paleontological resources and critical cultural resources and infrastructure; (3) lack of data to make informed decisions; (4) lack of funds and human resources to implement meaningful actions; (5) reluctance to replace a known set of problems with an unknown set of problems; (6) anticipated opposition to altering the status quo; and (7) reluctance to allow erosion to occur. Conflicting policy directives are most often associated with different agencies, but the NPS mission to protect cultural and natural resources result in conflicts within the same agency. Although adaptation is now being promoted (NPS 2010; Schupp et al. 2015), few examples of actual projects exist in the NPS (Jantarasami et al. 2010). The lack of a current use for many buildings in coastal parks, combined with the nature-protection mandate of the NPS, would seem to make the decision to accommodate natural changes to erosion and sea level rise easy, but existing policies for protection of natural and cultural resources make clear the need for parks to exercise discretion in making the tradeoffs between natural, cultural and recreational resources. This issue is especially important in parks like Colonial, which has enabling legislation and a purpose for the preservation of cultural resources. Nevertheless, NPS is aware of its opportunities for taking a leadership role in adapting to sea level rise and demonstrating how the public can reduce the impact of climate change by interpreting sustainable practices in parks (NPS 2010). The recent NPS policy documents underscore the need to provide better data defining the importance of park assets relative to new hazards and allowing some built and natural resources to be abandoned rather than rebuilt or restored following storms. Many of the protection structures and the facilities they protect are classified as contributing resources. The importance of a contributing resource may have to be reevaluated in light of present policy changes and the increasing difficulty of protecting against future sea level rise. Priorities are changing and will continue to change in the future.

Threats to critical cultural resources by coastal erosion are occurring in many parts of the world (Erlandson 2012; Milner 2012) as well as in NPS-managed parks (Maio et al. 2012), but little guidance exists in the management literature to determine when strategies to manage these threats should take precedence over competing strategies to manage habitat losses. Consideration for stabilization, in the form of new structures or repair of old structures, is likely to be appropriate in some areas but not all areas. An important issue is whether the specific site of the threatened cultural resource is a key to its value. The perception that unknown buried archaeological resources exist could be a deterrent to allowing natural processes to prevail, but allowing shorelines to erode is also a way of identifying unknown resources. The Carns site, a significant archeological find at Cape Cod, was revealed by coastal erosion in 1990. A rapid excavation of the 300 m² site filled gaps in human settlement history, even as storms ensured its loss. Many coastal archaeological sites are discovered in this way (Milner 2012). There is virtually no part of Jamestown Island that does not contain archeological resources of some kind, and the landscape still may yield undiscovered information (John Milner Associates 2006).

A more thorough investigation of specific archaeological sites would have to be conducted if consideration is given to remove shore protection structures or allow them to degrade. Excavations can more easily occur with these structures in place; excavations conducted later, when the resources are in the tidal zone, may require a coffer dam. Decisions will have to be made about whether the archaeological resources have greater value remaining in situ rather than being collected and incorporated into museum collections. Data would be required to back up the management decision. Sites that did not have a phase II survey would require one. If after the phase II survey the sites were deemed not eligible for inclusion to the National Register of Historic Places, the structures could be removed with a finding of “no adverse effect” pursuant to section 106 of the National Historic Preservation Act.

Impacts to cultural resources will also occur from rising water tables including effects of land subsidence combined with rising sea levels (e.g. Jamestown Island). Some archeological studies are starting to address the effects of marsh migration due to rising sea levels and water tables (Bickler et al. 2013; Newland 2013). NPS (2010) suggests expanding the NPS capacity to inventory and monitor archeological sites in anticipation of climate change impacts and increase the capacity of their museum program to preserve and protect resources.

Lack of data is a common reason for forestalling any management decision (Jantarasami et al. 2010). This problem is pronounced in predicting the future, because real-time data on future changes cannot exist, greatly increasing the uncertainty associated with potential actions. Changes can be modeled, but there is no guarantee that the new processes and end stage (even if the concept of a final stage is applicable) will resemble the target characteristics. Adaptive management will be an important key for maintaining resources in national parks given the high level of uncertainty associated with forecasting future climatic conditions (Harris et al. 2012). Adaptive management requires ongoing monitoring and assessment, which will provide data for anticipating potential outcomes of new projects in other areas.

Removal or relocation of structures will require economic resources, but plans that work with, rather than against, natural processes may result in land uses that are more sustainable or require less management input in the long-term. Having prototype strategies and demonstration areas in place may improve planning for future adaptation. Many of the existing shore protection structures in NPS parks would have to be raised or provided with splash protection against wave overtopping to make them effective barriers against future sea level rise. These new costs may make the alternative of removing shore protection structures and relocating buildings and human uses farther landward more attractive.

Some changes to shore protection practices may be resisted by stakeholders outside the parks. All parks have nearby lands managed to achieve policies or interests that may contrast with those of NPS. Some public and private organizations manage properties as enclaves within park boundaries, including other government and non-government organization (NGO) ownership of facilities at Boston Harbor Islands, private homes and communities within Fire Island and Cape Cod, and a state park on Assateague Island. Allowing natural processes to occur unimpeded in parks may threaten properties outside park boundaries and limit adaptation actions.

Managers in several parks have considered relocating user facilities farther from the shoreline, but resistance to relocation by park visitors can be strong. Provision of access to the shoreline is a key requirement, but this access does not have to be made as convenient as in the past. Transportation systems have become perceived as less of an intrusion than embedded components of the landscape that allow visitors to get to places and have the experience of viewing nature while driving (Hallo and Manning 2009; Youngs et al. 2008). Nevertheless, shorefront roads are major constraints to allowing natural processes to occur. Placing new facilities farther back than was customary in the past will still allow visitors the opportunity to experience the coast. Visitors may argue for more convenient access, but education programs may help them understand the true nature of the hazard and the tradeoffs involved in constricting the space for nature to evolve.

Good demonstration sites are important in aiding stakeholder acceptance of retreat strategies (Parrott and Burningham 2008; Nordstrom and Jackson 2013; Nordstrom et al. 2015), but the initial sites for removal of protection structures may have to be in locations where change will be most easily predicted and accepted. The human preference for the status quo will always be a deterrent to strategies that allow freer interplay of natural processes (Leafe et al. 1998; Tunstall and Penning-Rowsell 1998; Jeschke and Succow 2001), but equating maintenance of the status quo with the concept of stability cannot be applied in a dynamic coastal environment. Fear of the unknown effects of removing structures can be overcome by adopting a better perspective on the advantages of allowing coastal processes to occur unimpeded and by demonstrating the positive benefits of an eroding shore for adaptation to climate change.

Rebuilding facilities farther landward at Cape Cod, removing bulkheads at Gateway and relocating roads and parking areas and rebuilding them in a more environmentally-compatible way at Assateague are promising ways of demonstrating adaptation strategies. These actions occurred after the original structures became damaged. Storms are opportunities for adaptation when the prior planning and compliance are in place to take advantage of post-storm funding. Our preliminary assessment is that the number of structures that can be removed is great (Table 4), although the settings and landform assemblages vary considerably. These differences point to the need to develop a greater spectrum of adaptation projects within parks (including elevating facilities) that have a mix of important cultural and natural resources. The cost of removing structures and difficulties of obtaining approval from state historic preservation offices, conducting environmental assessments, obtaining permits and addressing the concerns of stakeholders will take time and effort. Having examples of successful projects will aid implementation of future projects. Designs that work with natural processes, such as erosion, are likely to be viewed as successful if the result (new sediment source or rejuvenated habitat) is specified in advance as a positive product.

Under natural conditions, the characteristic features of eroding landforms and their resulting habitat and aesthetic values are self-generating, in that erosion may displace the system farther landward or alongshore but the active processes will proceed unimpeded, restoring similar landforms in a new location. The physical functioning or integrity of the shore system are not compromised by erosion (Cooper and McKenna 2008). Losses to naturally functioning landforms and habitats occur where

human alterations prevent their reestablishment, which argues against use of static shore protection structures.

The importance of allowing erosion to occur and maintaining the coastal sediment budget is not a new concept (Pilkey 1981), but the importance of maintaining the linkages in sediment exchange from local to regional scales is more pressing than in the past, and accomplishing the task is more difficult. Past erosion control strategies to protect cultural resources have sequestered sediment. Finding ways of living with natural erosion of beaches, dunes and bluffs will help alleviate the need to exploit external sediment sources in beach nourishment operations.

Environmental impact statements that accompany designs for shore protection projects rarely present no-action alternatives in the best light. This is not surprising because the projects are site-specific and erosion is assumed to eliminate coastal resources, rather than displacing them, or that the resources associated with eroding landforms are not of value. A distinction should also be made between the concept of change and the concept of loss.

A major issue in adapting to shoreline change is that the specific landforms and habitats that will form by allowing natural processes to prevail cannot be specified in advance. These difficulties of prediction should not deter efforts to provide the space to accommodate the unknown changes that will occur (Barbour and Kueppers 2012). Sediment released from eroding dunes and bluffs can remain in place or move alongshore to be either reworked into beaches, dunes or marshes in adjacent areas. It may be tempting to control locations of scour and accretion using structures, earth moving machinery or vegetation plantings, but these hybrid environments may not be sustainable under natural conditions. There is a need to recognize that natural processes will produce new landforms and habitats that will eventually perform functions of equal or greater future value than existing eroding features.

Removing structures versus allowing them to deteriorate

Protection structures that are no longer considered necessary can be either removed or allowed to deteriorate in place. Allowing the structures to deteriorate may cost nothing, but construction materials would remain in the intertidal and subtidal zones (Nordstrom and Jackson 2013). Removing structures that are already in the water may be rendered difficult where strict state or national environmental regulations may prevent alteration without a comprehensive impact assessment. Allowing structures to deteriorate may be perceived as benign neglect and have some negative issues, but its formal adoption is actually a proactive approach to accommodating sea level rise that may be economically and environmentally acceptable. Most deteriorating structures may not compete well for limited project funds.

Removal of some structures would be difficult because of the high costs of gaining access for mechanized equipment or breaking up massive structures. Removal of even small protection structures will be costly, but removal can result in the most rapid reversion to a fully functioning natural system. Deteriorated structures may also be an eyesore and potential safety hazard even if not an ecological issue. Little value exists in leaving shore protection structures that can be readily removed or that can be altered to make them more environmentally compatible. Costs of removing

riprap structures can be defrayed by re-using the construction materials elsewhere, such as the rocks that could be removed from Groin Field 1 at Sandy Hook (Nordstrom and Jackson 2013) or the rocks at Lovells Island (Figures 12) that could be used to protect the fort on Georges Island.

Retaining or rebuilding protection structures

Rising sea levels will increase erosion of uplands and flooding of lowlands. Protection structures built in the past will become less effective due to deterioration with age and because their design elevations are based on lower sea levels and breaking wave energies. Some protective walls will have to be repaired or rebuilt (e.g. at historic Jamestown and along Colonial Parkway). New structures may be appropriate in some areas. The greatly increasing costs of protecting facilities will likely restrict new projects to protection of the most critical facilities. Significant gains in natural habitat may not be obtainable by removing shore protection structures where the surrounding land will continue to be maintained for intensive human use. Fort McHenry is the most obvious example. Maintaining protection for access roads and bridges is likely to be required, until use of these facilities becomes untenable because of loss of linkages to landward roads and causeways due to broader-scale impacts of sea level rise. Some historic buildings may not be presently functional, but the architecture or past use may make them worthy of protection in place, and the cost and difficulty of removing them may be excessive, e.g. Officer's Row on Sandy Hook (Nordstrom and Jackson 2013). The cost of remediating polluted or otherwise undesirable sediment from entering coastal waters may argue for providing new protection structures to seal up filled land. Other examples of the need to maintain or build shore protection structures exist, but the purpose of this report is to make the case for removal of structures, which has fewer precedents and requires greater documentation of benefits. A strong, integrated approach regarding the stewardship of cultural resources is needed to complement this report.

Where new protection structures are considered necessary, placing them as far back from the water as possible would provide space for natural landforms and habitats to develop. The expected future increases in sea level elevation will accelerate landward displacement of shorelines. Placing protection structures farther offshore than the current shoreline (such as building offshore breakwaters, as done at Jamestown Island (Figure 35A), or building bulkheads out into the water and backfilling them, as suggested for protecting the chapel at Sandy Hook (Figure 25A), are counter intuitive strategies, given sea level rise.

Removing functional buildings and changing landscaping practices in human-use areas

Some buildings that are still functional but threatened by erosion and flooding can be relocated, thus saving the cost of building new protection structures and ensuring maintenance of natural habitat. The precedent for moving infrastructure has already been established at the bathhouse at Herring Cove Beach on Cape Cod (National Park Service 2013). Two lighthouses at Cape Cod were also relocated in the past 20 years after much discussion and compromise about preserving their relationship to the coast and the need to protect them from erosion. Removal of the lighthouse at Cape Hatteras also demonstrated the viability of the option for massive structures. The chapel landward of Walls 3 and 4 on Sandy Hook (Figure 25A) is another good location to demonstrate

willingness to accommodate sea level rise and reversion to a naturally functioning environment (Nordstrom and Jackson 2013). Past management practice would likely have resulted in construction of a new protection structure, with continued use of the chapel and maintenance of the lawn surrounding it. Allowing the site to revert to natural processes would establish a precedent in a highly conspicuous location in a developed area (Nordstrom and Jackson 2013). Allowing human-altered environments to revert to natural processes may require rethinking the way the landscape is maintained as well as the way buildings are used, resulting in reevaluation of lawn grass as a landscaping agent.

Conclusions

Protection structures built in the past will become less effective as they deteriorate with age or their design elevations are exceeded. The increasing costs of protecting facilities will likely restrict new projects to protection of only the most critical facilities. Many landforms and habitats that are now stabilized will be subject to increased erosion or flooding whether shore protection structures remain in place or are removed. Protective walls could be removed or allowed to deteriorate through time in accordance with NPS policy to allow natural processes to prevail. Removal is a way of restoring habitats more fully in addition to addressing safety issues. Under natural conditions, the characteristic features of eroding landforms and their resulting habitat and aesthetic values are self-generating, in that erosion may displace the system farther landward or alongshore but the active processes will proceed unimpeded, restoring similar landforms in a new location. Management actions that seemed appropriate in the past and have shaped our image of the present must be tailored to the needs of the future. Managers are encouraged to accept that natural processes will produce new landforms and habitats, with associated ecosystem functions, and the distinction between the concept of loss (erosion of existing landforms and habitats) and the concept of gain (evolution of new landforms and habitats) should be made clear. A way of reevaluating past actions that placed human facilities close to the shoreline or constricted natural processes and habitats is important to allow for future actions unfettered by past decisions. Developing a new method for ranking and decommissioning resources, whether cultural or natural, would facilitate this reevaluation process. The many systems, processes and requirements that removal projects would be subjected to suggest that a workshop on ways to proceed would be an important next step.

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Appendix A: Characteristics of shore protection structures evaluated for removal

No protection structures interfere with shore processes at Sagamore Hill National Historic Site and George Washington Birthplace National monument.

Table 1. Shore protection structures within Acadia National Park.

Location	Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
Isle au Haut	Pier 1	Unknown	54	Perp.	Vegetated upland	Good	Low	Rocky upland	Pier does not appear to interfere with processes or landforms
Mount Desert Island	Wall 1	Riprap	1381	Parallel	Road; forest	Good	Low	Steep, rocky upland	Wall protects road; road would be difficult to relocate because of steep bedrock.
	Wall 2	Riprap	242	Parallel	Road; vegetated fill upland	Good	Low	Landfill causeway	Wall protects road; road would be difficult to relocate because of requirement for new causeway.
	Wall 3	Riprap	176	Parallel	Road	Good	Low	Landfill causeway	Wall protects road; road would be difficult to relocate because of requirement for new causeway.
	Wall 4	Riprap	199	Parallel	Road	Good	Low	Landfill causeway	Wall protects road; road would be difficult to relocate because of requirement for new causeway.
	Wall 5	Riprap	67	Parallel	Road	Good	Low	Landfill causeway	Wall protects road; road would be difficult to relocate because of requirement for new causeway.

Location	Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
Mount Desert Island (continued)	Wall 6	Riprap	107	Parallel	Road	Good	Low	Landfill causeway	Wall protects road; road would be difficult to relocate because of requirement for new causeway.
	Wall 7	Fitted stone	54	Parallel	Road; wetland; forest,	Good	Low	Perched wetland; steep, rocky upland,	Wall protects road, which would be difficult to relocate because of wetland and rocky slopes.
	Wall 8	Fitted stone	193	Parallel	Road; tidal basin, forest	Good	Low	Bayhead bar converted to causeway, adjacent to rocky upland	Wall protects road, which would be difficult to relocate because of wetland, rocky slopes.
Schoodic Peninsula	Pier 2	Walkway on pilings	64	Perp.	Grassy field used as picnic area	Good	Low	Low upland	Structure does not interfere with processes or landforms.
	Wall 9	Fitted stone	129	Parallel	Road	Good	Low	Filled causeway leading to bridge	Wall protects road, which would be difficult to relocate.
	Wall 10	Fitted stone	121	Parallel	Road	Good	Low	Filled causeway leading to bridge	Wall protects road, which would be difficult to relocate.
	Wall 11	Riprap	106	Parallel	Road; wetland, forest	Good	Low	Impounded wetland in former stream valley landward of road	Wall protects road, which would be difficult to relocate.
	Wall 12	Riprap	74	Parallel	Road; freshwater wetland; forest	Good	Low	Former valley cutoff by causeway	Wall protects road, which would be difficult to relocate.
	Wall 13	Riprap	46	Parallel	Road; forest	Good	Low	Low upland	Wall protects road, which would be difficult to relocate.
	Wall 14	Riprap	133	Parallel	Road; pond; forest	Good	Low	Freshwater pond, low upland	Wall protects road, which would be difficult to relocate.

Location	Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
Schoodic Peninsula (continued)	Wall 15	Riprap	118	Parallel	Road; shrub upland; shrub wetland	Good	Low	Low gradient slope	Wall protects road, which would be difficult to relocate.
	Wall 16	Riprap	37	Parallel	Road; forest	Good	Low	Rocky upland	Wall protects road, which would be difficult to relocate.
	Wall 17	Riprap	37	Parallel	Road; forest	Good	Low	Rocky upland adjacent to pond	Wall protects road, which would be difficult to relocate.

Table 2. Shore protection structures within Salem Maritime National Historic Site.

Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
Pier 1	Wood	22	Parallel	Wall 2; building; road.	Good	Low	Derby Wharf; low grassy upland.	Removal of pier would have little effect due to wharf.
Pier 2	Wood	24	Parallel	Wall 2; road.	Good	Low	Derby Wharf	Removal of pier would have little effect due to wharf.
Pier 3	Wood	27	Parallel	Wall 2; road.	Good	Low	Wharf	Removal of pier would have little effect due to wharf.
Wall 1	Quarry stone, cement	45	Parallel	Parking area; road; house.	Good	Low	Developed upland.	Urban development adjacent to park would be threatened.
Wall 2	Wood, stone, Cement	1,644	Parallel	Derby Wharf; lighthouse; buildings; road.	Good	Low	Artificial fill (Derby Wharf); upland; road.	Urban development adjacent to park would be threatened.

Table 3. Shore protection structures within Saugus Iron Works National Historic Site.

Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
Pier 1	Wood	11	Perp.	Wall 1, lawn grass; path; Iron Warehouse; Forge	Good	Low	Low backfill area backed by steeply rising upland.	The pier has limited effect on upland evolution.
Wall 1	Wood	31	Parallel	Pier, lawn grass, path; Iron Warehouse; Forge	Good	Low	Low fill backed by steeply rising upland.	The steep upland and proximity of historic structures would limit the extent of natural environment, but the cultural features can be relocated.
Wall 2	Fitted stone	31	Parallel	Path, lawn grass; Rolling and Slitting Mill	Good	Low	Low upland or fill backed by steeply rising upland.	The steep upland and proximity of historic structures would limit the extent of natural environment, but the cultural features can be relocated.
Wall 3	Fitted stone	55	Parallel	Path, lawn grass; Blacksmith Shop	Good	Low	Low gently rising upland.	The steep upland and proximity of historic structures would limit the extent of natural environment, but the cultural features can be relocated.

Table 4. Shore protection structures within Boston Harbor Islands National Recreation Area.

Island	Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
Bumpkin	Pier 1	Wood; Stone at pier end	73	Perp.	Grave; beach; ranger facility; wooded vegetation.	Good	Low	Stable upland on drumlin.	Pier has no effect on beach and upland change alongshore; no reason to remove stone bulkhead at end of pier.
Deer	Groin 1	Riprap	196	Perp.	Beach; wall 3; open field.	Fair	Low	Filled former lowland.	Erosion of beach would threaten facility; Wall 3 limits development as natural habitat
	Groin 2	Riprap	77	Perp.	Beach, open field.	Fair	Low	Filled former lowland.	Erosion of beach would threaten facility; Wall 3 limits development as natural habitat; treatment plant limits options.
	Groin 3	Riprap	93	Perp.	Beach, open field.	Good	Low	Filled former lowland.	Erosion of beach would threaten facility; Wall 3 limits development as natural habitat; treatment plant limits options.
	Pier 1	Unknown/ asphalt	147	Perp.	Deer Island Waste Water Treatment Plant.	Good	Low	N/A: totally developed.	Upland not maintained as natural habitat; treatment plant limits options.
	Wall 1	Concrete/ riprap	819	Parallel	Parking lot; trail; meadow; trees; burial ground; cemetery.	Good	Low	Drumlin	Erosion would threaten access; treatment plant limits options.
	Wall 2	Concrete/ riprap	1320	Parallel	Deer Island Waste Water Treatment Plant.	Good	Low	Drumlin; fill.	Upland not maintained as natural habitat; treatment plant would be vulnerable to wave attack.
	Wall 3	Unknown/ riprap	404	Parallel	Waste Water Treatment Plant; meadow.	Good	Low	Filled former lowland.	Upland not maintained as natural habitat; treatment plant limits options.
Deer (continued)	Wall 4	Unknown	339	Parallel	Waste Water Treatment Plant.	Good	Low	Drumlin; filled former lowland.	Upland not maintained as natural habitat; treatment plant limits options.

Island	Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
	Wall 5	Riprap	1350	Parallel	Waste Water Treatment Plant; parking lot; road; trail; meadow.	Good	Low	Drumlin; human-altered landscape.	Upland not maintained as natural habitat; treatment plant limits options.
	Wall 6	Riprap	39	Parallel	Deer Island Foghorn.	Good	Low	Shoal	No new critical habitat would be created; existing rocky intertidal habitat may have value.
Gallops	Pier 1	Wood	77	Perp.	Beach; wooded upland.	Good	Low	Drumlin	Pier has negligible effect on waves, currents and shoreline change
	Wall 1	Fitted stone/ riprap toe	1061	Parallel	Beach; grass; shrubs; wooded patches; buried structures.	Fair	Medium; may have to rebuild due to asbestos	Drumlin; spit to east.	Eastern ends of wall function as groins and hold beach in place. Other parts of wall may be critical because asbestos found in construction materials; allow to erode if pollutants removed.
	Groin 1	Riprap	189	Perp.	Beach; wooded upland.	Good	Low	Cuspate spit; drumlin.	Groin holds beach in place and stabilizes location of pier.
Georges	Pier 1	Wood	61	Perp.	Visitor center; road; beach.	Good	Low	Fill, graded landscape.	Pier accommodates boats for visitors. Development landward limits habitat potential.
	Pier 2	Wood/ fitted stone	266	Parallel/ perp.	Beach; road; ranger station.	Good	Low	Fill, graded landscape.	Pier accommodates boats for visitors. Development landward limits habitat potential.
	Wall 1	Fitted stone	1131	Parallel	Grass; shrubs; scattered trees; Fort Warren; road.	Good/fair	Low	Drumlin; filled and graded.	Wall protects fort, which is an important visitor attraction.
Georges (continued)	Wall 2	Fitted stone	110	Parallel	Visitor center; road; grass.	Good	Low	Drumlin; filled and graded.	Wall protects visitor center and land connection to pier.

Island	Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
Grape	Pier 1	Wood/ bulkhead landward	88	Perp.	Beach; mowed lawn; building foundation; woods.	Good	Low	Drumlin; low upland to east.	Only pier providing access; removal of bulkhead would result in minimal new habitat.
Great Brewster	Wall 1	Riprap/ cement	862	Parallel	Remnants of WWII military structures.	Poor	Low; let deteriorate	Drumlins	Structures have little visitor value. Cliff already evolving naturally in lee of deteriorated wall.
Little Brewster	Pier 1	Concrete on land	50	Perp.	Coast Guard navigational aid facility.	Good	Low	Bedrock island.	Access to facility required. Removal would not enhance bedrock habitat.
Long	Pier 1	Wood; built as a bulkhead	70	Perp.	Vegetated bluff; road; Long Island Health Campus facilities.	Fair	Low, let deteriorate	Drumlin; beach.	Beach accretion to the north and erosion to the south indicates that pier has groin effect, but erosion downdrift is not severe enough to result in conspicuous bluff failure.
	Pier 2	Wood	143	Perp.	Road; camp facility just landward.	Good	Low, let deteriorate	Base of drumlin.	Pier has value for camp and lighthouse access and could have value for access to Fort Strong area if tombolo connection in the low area currently used as camp recreation fields is threatened in future, but facility is not high priority visitor site.
	Wall 1	Riprap	110	Parallel	Bridge/road	Good	Low, rebuild	Drumlin, pine forest.	Wall protects bridge abutment; bridge was removed in winter 2014-15.
Long (continued)	Wall 2	Riprap fronting cement	179	Parallel	Long Island Health Campus facilities.	Good	Low	Tombolo connecting drumlins.	Structure protects facilities that are still in use.

Island	Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
	Wall 3	Fitted stone; rip-rap toe	1399	Parallel	Woodland; remnants of Fort Strong.	Good	Low, let deteriorate	Drumlin upland.	Erosion of bluff would create naturally functioning beach-upland contact and supply sediment to beaches; SW portion protects pier
	Wall 4	Riprap	125	Parallel	Vegetation	Fair	Low	Drumlin, building.	Protects building, but value of building undetermined.
Lovells	Groins 1-3 (Groin field 1)	Riprap harbor structure	71, 63, 62	Perp.	Open water.	Fair	Low, let deteriorate	Marsh, former battery.	Structures have no value in protecting upland; they can be removed, but their intertidal position may result in permit and EIS requirements that are not worth the effort.
	Groin 4	Riprap	41	Perp.	Wall 2; beach.	Poor	Low, let deteriorate	Beach	Wall 2 would still prevent natural evolution.
	Pier 1	Wood	95	Perp.	Dirt road; small 8m building	Good	Low	Upland (till)	Pier provides access to island, which is well used.
	Wall 1	Riprap	1119	Parallel	Battery Terrill; Beach; upland vegetation; marsh.	Poor	Medium, let deteriorate or remove	Drumlins, tombolo, with transgressing washover ridges fronting saltmarsh.	Erosion of bluff would create a naturally functioning beach-upland contact. Rip rap could be removed and reused (see text). See comment above on Harbor structures 1-3 for extension of this wall on the west side of the island.
Lovells (continued)	Wall 2	Riprap	335	Parallel	Batteries Williams and Whipple; open water; beach.	Poor	Low, let deteriorate	Former spit, fill in places	Structure now functions as a sill. Eventual erosion would create a naturally functioning beach-upland contact.

Island	Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
Moon	Wall 1	Riprap	1749	Parallel	Road; old treatment facility; firefighter training; vegetation.	Good	Low	Causeway, upland at east end.	Wall protects causeway and historic stone sewage tunnel as well as access to facilities at east end.
Moon (continued)	Wall 2	Unknown	337	Parallel	Firefighters' training area; road.	Good	Low	Developed upland.	Protects user facilities and bridge abutment at east end.
	Wall 3	Riprap	299	Parallel	Road; police firing range.	Poor	Low	Developed upland.	Protection of road important for access to facilities.
Nut	Groin 1	Riprap	144	Perp.	Road; trails; open field.	Good	Low	Drumlin remnant.	Removal of structures would be expensive. A dynamic, temporary environment close to residential development would be of little value.
	Pier 1	Unknown	116	Perp.	Road; trails; grassy open field.	Good	Low	Drumlin remnant or fill.	Removal of structure would be expensive. Creating a dynamic and temporary environment at expense of pier would be of little value.
	Wall 1	Riprap/ Cement	715	Parallel	Road; trails; open field; sewage treatment plant.	Good	Low	Drumlin remnant; filled tombolo in south.	Removal of structures would be expensive. Creating a dynamic and temporary environment close to residential development would be of little value.
Nut (continued)	Wall 2	Riprap	122	Parallel	Road; trails; grassy open field.	Good	Low	Drumlin remnant or fill.	Removal of wall would be expensive. Creating a dynamic and temporary environment close to development would be of little value.

Island	Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
	Wall 3	Riprap	324	Parallel	Sewage treatment plant; trails; open field.	Good	Low	Filled tombolo.	Removal of wall would be expensive. Creating a dynamic and temporary environment close to residential development would be of little value.
	Wall 4	Unknown	16	Parallel	Sewage treatment plant.	Good	Low	Drumlin remnant; filled tombolo in south.	Removal of wall would be expensive. Creating a dynamic and temporary environment close to residential development would be of little value
Outer Brewster	Pier 1 (Desalinization Plant)	Concrete	30	Perp.	Fort Jewell concrete barracks.	Poor	Low	Bedrock island.	Minimal new habitat would be created; safety less of an issue on undeveloped island where access difficult.
Peddocks	Pier 1	Wood	107	Perp.	Road; Fort Andrews; user facilities (buildings).	Good	Low	Cleared low area between drumlins.	Pier facilitates intensive visitor use.
	Wall 1	Concrete	233	Perp.	Cleared land, buildings.	Fair, poor	Low, rebuild if necessary	Cleared low area between drumlins.	Protects facilities during high water. Wave erosion less of an issue than formerly because a cusped fore-land at pier adds protection.
Rainsford	Pier 1	Wood	31	Perp.	Vegetation	Poor	Low	Low upland	Abandoned degraded pier has minimal impact on habitats.
Rainsford (continued)	Wall 1	Riprap	514	Parallel	Vegetation	Fair	Medium, let deteriorate	Upland	Erosion of bluff would create naturally functioning beach-upland contact and also supply sediment to beaches to southwest.

Island	Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
Spectacle	Pier 1	Wood/com	170	Perp.	Visitor Center; trails.	Good	Low	Human modified drumlin, fill.	Facilities are in use; modified landfill would make poor natural habitat. Base has concrete wall that would have to be removed.
	Wall 1	Concrete	255	Parallel	Marina; visitor center; trails; planted vegetation.	Good	Low	Human modified drumlin; fill in north.	Facilities are in use; modified landfill would make poor natural habitat.
	Wall 2	Riprap	188	Parallel	Trails; shrubs; grass.	Good	Low	Fill, graded and shaped.	Modified landfill would make poor natural habitat.
	Wall 3	Riprap	1654	Parallel	Trails; planted vegetation.	Good	Low	Human modified drumlin, fill.	Modified landfill would make poor natural habitat.
	Wall 4	Riprap	125	Parallel	Trails; planted vegetation.	Fair	Low	Human modified drumlin, fill.	Modified landfill would make poor natural habitat.
Thompson	Breakwater 1	Wood	37	Perp.	Open water.	Good	Low	Beach landward, user facilities.	Maintain if key to protection of pier.
	Pier 1	Wood	126	Perp.	Beach; boat shed.	Good	Low,	Beach, user facilities.	Provides major access to highly used facility.
	Wall 1	Riprap	381	Parallel	Wooded bluff; open field; campsites.	Fair	Medium; let deteriorate	Drumlin	Removal would create naturally functioning beach and not interfere with species migrating between upper and lower foreshore.
Thompson (continued)	Wall 2	Riprap	77	Parallel	Low upland, wooded.	Fair	High	Low upland.	Structure would restrict future landward migration of marsh.
	Wall 3	Riprap	85	Parallel	Causeway; marsh.	Fair	Low	Causeway sealing former marsh outlet.	Retain to protect access but consider using a culvert to aid flow to/from marsh.

Island	Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
World's End	Wall 1	Riprap	195	Parallel	Wooded bluff; grass and trails landward.	Good	Low; let deteriorate	Till	Naturally-functioning bluff would re-establish land/sea connection.

Table 5. Shore protection structures within Cape Cod National Seashore.

Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
Dike 1	Riprap	1,832	Perp.	Provincetown; open water; salt marsh.	Good	Low (retain)	Developed upland; undeveloped spit.	Removal may jeopardize marsh due to increased waves and currents, but increased tidal circulation could aid marsh.
Dike 2 (Hatches Harbor)	Earth; riprap	883	Parallel	Provincelands; restored <i>Spartina</i> marsh.	Good	Low (retain)	Flat land and marsh on both sides.	Dike protects airport approach.
Groin 1	Riprap	28	Perp.	Vegetated spit.	Fair	Medium	Spit; low dunes.	Removal would eliminate local rocky habitat but not alter habitat on spit.
Groin 2	Wood	35	Perp.	Vegetated spit.	Poor (few pilings)	Low; let deteriorate	Spit; low dunes.	Removal would not alter habitat on spit; there is no reason to rebuild the groin.
Groin 3	Riprap	24	Perp.	Wall 3; building (private).	Fair	Low	Seawall; upland; shrubs; grass; house.	Removal would not allow system to evolve naturally because of wall landward.
Wall 1 (armored road)	Asphalt	559	Parallel	Road; parking lot; bath house.	Poor	High	Dune covered upland; road; parking lot.	Removal (in progress) will allow truncated beach to regain full suite of landforms and will place facilities out of erosion zone temporarily.
Wall 2	Wood	41	Parallel	Vegetation	Poor	Low; let deteriorate	Upland; marsh.	Small size, private property and difficulty of removal without disturbing adjacent shore make removal impractical.
Wall 3	Riprap	164	Parallel	Building (private); pool (private)	Good	Low	Upland; shrubs; lawn grass; house; pool.	Removal would create eroding cliff and supply sediment to shore, but wall protects private home.
Wall 4	Riprap; quarry rock	260	Parallel	Dike; road	Good	Low	Open water; marsh.	Causeway protected by wall controls tide and flooding; opening dike would inundate lower marsh and developed land to east.
Wall 5	Quarry rock	79	Parallel	Dike; road	Good	Low	Open water; marsh.	Causeway protected by wall controls tide and flooding; opening dike would inundate lower marsh and developed land to east.

Table 6. Shore protection structures within Fire Island National Seashore. Not all of the structures listed in Coburn et al. (2010) are evaluated in this report. Structures outside park boundaries are not listed here.

Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
Breakwater 1	Riprap	61	Oblique	Beach; grasses; shrubs; boardwalk; boathouse	Poor	Low; let deteriorate	Washover deposit; small dunes	Removal would disturb bay bottom; boardwalk and boathouse may eventually have to be moved
Pier 1	Wood	84	Perp.	Beach; boardwalk; grass; shrubs	Poor	Low; let deteriorate	Washover deposit; small dunes	Removal would disturb bay bottom and not change landforms or habitats onshore
Wall 1 (bulkhead)	Steel, wood	369	Parallel	Sailors Haven marina; bare sand; snack bar; visitor center; forest	Good	Low	Filled land behind bulkhead; vegetated dunes landward	Bulkhead needed to protect the Sailors Haven Marina, which is an important access point
Wall 2 (eroded walkway)	Concrete	30	Parallel	Trees; shrubs	Poor where exposed	High	Beach; washover lobe; dunes	Concrete can be readily removed to allow shoreline to function naturally; path can be relocated
Pier 2	Wood; concrete, metal	130	Perp.	Bare sand; dune grass; shrubs	Good	Low	Beach; washover lobe; dunes	Pier is on pilings to reduce impact on shore. Pier is new and less obtrusive than the one it replaced.
Wall 3 (bulkhead)	Steel	1,103	Perp. inland	Watch Hill Marina; bare sand; snack bar; visitor center; shrubs; marsh	Good	Low	Washover lobe; marsh	Bulkhead needed to protect Watch Hill Marina, which is an important access point
Pier 3	Wood	45	Perp.	Pier remnant, shrubs; marsh	Poor	Low; let deteriorate	Washover lobe; marsh	Large pilings would be difficult to remove and greatly alter bay bottom

Table 7. Shore protection structures within Jamaica Bay Unit, Gateway. Not all of the structures listed in Dallas et al. (2013b) (the CEI numbers) are evaluated in this report. CEI 5 and 6 are outside park boundaries. CEI 3 is missing from their report. CEI 4 and 10 are underwater and have no clear impact. CEI 5-6, 44-46 and 49 are outside park boundaries. CEI 17 no longer exists. CEI 27 is an outfall pipe. CEI 48 is submerged and its local effects cannot be determined (no access) and is outside park boundaries. Pier 9 is not indicated in the CEI inventory. CEI 62 cannot be distinguished. CEI 88 is buried.

CEI ID	Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
1	Wall 1 (bulkhead)	Concrete	104	Parallel	Poorly vegetated fill.	Good	Low	N/A: Fill behind bulkhead; Non- NPS property.	Non-NPS property; if removed, transport would be into channel and not contribute to shorefront habitat.
2	Groin 1	Riprap	20	Parallel	Bulkhead and fill.	Good	Low	Fill behind bulkhead.	Holds beach in place. Wall 1 would still trap sand.
7	Pier 1	Wood	130	Perp.	Beach 40m landward fronting low vegetated upland backed by marina [Gateway Marina, Deep Creek Yacht Club].	Good	Low	Low upland.	No apparent effect on beach/upland.
8	Pier 2	Wood	18	Perp.	Ramp; marina [Gateway Marina, Deep Creek Yacht Club].	Good	Low	Paved upland.	Protects boat launch.
9	Pier 3 (boat slips)	Wood	450 (perp.) All slips = 2513	Perp. Main access pier	Narrow beach; road; marina [Gateway Marina; Deep Creek Yacht Club].	Good	Low	Narrow beach; restricted upland.	No apparent effect on beach. Slip space important.
11	Breakwater 1	Riprap	255	Parallel	Heath; grasses/shrubs.	Poor	Low	Narrow beach; eroding upland.	Removal would speed erosion of upland with no improved potential for habitat. Greater potential for shoaling at marina to marina to north.

CEI ID	Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
12	Wall 2 (bulkhead)	Steel	398	Parallel	Vegetated upland (trees, shrubs); road.	Poor	High	Fill landward of bulkhead; beach in front.	Erosion would threaten road, but road can be relocated. Seaplane ramp to east would have to be protected against end erosion.
13	Ramp 1	Concrete	45	Perp.	Parking lot.	Good	Low	N/A: Paved	Now functioning as a groin. Removal would cause erosion of beach to west. No benefit of sediment delivery to east.
15/16	Wall 3 (revetment)	Riprap, Concrete	15:793,16:96	Parallel	Paved lot in west; upland in east and north; concrete pads; bare sand; road; paved lot.	Good	Low	Upland fill.	Wall is new. Wall protects remnant infrastructure. May be historical features.
14*/18	Wall 4 (bulkhead)	Steel (Riprap in mid- section)	14:111,18:352	Parallel	Beach; scrub upland; lawn and paved lot in north, fronted by beach	Poor in mid and south, Good in north	Low; but high for 219 m of CEI 14	Upland fill	CEI 14 is a deteriorated structure and has little effect on upland. A length of 219 m of CEI 14 can be eliminated (see text).
19	Ramp 2	Concrete	68	Perp.	Paved lot; bulkhead.	Good	Low	Paved upland.	Functions as a groin and holds beach in place. Backed by bulkhead.
20	Wall 5 (bulkhead)	Wood	535	Parallel	Parking lot; buildings.	Good	Low	N/A: Paved; buildings.	Infrastructure threatened.
21	Pier 4	Wood	59	Perp.	Bulkhead; road; buildings	Good	Low	N/A: Paved; buildings	Minimal effect on shore.
22	Wall 6 (bulkhead and revetment)	Riprap, Wood	368	Parallel	Buildings; paved lots.	Good	Low	N/A: Paved; buildings.	No potential for natural habitat without removing infrastructure.
23	Ramp 3	Concrete	47	Perp.	Parking lot.	Good	Low	N/A: Paved lot	Functions as a groin. No potential for natural habitat without removing infrastructure.

CEI ID	Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
24	Wall 7 (bulkhead)	Wood	256	Parallel	Parking lot.	Good	Low	N/A: Paved lot.	No potential for natural habitat without removing infrastructure.
25	Wall 8 (bulkhead)	Wood	383	Parallel	Upland fill; airplane runway.	Poor	Low	Flat fill.	Removal would result in rapid erosion of fill headland exposing runway.
26	Groin 2	Wood	33	Perp.	Upland; shrubs.	Poor	Medium	Upland	Removal would supply beach sediment to starved area downdrift (west).
28	Wall 9 (revetment)	Concrete	44	Parallel	Building in poor condition; bare sand.	Good	Low	Flat filled upland.	Poor habitat potential. Degraded area.
29	Groin 3	Wood	28	Perp.	Upland; trees.	Poor	Low	Upland	Too little of structure left to matter.
30	Wall 10 (revetment)	Riprap	52	Perp.	Upland; shrubs; grass; adjacent to commercial pier.	Fair	Low	Flat fill.	Pier would be threatened.
31	Pier 5	Concrete	194	Perp.	Pier facilities; parking.	Good	Low	Flat; infrastructure.	Pier facilities would be threatened.
32	Wall 11 (revetment)	Riprap	51	Perp.	Upland; shrubs; grass; picnic tables; adjacent to commercial pier.	Good	Low	Flat fill	Pier would be threatened.
33	Wall 12 (revetment)	Rip-rap	264	Parallel	Landfill	Good	Low	Landfill	New wall protects landfill.
34	Pier 6	Wood?	170 (perp.); 514 total	Perp.	Landfill	Good	Low	Landfill	Facility would be threatened.
35	Wall 13 (revetment)	Riprap	143	Parallel	Landfill	Fair	Low	Landfill	Protects landfill.
36	Pier 7	Wood?	77	Perp.	Landfill	Good	Low	Landfill	Removal would have no effect.
37	Wall 14 (revetment)	Riprap	979	Parallel	Road; landfill; facility at east end.	Fair	Low	Landfill	Protects landfill.

CEI ID	Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
38	Wall 15 (bulkhead)	Wood	426	Parallel	Fill; Cross Bay Blvd.; Addabbo Bridge.	Good	Low	Flat fill; road.	Protects major road.
39	Wall 16 (revetment)	Riprap	93	Parallel	Bridge abutment; building.	Good	Low	Bridge fill.	Protects bridge.
40	Wall 17 (revetment)	Riprap	197	Parallel	Bridge abutment	Good	Low	Bridge fill.	Protects bridge. Has groin effect.
41	Wall 18 (bulkhead)	Wood?	138	Parallel	Abandoned structure; ponds.	Poor	Low	Peninsula; low upland; possibly fill.	Narrow peninsula exposed to erosion. Removal costly. Part of structure outside park boundary.
42	Groin 4	Not known	81	Perp.	Fill at runway; shrubs; grass.	Good	Low	Flat fill.	Removal would not create additional habitat. Wall landward outside park makes removal moot.
47	Pier 8	Wood	808	Perp.	Road; parking area for airport.	Good	Low	Flat fill.	Pier has no noticeable effect on shoreline.
50	Wall 19 (revetment)	Riprap	921	Parallel	Grass; runway.	Good	Low	Flat fill.	Protects runway (within 24m)
51	Groin 5	Not known	51	Perp.	Beach; revetment (Wall 29); grass runway.	Good	Medium	Flat fill.	Beach to west would be displaced. Without net gain in beach, revetment landward makes removal moot.
52	Wall 20 (revetment)	Riprap	79	Parallel	Abutment on bridge on rail line; shrubs.	Good	Low	Fill	Protects bridge.
53	Wall 21 (revetment)	Riprap	77	Parallel	Abutment on bridge on rain line; shrubs.	Good	Low	Fill	Protects bridge.
54	Wall 22 (revetment)	Riprap	54	Parallel	Abutment on bridge on rail line; rail station; buildings.	Good	Low	Fill	Protects bridge and buildings.
55	Wall 23 (revetment)	Riprap	107	Parallel	Fill and road (Cross Bay Blvd.).	Good	Low	Fill	Protects road (within 5m)

CEI ID	Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
56	Wall 24 (bulkhead)	Steel	3800	Parallel	Grass; bare sand; walkway; road (20m away) to the west; houses to east.	Good	Low	Graded barrier island.	Protects infrastructure and houses.
57	Wall 25 (revetment)	Riprap	405	Parallel	Grass; walkway; bridge; road.	Good	Low	Graded barrier island.	Protects infrastructure.
58	Breakwater 2	Wood?	65	Perp.	Fill; marina; parking lot.	Good	Low	Graded barrier island.	Protects marina. Bulkhead landward of marina makes removal moot.
59	Pier 9	Wood	47	Perp.	Paved; grass.	Good	Low	Graded barrier island.	Bulkhead landward makes removal moot.
60	Pier 10	Wood	17	Perp.	Paved; grass.	Good	Low	Graded barrier island.	Bulkhead landward makes removal moot.
61	Pier 11	Wood	20	Perp.	Paved; grass.	Good	Low	Graded barrier island.	Bulkhead landward makes removal moot.
63	Pier 12	Wood	45	Parallel	Grass; bare ground; building.	Good	Low	Graded barrier island.	Bulkhead landward makes removal moot.
64	Wall 26 (bulkhead)	Steel	225	Parallel	Paved; grass; buildings; parking lot.	Good	Low	Graded barrier island.	Infrastructure (including marina) threatened.
65	Pier 13	Wood	55	Perp.	Grass; bare ground.	Good	Low	Graded barrier island.	Bulkhead landward makes removal moot.
66	Pier 14	Wood	25	Parallel	Grass; bare ground.	Good	Low	Graded barrier island.	Bulkhead landward makes removal moot.
67	Breakwater 3	Wood?	69	Perp.	Marina; Wall 36.	Good	Low	Graded barrier island.	Marina threatened. Bulkhead landward makes removal moot.
68	Wall 27 (bulkhead)	Wood?	247 (only 30 showing)	Parallel	Parking lot; grass; bare sand.	Poor	Low	Graded barrier island.	Old deteriorating structure. Has minimal effect.
69	Groin 6	Riprap	33	Perp.	Beach; intensive housing development.	Good	Low	Barrier island, graded for housing.	Terminal groin that anchors shoreline.

CEI ID	Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
70-74	Groin Field 1 (5 groins)	Wood	14-23 (mean = 20.0)	Perp.	Beach; intensive housing development.	Fair	Low	Barrier island, graded for housing.	Protects houses (within 20m of water)
75	Groin 7	Riprap	100	Perp.	Houses to east; barrier upland (grass, shrubs) to west.	Good	Low	Graded barrier island at houses; natural to west.	Terminal groin. Houses too close to water.
76	Groin 8	Riprap	33	Perp.	Barrier upland (grass, shrubs, bare sand).	Good	Medium/ High	Naturally evolving barrier upland (formerly disturbed).	Removal of groin would help nourish beach near road to east.
77	Groin 9	Riprap	74	Perp.	Barrier upland (trees).	Fair	Medium/ High	Barrier upland.	Shoreline would smooth out.
78	Pier 15	Wood	81	Perp.	Parking area; building.	Good	Low	Human modified barrier upland; building; parking area in use.	Too much investment in infrastructure.
79	Groin 10	Riprap?	23	Perp.	Parking area; building.	Poor	Low	Human modified barrier upland; building; parking area in use	Too much investment in infrastructure.
80-82, 84	Groin Field 2 (4 groins)	Wood	24-37 mean = 32.5	Perp.	Parking lot and pier facility to west; undeveloped land to east.	Fair	Low	Developed barrier upland at west and east end; undeveloped enclave in mid-east section.	Groins anchor shoreline at this salient. Removal would threaten infrastructure.
83	Pier 16	Wood	143	Perp.	Parking lot and pier facility.	Good	Low	Developed barrier upland.	Removal would not change landforms and habitats.
85	Groin 11	Riprap	17	Perp.	Intensively developed in houses.	Fair	Low	Developed barrier upland.	Removal would not create landforms and habitats.
86	Pier 17	Wood	126	Perp.	Intensively developed in houses.	Good	Low	Developed barrier upland.	Removal would not create landforms and habitats.

CEI ID	Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
87	Jetty 1	Riprap	1143	Perp.	Undeveloped barrier island; multiple dune ridges.	Good	Low	Accreted barrier island resulting from long-term trapping by jetty.	Removal would contribute to inlet shoaling and loss of sediment from existing barrier.
89-90	Groin Field 3 (2 groins)	Wood	61, 72 mean = 66.5	Perp.	Beach club	Fair	Low	Developed barrier island.	Groins part of the wooden groins in Groin Field 4.
91	Wall 28 (bulkhead)	Wood, Riprap	1799	Parallel	Narrow (20m wide) barrier upland, backed by shore-parallel road; undeveloped upland landward of road.	Poor	Low; let deteriorate	Evolving backshore and dune landward of deteriorated portions; patchy habitats.	Removal costly with little effect on morphology and habitat. Wall could be allowed to deteriorate. Road is not needed. See Case Study 3 in text.
92-130, 132-144	Groin Field 4 (52 groins)	13 riprap or wood/ riprap 39 wood	Riprap mean = 84.2 Wood mean = 57.2	Perp.	Narrow (20m wide) barrier upland backed by shore-parallel road and undeveloped upland landward of road, to west; developed For Tilden in center of segment; Riis Park in east.	Rip-rap: good. Wood: poor to west, fair fronting Riis Park.	Low, let wood groins deteriorate	Evolving backshore and dune landward of deteriorating groins with patchy habitats in west; degraded upland and dunes with buildings backed by woods or grass at Fort Tilden; wide beach with promenade and recreational buildings (Riis Park)	Removal/deterioration of wood groins would have little effect without modification of rock groins. Rock groins in west end could be modified to allow sand bypass, allowing upland to evolve naturally. Road would be lost, but access provided farther landward. Groins could be allowed to deteriorate. Groins at Riis Park important to protect infrastructure.
131	Wall 29 (seawall)	Concrete	1365	Parallel	Recreational facilities (golf course, promenade, bath house).	Good	Low	N/A (facilities)	Facilities would be threatened.

* CEI 14 is part of a double wall; our lengths reflect the longer wall (14).

Table 8. Shore protection structures within Staten Island Unit, Gateway. Structures that are identified in (Dallas et al. 2013b) but are now buried (e.g. CEI 171, 183) are not evaluated here.

CEI ID	Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
145.1	Pier 1	Fitted stone	24	Perp.	Forested upland.	Good	Low	Eroding bluff.	Pier has no major effect on upland change.
145.2	Wall 1 (seawall)	Fitted stone	178	Parallel	Forested upland, Battery Catlin.	Good	Low	Eroding bluff.	Bluff is close to house; battery Catlin threatened. Battery would interfere with natural evolution.
147	Pier 2 (Torpedo Wharf)	Fitted stone	25	Perp.	Unused former cargo pier; shrubs, trees.	Fair	Low	Fill backed by steep upland.	Costly to remove. New habitat better accommodated landward of Wall 1. Some historical interest.
146	Wall 2 (seawall)	Fitted stone	284	Parallel	Battery Weed; flat grassy area to north.	Good	Low	Fill backed by steep upland.	Fort maintained for historical value.
148	Wall 3 (revetment)	Riprap	435	Parallel	Forested upland.	Poor	Low	Eroding bluff.	At narrowest part of Narrows. See Case Study 1 in text.
149-151	Wall 4 (revetment/Groin 1)	Riprap;	Wall 146 Groin: 48	Parallel/Perp.	Degraded filled upland (grass, shrubs, bare ground; deteriorated hangar).	Good (149-150); fair (151)	Low; let deteriorate	Partially accreted and filled low flat upland; northern terminus of drift cell.	Groin traps the small amount of sand entering from the south. Revetment at 151 (the southwest portion) may be removed to allow beach/upland contact to evolve.
152	Breakwater 1 (intertidal sill)	Riprap	193	Parallel	Degraded upland; deteriorated hangars.	Poor	Low; let deteriorate	Partially accreted and filled low flat upland.	Underwater at high tide. Structure has no effect on change at upland landward of it.
153, 154	Groin field 1 (two structures)	Concrete; wood groin 7 m south of it	38, 79	Perp.	Beach, shrubs, trees; paved path; wooded upland.	Fair	Low, let deteriorate	Nourished beach; steep upland.	Concrete structure still intact and provides trap; wood groin has no additional effect; little effect of both structures on landward upland.

CEI ID	Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
155	Boardwalk 1	Wood	2216	Parallel	Parking lot; ball fields; playground; buildings; segments with grass, shrubs, trees.	Good	Low	Human modified low flat upland.	Boardwalk is elevated and does not interfere with process, but shore protection structures and dune dike prevent conversion to natural habitat.
156, 157, 159-163	Groin Field 2 (7 groins)	Concrete, riprap (new), Wood (old) 160-161	40-120 (mean = 89.6)(40, 61 for CEI 160, 161	Perp.	Boardwalk 1; parking lot; ball fields; playground; buildings; segments with grass, shrubs, trees.	Good (new groins) Poor (old)	Low; old wood groins can deteriorate	Dune dike; human modified low flat upland.	Wood groins ineffective. Many structures unnecessary at present because of wide beach and new dune dike, but area subject to flooding and too much human investment landward.
158	Pier 3	Concrete, steel, paved	280	Perp.	Dune dike; boardwalk; buildings; parking lot; road.	Good	Low	Human modified low flat upland.	Pier on pilings has minimal effect on landforms, but landward facilities prevent conversion to natural habitat.
164-169	Groin Field 3 (6 groins; 1 remnant)	Concrete, Riprap, Wood	51-156 (mean = 111.8)	Perp.	Parking lots; ball fields; buildings; undeveloped upland in middle and south end.	Good	Low	Human modified low flat upland.	Severe erosion offsets to south (downdrift), but too many threatened facilities landward to reintroduce erosion.
170	Wall 5 (revetment)	Riprap	511 More is buried	Parallel	Marsh; drainage channel; abandoned road end.	Fair	Low	Beach ridge, marsh.	Removing wall and not the groin at 169 would create rapidly migrating, beach ridge, threatening buildings landward; removing the groin would threaten shorefront houses updrift.

CEI ID	Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
172	Groin 2 (training wall at channel)	Concrete, wood, riprap to landward	97	Perp.	Unpaved road, parking lot; marsh; undeveloped upland; sewage outfall pipe; drainage channel.	Good, fair in parts	Low	Beach fronting upland updrift; low beach ridge and marsh downdrift at Wall 6.	Threat to sewage outfall and diversion of channel.
173	Wall 6 (bulkhead, planks above)	Wood	122	Parallel	Undeveloped land, with salt marsh and <i>Phragmites</i> marsh.	Fair	Low; let deteriorate	Marsh; fill; low washover deposit; pocket beaches where gaps in wall.	Area is reverting to natural habitat, including saltmarsh in low areas. Training wall may need relocation.
174	Wall 7 (revetment)	Rip-rap	123	Parallel	Undeveloped land with shrubs and isolated trees.	Fair	Low; let deteriorate	Unconsolidated low upland, apparently former washover deposit.	Can allow to deteriorate to form natural ecotone and provide sediment to downdrift beach. Removal could make erosion rate too high.
175	Wall 8 (bulkhead)	Wood	919	Parallel	Grassy undeveloped upland backed by road 12m from shore at closest.	Fair in west; good in east	Low; let deteriorate	Unconsolidated upland created by fill emplacement.	Can allow to deteriorate in west, but road would have to be removed in places to form natural ecotone. Pollutants in fill could be an issue.
176, 180	Wall 9 (revetment)	Riprap	25, 118	Parallel	Parking areas; paved path; road, grass, with trees in places.	Good	Low	Filled upland creating a spit.	Threat to user facilities now close to shoreline.
177, 178	Piers 4,5	Wood	40, 40	Perp.	Boat ramp, paved path, road.	Good	Low	Filled upland.	Removal would not affect habitat due to Wall 9.
179	BulkheadNo number	Wood	13	Parallel, perp.	Boat ramp, piers, paved path, road.	Good	Low	Filled upland.	Removal would not affect habitat due to Wall 9.
181	Wall 10 (bulkhead)	Wood	558	Parallel	Marina parking; boat storage.	Good	Low	Low spit deposit.	Threat to user facilities and eventual spit breaching.

CEI ID	Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
182	Wall 11 (revetment)	Riprap	563	Parallel	Road; vegetated upland (grass, trees).	Good	Low	Low spit deposit.	Can allow to deteriorate, but road would have to be removed to create natural ecotone.
184	Jetty 1	Riprap	152	Perp.	Vegetated upland.	Good	Low	Low spit-formed upland; low dunes.	Jetty has little effect (mostly buried), and removal would do little for natural system.
185, 186	Wall 12A, B (seawall, revetment)	Riprap, concrete (dual wall)	832, 761	Parallel	Vegetated fill.	Good	Low	Featureless filled upland.	Island vulnerable to wave attack. Unknown pollutants in fill.
187	Pier 6	Wood	143	Perp.	Wall 13	Poor	Low	Featureless filled upland.	Little effect because of Wall 13.
188	Pier 7	Wood	17	Perp.	Wall 13	Poor	Low	Featureless filled upland.	Little effect because of Wall 13.
189-190	Wall 13A, B (seawall, revetment)	Riprap, concrete (dual wall)	656	Parallel	Building remnants; disturbed upland.	Good	Low	Featureless filled upland.	Island vulnerable to wave attack. Unknown pollutants in fill.

Table 9. Shore protection structures within Sandy Hook Unit, Gateway. CEI 204-205 are buried and have no effect. SEI 238 is underwater, deteriorated and has no effect on shore. CEI 243 is separated into two parts because the portions function in different ways. CEI 246, 247 are ammunition bunkers and not evaluated here as protection structures. Other structures listed in the CEI report are off NPS property.

CEI ID	Structure/ material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
191	Wall 1 (riprap seawall)	2,360 (to south limit of NPS land)	Parallel	Maritime dunes; toll booths; parking lot; road; maritime shrubland; bath house; salt shrub.	Good	Low	Southern part is backed by fill. Northern part is former overwash platform. Recent nourishment created a wide beach and dune.	Seawall protects the access road and should remain due to uncertainties of future funding for beach nourishment. Wall helps prevent spit breaching during major storm.
203	Wall 2 (metal bulkhead)	184		Road; salt shrub.	Good	Low	Upland landward of bulkhead is overwash area that was critically eroding prior to fill. Nourished beach and dune are now seaward of bulkhead.	Bulkhead provides backup protection to the access road and should be left in place due to uncertainties of funding for nourishment.
215-217	Wall 3 (wood bulkhead; stone seawall)	493 plus 80 break-water; 175 m in NPS land	Parallel	USCG buildings behind northern portion. Parking area and chapel behind bulkhead and seawall on NPS land.	Good (USCG land); Poor (NPS land).	Low; let 175 m in NPS land deteriorate	Former beach ridge plain now graded and vegetated with lawn grass. Dredging at Coast Guard piers and the cove updrift restrict sediment input.	Bulkhead has deteriorated and fronting seawall is too low to prevent upland erosion. Chapel is 12 m landward of erosion scarp. Chapel could be moved to allow for succession to natural upland habitat. No reason to continue maintaining lawn grass if chapel is moved.
218	Pier 1 (metal/ wood)	96	Perp.	Developed area (unpaved parking lot).	Good	Low	1.66-2.00 m high eroding former beach ridge plain used as a parking area.	Pier is floating, and access is on pilings, resulting in little interference with processes and habitat.

CEI ID	Structure/ material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
217 So. end	Wall 4 (wood bulkheads)	120	Parallel	Beach; developed grassy area with chapel.	Poor	Low; let deteriorate	Low upland. Portion of shore that is not maintained as lawn reveals the type of habitat that can form if lawn grass is not used in the historic area.	Bulkhead is too low to prevent erosion of upland. Loss of southeast part of the upland would cause in flanking of Wall 5. Wall 4 should remain intact for now but not be rebuilt. Wall 5 can be extended to prevent flanking.
220	Wall 5 (riprap seawall)	866	Parallel	Wall at CEI 219; developed grassy area; bike path; road; many historic officer quarters.	Good	Low	Upland is former beach ridge plain and dune field, flattened in places to accommodate human use.	Path, road and building only 6, 20 and 37 m from seawall. Buildings too massive to move easily. Value of natural habitat enclave in intensively used historic area is questionable.
221 to 233	Groin field 1 (stone) 13 structs.	17-124 (mean = 33.3)	Perp.	Wall 4; former officer quarters.	Good	High	Upland is former beach ridge plain and dunes, flattened in places to accommodate human use.	Groins are empty and could be dismantled and rocks used elsewhere. The 636 m length between structures is protected by seawall.
234	Wall 6 (riprap seawall)	651	Parallel	Developed area; successional maritime forest.	Good	Low	Upland is former beach ridge plain and dunes; filled marsh in places. Walls 5 and 6 contribute to sediment starvation/rapid erosion downdrift.	Wall is only 3-5 m from road. Wall could be removed and a road built inland. Sediment movement to south may cause beach accretion and protect eroding marsh.
235	Wall 7 (riprap seawall)	155	Parallel	Battery Arrowsmith; maritime beach; shrubland.	Fair	Low	Wall protects Battery Arrowsmith, originally built on a former bayside spit.	Little gained by removing riprap and leaving eroding battery. Removal of battery appears cost prohibitive.

CEI ID	Structure/ material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
236	Wall 8 (building rubble)	38	Parallel	Maritime beach; maritime shrubland (tall).	Poor	Medium (based on safety).	Rubble is destroyed building that now functions as a revetment fronting upland created by cultural fill.	Rubble removal would increase erosion of upland and not aid marsh development, but rubble interferes with access and is unsafe.
237	Wall 9 (wood bulkhead)	55	Parallel	Beach; maritime beach vegetation; shrubland.	Poor	Low	Beach landward of structure is low at spring wrack line. Upland landward is fill.	Structure acts as hinge point, helping retain the break in shoreline orientation. Removal would be costly with no gain in habitat value.
239 to 241	Wall 10 (gabions)	72, 3,19	Parallel	Unpaved path;salt marsh.	Good	Medium	Upland landward is artificially filled pathway on low, narrow overwashed barrier.	Path is main access. Removal of gabions may cause beach to transgress wetland.
242	Wall 11 (riprap seawall)	887	Parallel	Paved road; successional maritime forest;red cedar forest; sand path; holly forest; maritime dunes.	Good	Low	Upland is one of lowest surfaces on the spit. Overwash occurs at weak points in wall. Road is near elevation of the backshore and only 9 m from wall. Wall cannot protect against storm flooding.	Removal would cause rapid shoreline retreat and overwash onto road. Relocation of road costly. Building an elevated causeway could allow wetland habitat to form and provide access, but would eventually be in water.
243 north part	Wall 12 (wood bulkhead)	715	Parallel; overlaps Wall 13 to south	Maritime beach and dune; holly forest; unpaved road; hardwoods; Batteries Kingman and Mills.	Poor	High	Northern part of former wall that once extended alongshore and protected batteries and ammunition bunkers. Upland is natural overwash area, with a low bayside dune	Wall is now only isolated pilings except north end that functions as a groin. Low area may revert to marsh with rising sea levels, but human action may be required to favor inundation.

CEI ID	Structure/ material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
244	Wall 13 (riprap seawall)	288	Parallel	Unpaved road; successional southern hardwoods; Battery Kingman; brackish meadow.	Good	Low	Riprap protects Battery Kingman. Upland is natural overwash area modified by battery and road construction. Wall contributes to sand starvation south.	No public access to battery, which remains a historic feature. Eroded battery would function as riprap and be difficult to remove, so removal of Wall 13 accomplishes little.
245	Wall 14 (concrete and asphalt)	191	Parallel; groin in north	Brackish meadow; unpaved road/path; low salt marsh;salt shrub.	Poor	High	Concrete and asphalt rubble protecting a graded road connecting batteries to ammunition bunkers after Wall 15 deteriorated. (See case study.)	Wall is failing and the upland eroding. Rubble can be removed and used in front of Battery Mills. Asphalt should be removed.
243 south part	Wall 15(wood bulkhead; south part of Wall 12)	450	Parallel; perp. at south end	Maritime beach; emergent marsh; brackish meadow; Wall 12; path; ammunition bunkers; salt panne; low salt marsh; tidal creek.	Poor	High in south and east; let deteriorate in west	Upland is former bayside spit/dune modified by fill and road construction. Wall is a deteriorated bulkhead that protected 2 ammunition bunkers now exposed. Landward marsh is 7 m from the erosion scarp. (See case study.)	Remnant pilings on western part used as roosting sites. No reason to remove them for safety due to limited visitors. Landward portion of southern part of wall is intact but threatened by erosion. This part can be removed to reestablished natural processes.
248	Wall 16 (wood bulkhead)	650 remains	Parallel	Bay	Poor	Low	Training wall emplaced by 1901 to prevent tidal flow into Spermacetti Cove. Wall is deteriorated, well offshore, and too low to protect the upland landward.	Visitors can wade to the wall at low tide, so it can be considered a safety hazard. Removal is not likely to affect shoreline response or landward habitats.
249	Wall 17 (riprap; rubble at north end)	53	Parallel	Maritime dunes; paved road; salt shrub; maritime dunes.	Poor in north; good in south	Low	Riprap protects the spit access road built on former ocean overwash covered with fill.	Access road is 0-22 m from wall and would be lost if riprap removed. Road cannot be moved due to limited space. Collapsing rubble in north should be repositioned.

CEI ID	Structure/ material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
250	Wall 18 (riprap seawall)	573 (only 119 exposed)	Parallel	Paved road; salt shrub; maritime dunes; Wall 1.	Good	Low	Rip rap protects the road built on fill. Fill and wall are covered in places by dunes. A dune field subsequently formed bayward of rip rap.	Access road is 0-47 m from wall and portions would be lost immediately if riprap removed. Road cannot be moved due to limited space.
251	Wall 19 (concrete; steel base)	171 (only 56 exposed)	Parallel	Maritime beach; salt panne; paved road; maritime dune.	Good	Low	Wall protects high road built on fill.	Access road would be lost by removal. Relocating access road is not possible because of limited space.
252	Groin 2 (wood)	26 remains	Perp.	Maritime beach; paved road; maritime dunes.	Fair	Low	Groin diverts tidal flow offshore. Removal would allow tidal channel to migrate south and accelerate erosion of upland south of it.	Groin helps retain beach to south. Removal would cause unpredictable changes and possibly threaten road at no gain in habitat.

Table 10. Shore protection structures within Assateague Island National Seashore. *

Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
Jetty 1	Riprap	741	Parallel/ Perp.	Beach; vegetated spoil.	Good	Low	Northern tip of barrier island; dune.	Jetty required to maintain inlet; active Corps project.
Breakwater 1	Riprap	68	Parallel	Open water; beach; vegetation.	Good	Low	Spoil pile at northern tip of island functioning as dune.	Breakwater reduces erosion of fill and filling of channel.
Breakwater 2	Riprap	70	Parallel	Beach; vegetation.	Good	Low	Spoil at northern tip of island functioning as dune.	Breakwater reduces erosion of fill and filling of channel.
Breakwater 3	Wood	27	Perp.	Building	Poor	Low; let deteriorate	Marsh; upland.	Breakwater deteriorated; little effect on marsh/upland.
Causeway 1 (High Winds)	Earth	837	Parallel/ Perp.	Marsh (north); open water (south); flanking ditches.	Good	High	Former flood delta to west; washover to east; dredged basin functioning naturally.	Causeway is an unnecessary artificial barrier to flows between two habitats functioning differently.
Pier 1	Wood	25	Perp.	Building	Poor	Low, let deteriorate	Marsh; upland.	Pier deteriorated and damaged by storm; little effect on marsh/upland.
Pier 2	Wood	23	Parallel	Building	Poor	Low; let deteriorate	Marsh; upland.	Pier deteriorated and damaged by storm; little effect on marsh/upland.
Pier 3 (Clements)	Wood	12	Parallel	Marsh, upland.	Good	Low	Washover or delta.	Structure has little effect on landward habitat.
Pier 4 (Musser)	Wood	15	Perp.	Open water; marsh; unpaved road.	Fair	Low; let deteriorate	Backbarrier marsh.	Structure is detached from barrier and has minimum effect on landward habitat.
Pier 5	Wood	194	Perp.	Beach; vegetated upland; boardwalk trail.	Fair to poor	Low; let deteriorate	Eroding beach on bayward side of spit recurve.	Removal would have little effect in enhancing habitat.
Pier 6 and building	Wood	68	Perp.	Beach	Good	Low	Eroding beach on bayward side of spit recurve.	Building is historic structure; removal would have little effect in enhancing habitat.

Table 10 (continued). Shore protection structures within Assateague Island National Seashore. *

Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
Wall 1	Riprap (rock and concrete)	623	Parallel	Road	Good	Low	Filled causeway and upland.	Riprap required to protect main access road to NPS and state parks.
Wall 2	Wood	57	Parallel/ perp.	Parking lot.	Good	Low	Improved upland; natural upland adjoining to south.	Bulkhead protects new parking lot and interpretive facility.

* A bulkhead also exists offshore of the northern parking area on the bayside. This structure may be a safety hazard, but it does not appear to affect shoreline processes and habitats and is not included in the inventory.

Table 11. Shore protection structures within Fort McHenry National Monument.

Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
Pier 1	Wood	47	Perp.	Wall 1; grassy field, lawn grass; pathway	Good	Low	Upland with fill	Wall landward would prevent natural evolution.
Wall 1	Cut stone; riprap in front	1154	Parallel	Pathway; grassy field; fort; magazine	Good	Low	Upland with fill	Historic resource would be damaged. Eroding upland in urbanized environment is of questionable value.

Table 12. Shore protection structures within Colonial National Historical Park. Numbers preceded by CEI are designations given by Dallas et al. (2013a). CEI 1-7 are outside the park in the alongshore direction. CEI 103-109 are outside the park but seaward and are thus included in this table.

CEI ID	Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
8-9	Wall 1 (revetment)	Riprap	225	Parallel	Wooded upland; Glass House; visitor buildings.	Good	Low	Undeveloped upland to northwest; low upland and freshwater wetland to southeast.	Removal may jeopardize historic and visitor structures, but would also reestablish naturally functioning coast.
10-12	Wall 2 (revetment)	Riprap	962	Parallel	Lawn grass; road; inlet; marsh on landward side.	Good	Low	Artificially filled and graded isthmus.	Removal would threaten access road and change hydraulics within Sandy Bay.
13	Wall 3 (seawall)	Concrete	731	Parallel	Lawn grass; historic structures; visitor attractions.	Good	Low	Developed upland.	Removal would result in erosion and loss of historic and visitor structures; recent repairs to the wall result in the designation of good condition.
14	Wall 4 (revetment)	Riprap	966	Parallel	Lawn grass; path; historic structures; visitor attractions in northwest; wooded upland in southeast.	Good	Low in northwest; let deteriorate in southeast	Developed upland to northwest; undeveloped upland to southeast.	Removal of portion of wall to southeast would reinitiate natural processes; create beach and deliver sediment alongshore.
15-32	Breakwater Series 1 18 structs.	Riprap 1265	23-161 (mean = 70.3) shore length 3,964	Parallel	Beaches, beach ridges; saltmarsh; upland shrubs and trees; known and unknown archaeological sites.	Good	High	Saltmarsh interspersed with former spit recurves and beach ridges where wave energy and sediment input relatively great.	Removal would reestablish natural conditions and contribute to the marsh sediment budget (see text).

CEI ID	Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
33	Wall 5 (revetment)	Riprap	353	Parallel	Low, wooded upland; Confederate earthworks, archaeological sites.	Good	Low; let deteriorate	Former spit recurve.	Structure now "anchors" the shore. No immediate need for eroding upland habitat at this location. Increasing the level of protection in the future should have low priority relative to many other sites.
34-55	Breakwater Series 2 (incl. sills) 22 structs.	Riprap 792	14-132 (mean = 36) shore length 2,360	Parallel	Wooded upland; saltmarsh; archaeological sites.	Good	High, except CEI 34-35 at Black Point	Pocket beaches; undeveloped upland; spit recurves and interfluves; marshes.	Removal would reestablish natural conditions and help reestablish the marsh sediment budget. 34-35 help "anchor" the shore.
56-60	Breakwater Series 3 (sills) 5 structs.	Riprap 444	46-116 (mean = 88.8) shore length 940	Parallel	Wooded upland; road at CEI Site 59; archaeological sites.	Good	High, (but low at CEI Site 59)	Wooded uplands; small portions of marsh.	Removal would reestablish natural conditions. CEI Site 59 protects a serviceable road and removal priority would be low there.
61-62	Wall 6 Bulkhead	Wood	707	Parallel	Lawn grass; road.	Good	High on southeast side; low elsewhere	Artificially filled and graded isthmus.	Removal of bulkhead on the southeast side would reestablish marsh habitat without due threat to road (see text).
63	Wall 6b (revetment) (CEI sill)	Riprap	119	Parallel	Wooded upland; road; parking lot.	Good	Low	Upland	Revetment helps train creek and prevents it from lateral erosion at bend in stream.
64-68	Wall 7 (revetment, bulkhead)	Riprap and wood	443	Perp. and parallel	Bridge foundation; road; entrance to Rock Creek.	Good, poor	Low, need repair to bulkhead	Graded road bed; upland; saltmarsh.	Revetment and bulkhead protect bridge foundation.

CEI ID	Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
69-71	Wall 8 (revetment, bulkhead)	Riprap and wood	385	Parallel	Grassy, partially wooded upland.	Fair	Low; let deteriorate	Upland.	Little reason to remove to create habitat redundant with adjacent shore, but road is not threatened, so future rehab not necessary.
72	Wall 9 (revetment)	Riprap	192	Parallel	Wooded upland with portions of mowed lawns; road.	Good	Moderate; let deteriorate	Upland.	Removal would supply beach sediment to adjacent shore and road would not be threatened in near future.
73-79	Wall 10 (revetment, bulkhead)	Riprap, wood, steel	181	Perp. and parallel	Bridge foundation; road; entrance to College Creek.	Good	Low	Graded road bed; upland; saltmarsh.	Revetment and bulkhead protect bridge foundation.
80-82	Wall 11 (revetment)	Riprap	49	Perp. and parallel	Bridge foundation; road; entrance to Fellgates Creek.	Good	Low	Graded road bed; fill; upland.	Revetment protects bridge foundation.
83-84	Wall 12	Riprap	2,827	Parallel, perp. at creek	Wooded and grassy upland; main road through park.	Good	Low	Upland	Road through park is already threatened in places, and it would be eroded soon after removal of riprap.
85-86	Wall 13 (Sills)	Riprap	345	Parallel	Grassy upland.	Good	Low	Upland	Road through park would eventually be threatened, but this location is not as critical as others.
87-91	Breakwater Series 4, 5 structs.	Riprap concrete blocks 49	9-11 (mean = 9.8 shore length 168	Parallel	Beach; grassy and wooded upland; main road.	Fair	Low	Upland	Road through park is close to shoreline, and it would be threatened soon after removal.

CEI ID	Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
92-93	Wall 14	Riprap	569	Parallel	Wooded and grassy upland; main road.	Good	Low	Upland	Road through park is close to shoreline, and it would be threatened soon after removal.
94	Pier 1	Concrete	964	Perp., parallel	Beach; wooded upland; main road.	Good	Low	Upland	Structure is out of NPS jurisdiction
95-98	Wall 15 (revetment) (series of segments)	Riprap	1,189	Parallel	Wooded and grassy upland; roads; parking areas; historic site.	Good	Low	Upland	Roads parking lot and redoubt are close to shoreline, and would be eroded or threatened soon after removal.
99-102, 104, 107, 110,112-113, 115-118, 120	Breakwater Series 5 14 structs.	Riprap 560	16-54 (mean = 40 Shore length 1,177	Parallel	Beach, developed upland with road; parking areas; buildings.	Good	Low	Intensively developed upland.	Intensity of development landward would preclude evolution of natural shore. Breakwaters below mean low water are out of NPS jurisdiction.
105-6, 109, 114	Wall 16 (revetment) (series of segments)	Riprap	295	Parallel	Beach, developed upland with road; parking areas; buildings.	Good	Low	Intensively developed upland.	Intensity of development landward would preclude evolution of natural shore.
103, 108, 111	Pier Series 1	Wood	225 (Parallel part)	Parallel and perp.	Breakwaters; beach; revetment; developed upland with road; buildings.	Good	Low	Intensively developed upland.	Piers are out of NPS jurisdiction. Piers have little effect, especially given the other protection structures. Development landward precludes evolution of natural shore.

CEI ID	Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
119	Pier 2	Wood	103	Perp.	Grassy upland.	Good	Low	Upland (developed or maintained as grassy surface).	Pier was installed and maintained by the County. Pier has little effect, especially given the adjacent protection structures.
121-124, 131	Wall 17 (revetment) (series of segments)	Riprap	2,476	Parallel	Grassy upland; wooded upland; roads; parking areas; paths battlefield.	Good, fair in places	Low	Upland (developed or maintained as grassy surface).	Bluff would erode rapidly if removed. Battlefield to west and buildings to east would be threatened.
125-130, 132	Pier Series 2	Wood	336	Perp.	Revetment; grassy upland; paths; buildings.	Good	Low	Developed upland with private residences.	Piers have little effect. The presence of the revetment and private residences landward of them would preclude natural development if piers are removed.

Appendix B. Evaluation of structures at Fort Monroe National Monument

Purpose

The purpose of this appendix is to make a preliminary assessment of the potential for removing shore protection structures to allow natural shoreline processes to prevail on the spit on which Fort Monroe National Monument (here called the park) is located. Transfer of lands to the park is being done incrementally. This inventory includes structures in portions of the spit that are not presently under direct NPS jurisdiction, but may be transferred in the future. Preliminary suggestions for removing structures are based on tradeoffs between environmental gains and potential increases in vulnerability of cultural resources. A key feature of the park (and other coastal parks managed by NPS) is that many protection structures were built before the locations came under NPS jurisdiction. As a result, the uses of many of the facilities have changed, as has the significance of the structures protecting the facilities. Another key feature, which differs from many other coastal parks, is that the park is evolving at a time when adaptation to climate change is being promoted as an NPS management strategy to increase ecosystem resilience (NPS 2010), and memoranda on climate change have been introduced recently by the NPS director (NPS 2012, 2014, 2015) to better define the agency role in adaptation.

Methods

Data taken from aerial images available in Google Earth were used to provide a preliminary identification of protection structures (Figure 1). Shoreline changes through time were evaluated by comparing historic aerial photographs available from NASA. A reconnaissance-level investigation of the park was made 27 March 2015 to identify the extent to which structures interfere with the evolution of the shoreline and development of coastal habitats. The on-site investigation involved a discussion with the superintendent to provide the environmental and policy contexts. This was followed by a trip around the grounds to identify existing shore protection structures and other structures located at or near the shoreline and locations where protection structures could be removed to allow habitats to evolve more naturally.

Setting

Fort Monroe is located on a 4.2 km-long spit that extends south from Hampton, Virginia and is between the open Chesapeake Bay (here called the bay) to the east and Mill Creek (called the creek) to the west (Figure 1). The fetch distance for wave generation in the bay to the east is about 30 km, but the site is also exposed to waves entering the bay from the ocean. Fetch distance to the north is over 90 km on the bay side, contributing to net southerly longshore transport. Fetch distances on the creek side are less than 2 km. Wave energies on the northern portion of the creek shore have been too low to prevent colonization of the shoreline by vegetation. Local sources indicate that low portions in the interior of the spit are subject to flooding, but the source of the flooding is unclear.



Figure 1. Location of structures evaluated for removal at Fort Monroe National Monument. Photo April 2014. Source: Google Earth.

The south end of the spit is highly developed and contains the fort and numerous ancillary buildings and houses. The central portion is less developed and contains three batteries and a recreation facility (the Officer's Club) near the bay side and a former airstrip near the creek side, with extensive areas of lawn between. The northern portion is relatively undeveloped and contains only a paved road and parking areas. Aerial photographs dating back to the 1930s reveal periodic fresh washover deposits in this region. The shore north of the park is developed in private residences. Shore protection efforts north of the park include beach nourishment and construction of groins to hold sand in place. The past beach nourishment projects contributed sediment to the park, but future nourishment is not assured, and natural sediment sources north of the park have been reduced because of encroachment of buildings and infrastructure.

Thirteen individual protection structures or groups of structures with similar functions (Figure 1, Table 1) prevent the shore from evolving naturally. These structures vary in age and condition. Walls 1-4 on the creek side are composed of disjointed dumped concrete blocks that have little usefulness in preventing wave erosion or flooding. Walls 5 and 6 are in good condition and backed along most of their length by a low earth berm that restricts uprush and flooding. Most of the structures on the bay side are newer and built to be more resistant to the higher energy waves generated in the open Chesapeake. The entire bayshore is protected by three walls composed of different materials. Wall 8 is constructed primarily of concrete riprap and may be under-designed for storm waves in the bay. Wall 7 in the middle of the spit is a more massive concrete structure backed by a paved promenade. Wall 9 on the south side is composed of quarry rock and backed by a paved walkway. Groins and breakwaters have been emplaced to hold beach sand in place in front of Walls 7 and 8. Erosion has continued in front of Wall 8, especially on the downdrift sides of the groins (Figure 2).



Figure 2. Shoreline downdrift of the middle groin in Groin Field 1, showing erosional scarp and concrete riprap in Wall 8 at left.

Suggestions for structure removal

The presence of vegetation along the creek shoreline north of the recreational vehicle (RV) park facilities (Figure 3) implies that shoreline retreat is not presently critical there, although portions of the interior of the spit are subject to flooding. Removal of Walls 1-4 is expected to have little effect on shore processes and evolution of habitats, and the concrete blocks used to construct the walls could remain in place.



Figure 3. North end of Wall 6, looking north.

Removal of Wall 5 and the berm landward of it is likely to convert grassland (Figure 3) to more diverse wetland habitat and thus should be considered a future option. This location would make a good demonstration area for evaluating the advantages and disadvantages of removing structures that are still functional but have lost their original rationale. Maintaining so many areas of lawn does not appear necessary for recreation, and lawns have little habitat value relative to wetland. Large expanses of lawn would still exist elsewhere on the spit for future uses. If flooding of the facilities at the RV park becomes an issue, a ring levee could be built around them. A simple earth structure would provide enough protection because wave erosion would not be an issue in this portion of the creek shore.

Removal of portions of Wall 6 and its associated berm would also increase the area of wetland but would require removal of the landing strip, which would otherwise be a barrier to natural processes. Removal of Wall 6 would be more complicated than removal of Wall 5 because it would require breaking up a concrete cap (e.g. foreground of Figure 3) before removing the cobble core beneath it. Wave energies are higher in the southern portion of Wall 6. Establishment of vegetation cover in the swash zone there is unlikely. The shoreline could evolve to a beach, but erosion would occur, and the nearby road would then become a barrier to shoreline evolution. The difficulty of removing the wall and the road and the loss of access in the developed part of the spit do not seem to justify creation of a small beach habitat without a naturally functioning upland landward.

Shore protection structures on the Chesapeake Bay shore within and north of the park have diminished sediment inputs and restricted beach space. The beaches are narrow, especially along the portions of Wall 7 where there are no groins or breakwaters to trap sand. Removing Wall 7 and the promenade would provide sediment to the beach and reestablish the natural dune system but would be impractical given the scale of the structures and currently unnecessary given the presence of a still-usable beach and representative dune near the groins and breakwaters. The northern portion of the park, in contrast, is undeveloped, presently unused by visitors, and protected by a less massive wall (Wall 8). This area could be allowed to evolve by natural processes, reestablishing a naturally functioning beach/dune/washover system and providing sediment to nourish beaches in the more intensively used areas to the south. There appears to be no need to enhance protection in the northern portion of the park because no critical facilities are present. The existing wall and groins are already contributing to sand starvation in the south and will reduce sediment inputs further when more of the shoreline migrates back to Wall 8. Assuming that no nourishment of the beaches in the developed community to the north occurs, sediment inputs from the north would be reduced; the wall would eventually fail; and the road would be undermined; but a new naturally-functioning system would be established. In the past, anticipation of this kind of change would result in an attempt to stabilize the shore. The need to adapt, rather than resist change, requires a new kind of solution that emphasizes a more dynamic shoreline. It can be argued that only allowing sufficient space for natural processes truly achieves the goal of working with those processes and permitting natural ecosystems to flourish (Cooper and McKenna 2008). Attempts to establish a new set of stable natural or cultural resources in the northern segment would be incompatible with the need to increase ecosystem resilience.

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Table 1. Shore protection structures within Fort Monroe National Monument, and their characteristics.

Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
Wall 1	Riprap (dumped concrete)	72	Parallel	Marsh; shrubs. Access too difficult to specify threatened resources.	Poor	Low; let deteriorate	Washover deposit on landward side of spit	Erosion not a current threat. Concrete is discontinuous and would have little effect in protecting upland if erosion or flooding occur.
Wall 2	Riprap (dumped concrete)	102	Parallel	Marsh; shrubs; trees; non-sanitary landfill	Poor	Low; let deteriorate	Marsh and low upland on washover deposit; covered in places by landfill (waste).	Erosion not a current threat. Concrete is discontinuous and would have little effect in protecting landfill if erosion or flooding occur.
Wall 3	Riprap (dumped concrete)	76	Parallel	Shrubs; grass.	Poor	Low; let deteriorate	Low upland and filled land on washover deposit.	No threatened facilities apparent.
Wall 4	Riprap (dumped concrete)	20	Parallel	Shrubs; trees	Poor	Low; let deteriorate	Washover deposit and filled land on landward side of spit	No threatened facilities remain. Old concrete ramp may have been reason for protection, but access is now overgrown.
Wall 5	Quarry stone revetment	322	Parallel	Grass; path; concrete pad; road; buildings	Good	High	Filled washover deposit on landward side of spit	Wall bisects ecotone. Good location to demonstrate re-initiation of wetlands. Removal of structure could make water access easier for users of trailer park. May require ring levee near trailer park.
Wall 6	Riprap covered by poured concrete	1,270 In park	Parallel	Berm; grass; trees; road; buildings; RV park (north); landing strip (middle); road (south)	Good	Moderate (middle); low (ends)	Fill over bay and washover deposit on landward side of spit	Berm and landing strip would also have to be eliminated in middle of segment. Facilities in use at ends and exposure to creek flooding may argue against removal at those locations.
Wall 7 (seawall)	Concrete	1,580 In park	Parallel	Promenade on raised berm; grass; batteries; O Club; trees; parking lots	Good	Low	Spit, modified by grading and filling	Wall protects promenade and Officer's Club from erosion and landward buildings and parking areas from overwash

Structure	Material	Length (m)	Orientation	Landward habitat/ infrastructure	Condition	Removal priority	Landform characteristics	Rationale for removal priority
Wall 8	Riprap concrete; rock in far south		Parallel	Dune; grass; shrubs; access road	Fair	Low; let deteriorate	Spit, with dune cap over wall	Wall delays breaching of spit and protects road, but paved road access not required. No reason to remove wall until decision made on use of segment
Groin Field 1 (3 groins)	Riprap	54-68	Perp.	Beach; dune grass; shrubs; road	Good	Low; let deteriorate	Spit, with dune cap over wall	Groins delay breaching of spit and protect road, but paved road access not required. No reason to remove groins until decision made on use of northern segment
Groin 2	Riprap	130	Perp.	Dune; seawall; promenade; grass; batteries; O Club; trees; parking lot	Good	Low	Spit, modified by grading and filling	Groin is in a key position to create a beach to protect O Club and provide recreation space. No new habitat would be created due to seawall landward.
Groin 3	Riprap (concrete)		Perp.	Dune; seawall; promenade; grass; buildings; parking lot	Good	Low	Spit, modified by grading and filling	Groin maintains beach to north but creates erosion zone just south of it. No new habitat would be created due to seawall landward.
Breakwater Series 1	Riprap (quarry stone)		Perp.	Beach; dune grass; seawall; promenade	Good	Low	Spit, modified by grading and filling	Breakwaters maintain beach landward of them. No new habitat would be created due to seawall landward.
Wall 9	Riprap (quarry stone)		Perp.	Walkway; grass	Good	Low	Spit, modified by grading and filling	Erosion rate would be high if wall removed; road and buildings would be threatened.

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