



Coastal Geomorphology of the Ocean Shoreline, Gateway National Recreation Area

Natural Evolution and Cultural Modifications, a Synthesis

Natural Resource Report NPS/NERO/NRR—2010/184



ON THE COVER

Upper left: Recreational beach, parking lot D, Sandy Hook. Upper right: Bathhouse, Riis Park.

Lower left: Erosional scarp at location of former bathhouse, Great Kills. Lower right:

Impinging scarp at bike path, Plumb Beach.

Photography by: Norbert P. Psuty

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March 2010

U.S. Department of the Interior
National Park Service
Natural Resource Program Center
Fort Collins, Colorado

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Please cite this publication as:

Psuty, N. P., P. Dennehy, T. Silveira, and N. Apostolou. 2010. Coastal geomorphology of the ocean shoreline, Gateway National Recreation Area: natural evolution and cultural modifications, a synthesis. Natural Resource Report NPS/NERO/NRR—2010/184. Fort Collins, Colorado.

Contents

NPS 646/101463, March 2010

Figures.....	v
Tables.....	vi
Acknowledgements.....	vii
Introduction and Rationale.....	1
Methodology	2
Basic Geomorphological Controls.....	3
Tides.....	3
Wave Climate.....	3
Storm History.....	3
Sea-Level Rise	5
Sediment Supply	6
Sediment Budget.....	10
Human Manipulation	11
Landform Responses.....	13
Sandy Hook.....	13
Staten Island.....	18
<i>Great Kills</i>	18
<i>Miller Field</i>	22
<i>Fort Wadsworth</i>	22
Breezy Point.....	22
Plumb Beach	27
Sediment Management.....	35
Areas for Future Inquiry	36
Literature Cited	37

Figures

	Page
Figure 1. The coastal units of Gateway and the ocean shorelines incorporated herein.	2
Figure 2. Wave roses incorporating frequency and magnitude of incident significant waves at two offshore station locations, 1980-1999.....	4
Figure 3. The beach-dune system exchanges sediment among the foredune, the beach, and the offshore bar feature during the seasonal variation of wave and current energies.	4
Figure 4. The mean sea level trend is 3.90 millimeters/year with a 95% confidence interval of +/- 0.25 mm/yr based on monthly mean sea level data from 1932 to 2006, equivalent to a change of 0.39 m (1.28 ft) in 100 years..	8
Figure 5. The mean sea level trend is 2.77 millimeters/year with a 95% confidence interval of +/- 0.09 mm/yr based on monthly mean sea level data from 1856 to 2006, equivalent to a change of 0.28 m (0.91 ft) in 100 years.	8
Figure 6. Statistical comparison of linear rate of SLR to exponential rate, derived from Sandy Hook tide gauge data, 1933-2008..	9
Figure 7. Natural beach-dune configuration with adequate sediment budget, incorporating a foredune, an upper berm reached during storm conditions, and a lower surface that is affected by the normal tidal variations and incident waves.....	11
Figure 8. Coastal topography and engineering structures on the Sandy Hook Unit.....	14
Figure 9. The artificially wide beach following beach nourishment at the Park entrance.....	16
Figure 10. Coastal topography of Sandy Hook derived from first-return LiDAR data.....	17
Figure 11. Inland offset of shoreline downdrift of terminus of seawall, the Critical Zone, September 11, 2008.	19
Figure 12. Great Kills Park Staten Island Unit	21
Figure 13. Comparison of topography from 1891 topographic map and location of existing park shoreline on 2002 aerial photograph at Great Kills (Mellander, 2007).	21
Figure 14. Severe erosion downdrift of projecting headland. Pilings are at site of demolished bath house. March 31, 2009.....	22
Figure 15. Miller Field, Staten Island Unit, with coastal features and structures.....	23
Figure 16. Beach seaward of constructed sand dike at Miller Field, March 31, 2009.	24
Figure 17. Fort Wadsworth, Staten Island Unit, coastal topography and structures.	24
Figure 18. Beach-dune profile seaward of constructed sand dike, Fort Wadsworth..	25

Figures (Continued)

	Page
Figure 19. Ocean coast extends from the jettied Rockaway Inlet updrift to the eastern margin of Riis Park.	28
Figure 20. Portions of the wooden bulkhead and riprap wall exposed at base of foredune in Ft. Tilden. March 31, 2009.....	28
Figure 21. Coastal topography of Breezy Point spit, derived from first-return measurements collected in 2005 using the NASA Experimental Advanced Airborne Research LiDAR (EAARL); part of a collaborative effort among the USGS, NASA, and NPS..	29
Figure 22. Topography and structures at Plumb Beach.	31
Figure 23. Small foredune developing at eastern margin of Plumb Beach, migrating inland over wetland and tidal channel. April 10, 2008.	31
Figure 24. Coastal topography of Plumb Beach, derived from first-return measurements collected in 2005 using the NASA Experimental Advanced Airborne Research LiDAR (EAARL); part of a collaborative effort among the USGS, NASA, and NPS.....	32
Figure 25. Riprap exposed at eroding sector, central Plumb Beach, March 31, 2009.....	33

Tables

	Page
Table 1. Storm Water Elevations	7

Acknowledgements

Conducting a literature review and digesting a vast suite of information required the able participation of people in various offices and agencies where data are stored. This is especially true for this product because much of the material was in the gray literature housed on shelves and files rather than in the traditional scientific journals. The following people were especially helpful and contributed both their knowledge of the park as well as information contained in the dusty reports: Kathyryn Mellander, Mark Christiano, Bruce Lane, Tom Hoffman and Felice Ciccione of the Gateway National Recreation Area; Annette Baden, Rita Fisher, and Christina Rasmussen of the New York District, U.S. Army Corps of Engineers; David Robinson, New Jersey State Climatologist, Rutgers University; Barry Pendergrass, New York State Department of State, W. Frank Bohlen, Department of marine Science, University of Connecticut; June Gallegos, National Park Service Technical Information Center; and Chris Shafer, Sandy Hook Cooperative Research Programs, Rutgers University. Their inputs contributed immensely to the breadth of resources involved in the production of this paper. Dennis Skidds of the national Park Service, Northeast Coastal and Barrier Network , provided the LiDAR data used in the creation of the coastal topography maps for the Gateway units. A special note of appreciation is extended to Dr. Charles T. Roman for his constructive review of the draft of this document and to the anonymous reviewers for their very helpful comments. The resulting product is truly a team effort.

Introduction and Rationale

Coastal geomorphology is a basic component of the environmental system at the Gateway National Recreation Area. The evolution of the physical characteristics of the coastal system is based in the geologically-recent history of a rising sea level interacting with the sediments occurring on and supplied to portions of the continental shelf (Walker and Coleman, 1987). The product of that interaction and the natural processes drive the continuing development of the ambient coastal morphology with its variety of barrier island forms and the variable dimensions and sequences of beaches and dunes. Further, knowledge of the natural vectors of development, direction, and magnitude of morphological change is an important element in the consideration of any strategy directed at the shepherding of the existing natural and cultural resources in the park (Sherman, et al., 1979). Working within the limits imposed by the natural system and incorporating the myriad of cultural modifications offers an opportunity to address issues of sustainability and resilience in this dynamic area. An understanding of the vectors of the geomorphological evolution and the dimensions of the human modifications provides perspective to the impacts of future management decisions.

This paper is a synthesis of the scientific literature pertaining to the geomorphological evolution of the ocean shoreline of the units of Gateway National Recreation Area (GNRA). It is a description of the studies that have been undertaken within the Park and it also brings together a suite of data that pertain to the environs of the Park, such as the wave climate, the measures of sea-level rise, and some of the storm history. In addition, this paper incorporates aspects of the human manipulation of the Park's shoreline, both within the confines of the Park and adjacent to the Park. The history of inquiry into the physical processes and the resulting landforms is quite uneven for the several units of Gateway. The Sandy Hook area has been the subject of study for over a century, including Johnson (1919, p. 296) through Psuty, et al. (2009), whereas the remainder of the Gateway ocean shoreline is largely unstudied, or certainly not the subject of continuous inquiry. Information pertaining to components of Gateway has been included in many US Army Corps of Engineers (USACOE) reports (Taney, 1951: through USACOE, 2002) and they are sources of observations and histories of change, especially data regarding storm events and engineering modifications to the shore environment.

In addition to the natural evolution of the coastal system within the boundary of Gateway, there are many human interventions that have altered the processes that create elements of the topography and there are alterations of the forms that exist on-site. The presence of engineering structures, both within and external to the Park, produce positive and negative modifications. Further, episodes of dredging and subsequent discharge of the excavated sediment have adjusted the availability and transport pathways of the local materials. Together, the natural conditions and the human alterations have created the coastal products in Gateway. The results of this combination of processes, sediments, and manipulations are the focus of this paper.

Methodology

GNRA is a fairly large geographical area with considerable variety in processes and forms. The approach to presentation of the information will be to establish the general condition of the coastal system and then to describe the specifics of portions of Gateway NRA, incorporating the human modification of the particular sites. The central theme of this paper will be the ocean-facing shoreline of the several units of GNRA. These components are identified on Figure 1. They consist of the ocean side and northern coast of Sandy Hook, the coastal stretch from Riis Park to the terminus of Breezy Point, a small section of beach exposed to ocean waves at Plumb Beach, and three seaward-facing beaches on Staten Island: Fort Wadsworth, Miller Field, and Great Kills. Each of these sites incorporates a mixture of natural system modified to varying degrees by human factors. An outcome of this synthesis will be an improved understanding of the existing balance achieved at each site and an appreciation of the possibilities at future times.

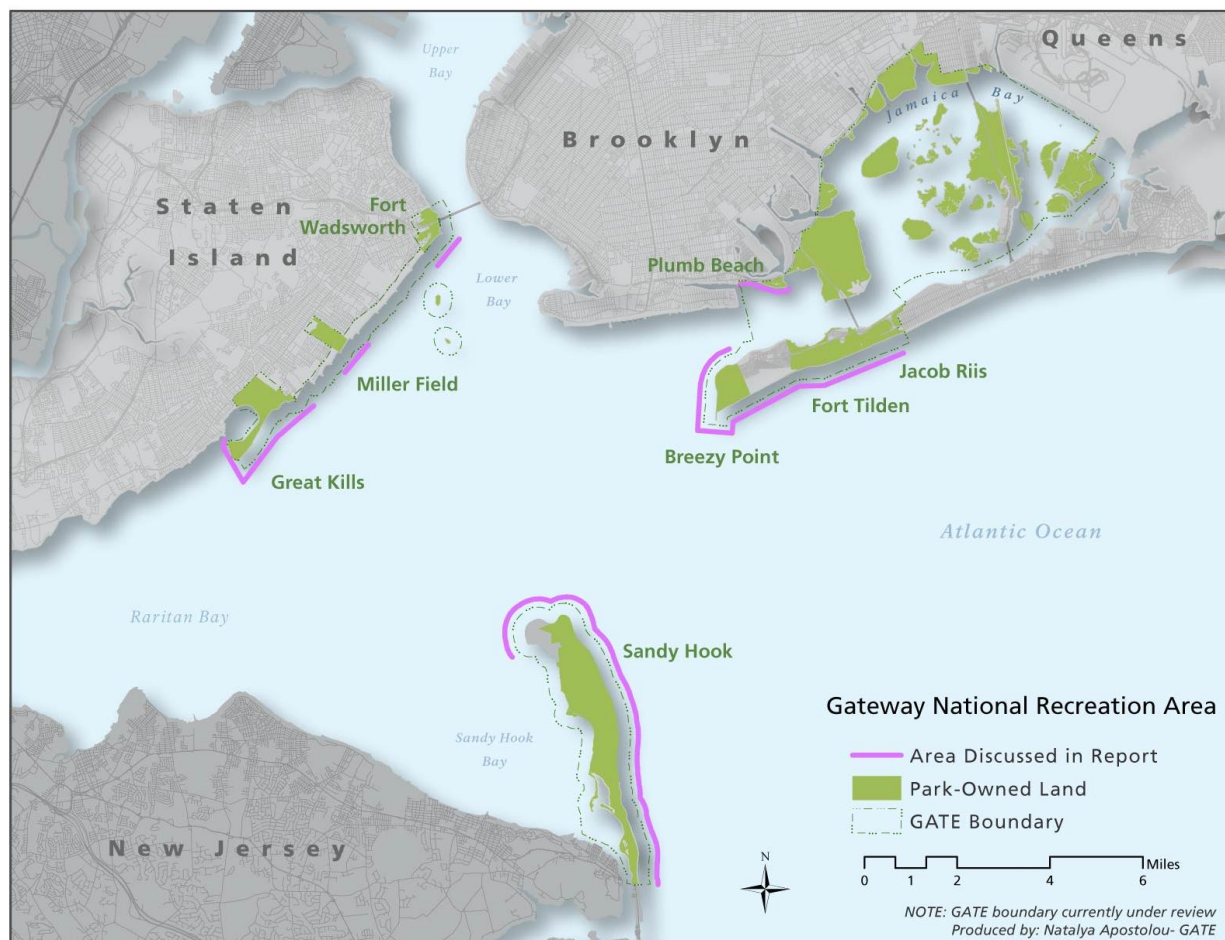


Figure 1. The coastal units of Gateway and the ocean shorelines incorporated herein.

Basic Geomorphological Controls

Tides

This portion of the coast has a semi-diurnal tide (two highs per day) with a mean spring tidal range of 1.59 m (5.22 ft) at the Sandy Hook tide gauge (this value is derived from the tidal epoch of 1983-20011). The tidal range has an influence on the beach profile by defining the vertical dimension of the beach face. Also, the tidal range generates current flows through coastal inlets or entrances. These tidal currents have the capacity to transport sediment and to create tidal deltaic deposits on the baysides or ocean sides of inlets/entrances, thereby sequestering sediment that would otherwise be transported alongshore to the next downdrift portion of the shore.

Wave Climate

Waves are the basic drivers of coastal development and coastal change. They supply most of the energy to mobilize and transport sediment. The direction of wave approach dictates the direction of sediment transport. Therefore, a fundamental data set is the magnitude and direction of oncoming waves throughout this coastal area. Wave roses of significant wave heights (mean of the highest one-third) have been generated for a range of sites in the offshore by the Wave Information Studies of the US Army Corps of Engineers for the entire Eastern Seaboard (USACOE, 2009). The application of these data depict the dominance of the incident waves arriving from the southeast quadrant (Fig. 2). This spatial limitation is not surprising. This is the only quadrant for effective wave generation in the New York Bight. Other directions have much shorter fetch distances for wave generation and therefore create much smaller and shorter waves (less ambient energy to mobilize and transport sediment). Importantly, under conditions of strong winds out of the northeast, the sheltering function of New England causes the winter storm waves to wrap around New England (refract) and arrive from the east-southeast in both New Jersey and New York. As a result, the wave action and the local currents transport sediments toward the entrance to New York Harbor, westerly along the Long Island shore and northerly along the New Jersey shore. The transport direction is essentially unidirectional and leads to a downdrift extension of the coastal topography toward New York Harbor.

Storm History

Stormy periods are the times of large waves and abundant energy to move sediment on the beach profile. The waves operate on the offshore as well as beach portion. Storm winds add another component of sediment mobilization and tend to move material on the beach berm and foredune (Fig. 3). Much of the erosion and sediment loss occurs during the stormy fall, winter, and spring seasons when traveling low pressure cells spur cyclonic storms referred to as nor'easters. The summer season tends to be a time of lower winds and waves, and consequently there is a recovery of sediment and an accumulation on the dune-beach profile (Fig. 3). Occasionally, the summer is a time for hurricane development and locally intense erosion and sediment mobilization. Hurricanes tend to be more intense but of shorter duration than nor'easters. The nor'easters tend to have impacts over several days (several tidal cycles) and cause considerable

¹ The tidal epoch is a 19-year cycle of earth-sun-moon interaction that affects the tidal variations and the range of tide at the recording station. Each NOAA tide gauge station uses a tidal epoch as a means of calculating the range of tide during one complete 19-year cycle (the 1983-2001 tidal epoch is the most recent calculated for Sandy Hook).

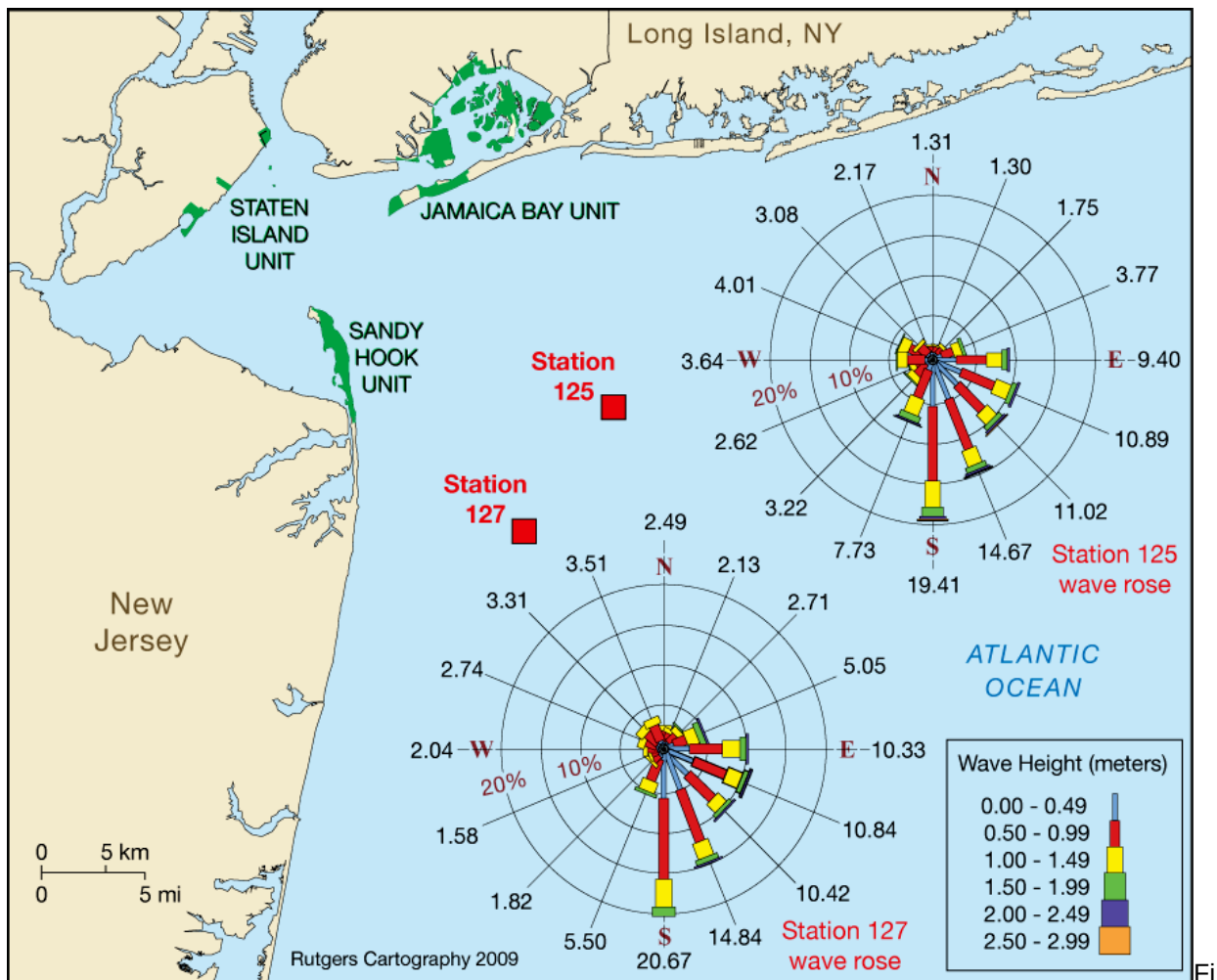


Figure 2. Wave roses incorporating frequency and magnitude of incident significant waves at two offshore station locations, 1980-1999. Values on the perimeter of the roses pertain to annual percentage of waves from that direction. (USACOE, 2009).

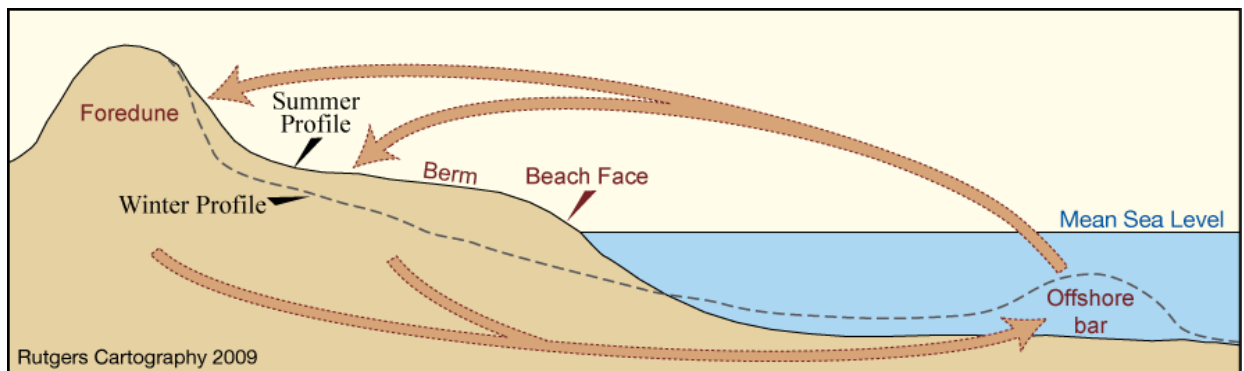


Figure 3. The beach-dune system exchanges sediment among the foredune, the beach, and the offshore bar feature during the seasonal variation of wave and current energies. The foredune tends to store sand high on the profile during low energy periods, whereas the offshore bar stores sand offshore during high energy periods. A similar exchange occurs with each storm. The stormy season does not permit recovery between storms.

change because of their duration as well as severe winds and waves.

Storms happen. Each year there will be some severe weather that will cause change to the coastal topography. Past storm events have produced major changes to the coastal systems (Coch, 1993). The potential for storm impacts at Gateway are addressed in a report produced by the U.S. Geological Survey (Pendleton, et al., 2005) that relates local inundation vulnerability to exposure and physical characteristics. A brief history of storm events and their associated water elevation (impact on the beach-dune system) is presented in Table 1. Storm water elevations above 1.12 m NAVD88 will cause changes to the upper beach (based on monitoring program at Sandy Hook, summarized in Psuty, et al., 2009). Storm water elevations above 1.27 m NAVD88 will scarp the foredune and lower the beach berm (see Fig. 3). Each of the storm water elevations has been adjusted to the NAVD88 datum for comparative purposes. According to USACOE and Coastal Planning & Engineering, Inc. (CPE) (1994) and the Federal Emergency Management Agency (FEMA) website, the hundred-year recurrence interval storm at the Sandy Hook tide gauge will reach 2.95 m (10.8 ft) NAVD88, the fifty-year storm will be at 2.77 m (10.2 ft), and the 20-year storm will be at 2.16 m (8.2 ft).

Sea-Level Rise

The issue of sea-level rise (SLR) is important to all coastal locations because of the likely inland displacement of the shoreline as the global water-level rises. As a driver, SLR may cause an inland shift of the beach-dune system by the simple drowning of the existing beach position, thereby causing a re-location of the zone of wave and current processes interacting with available sediment. Furthermore, an ancillary effect of SLR will be to hasten the exposure of inland features to the effects of storm surge and sediment mobilization and to exacerbate the rates of sediment loss in areas of negative sediment budget.

There is a very good record of SLR in Gateway NRA because of the presence of two long-term tidal gauges, Sandy Hook (Fig. 4) and The Battery (Fig. 5). These gauges record the recent history of water level in and near the Park and offer a means to appreciate the effects. The Sandy Hook record of 3.9 mm/yr rise is appropriate for the ocean shoreline of Gateway because of the similarity of geomorphological heritage of the ocean shoreline in the Park (a barrier island development with relatively thick accumulations of modern sediment). The Battery rate of rise is a bit lower (2.77 mm/yr) because it is at a location that is not in a barrier island setting and the depth of modern sediment undergoing compaction is much less. The Battery record is probably a better model for rate of inundation along portions of Staten Island.

The importance of any SLR calculation is the subsequent impact of a higher water level (storm surge) during low-frequency, high-magnitude storm events. As the local sea level rises during the next decades, storm events will reach higher on the beach profile and will penetrate farther inland to mobilize portions of the topography that heretofore were above the reach of these storms. Among the results will be an increase in sediment removal and shoreline displacement related to sea-level rise (Buttner, 1987; Nicholls, et al., 2007). Therefore, natural and cultural

resources will be increasingly exposed to the impacts of storm events and changes in coastal topography will be accelerated. Further, the rates of SLR may be escalating into the future. Evidence summarized in the recent Intergovernmental Panel on Climate Change report (Bindoff, et al., 2007) indicates that sea level will rise at an increasing rate. Statistical analysis of data from

the Sandy Hook tide gauge (Fig. 6) and other local gauge data (Psuty and Ofiara, 2002) show that the increasing rate is recognized in the present-day trends. As further evidence of the current trend, the absolute elevation of mean sea-level at Sandy Hook and other tidal reference marks related to mean water levels at this site have increased by 79.25 mm (0.26 ft) from the previous tidal epoch to the tidal epoch of 1983-2001 (NOAA, 2009).

Sediment Supply

The availability of sediment to supply the coastal topography in GNRA is derived from several sources. The source provided to the Breezy Point unit is part of the barrier island chain along the southern shore of Long Island that receives sediment from eastern Long Island via alongshore transport as well as some onshore transport (Taney, 1961; Fairchild, 1966; Williams, 1976; Williams and Meisburger, 1987, Williams and Morgan, 1993). Breezy Point and Plumb Beach are at the far western end of the barrier-island sediment chain and there are numerous interruptions in the continuity of transport created by inlets. Many of the inlets have been sites of sediment sequestration as large flood tide deltaic deposits have reduced the sediment flows along the westerly pathway. Much of this sediment was originally deposited as glacial outwash at the eastern margin of Long Island (Williams and Meisburger, 1987). It is likely that the glacially-derived supply is nearly exhausted and there is inadequate natural erosion of that source to continue to sustain the present barrier island system in central and eastern Long Island (Kana, 1995, 1999; Wolff, 1989; Rosati, et al., 1999). A part of the deficit is currently being met by beach nourishment and transfers from sediment sequestered in the tidal deltas at the various inlets. However, the many Corps of Engineer reports offer testimony to the long-term erosional trend of the shoreline and the narrowing of the barrier island system (USACOE, 1965a, 1973, 1979, 1992; USACOE & CPE, 1994).

The Sandy Hook unit derives its sediment from northerly transport along the New Jersey shoreline (USACOE, 1954; McMaster, 1954; Minard, 1969). There may have been more sand in the past, but the current sources of eroding headlands immediately updrift from the Hook are insufficient to maintain the shoreline position. A seawall constructed about one century ago plus several episodes of beach nourishment are supporting the continuity of the Hook.

The eastern shore of Staten Island has a natural sediment supply in the form of glacial deposits that form a large terminal moraine near the Verrazano-Narrows Bridge and a large glacial outwash plain that extends southeasterly into the harbor from the moraine (Multer, et al., 1984). These deposits are easily eroded and supply sediment that is transported to the southwest to form a short spit extending to Crooke's Point. This source contributes an inadequate quantity of sediment to maintain this southeastern shore of Staten Island (USACOE, 1995).

Table 1. Storm Water Elevations. H = hurricane; NE = nor'easter; ¹data from NOAA (2009)

Date	Storm Type	Elevation m NAVD88	Reference Station	Source
Published reports				
3 Sept 1821	H	ca. 2.3-2.6	Ft Hamilton (?)	USACOE 1979
24 Nov 1901	NE	1.49	Ft Hamilton	USACOE/CPE 94
16-17 Sept 1903	H	1.09	Ft Hamilton	USACOE/CPE 94
7 Dec 1914	NE	1.25	Ft Hamilton	USACOE/CPE 94
11-12 April 1918	NE	1.74	Battery	USACOE 1979
5 Feb 1920	NE	1.61	Ft Hamilton	USACOE/CPE 94
20 Feb 1927	NE	1.77	Battery	USACOE 1979
3 Mar 1931	NE			Govs Task Force 1994
17 Nov 1935				Govs Task Force 1994
21 Sept 1938	H	1.67 1.65	Battery Sandy Hook	USACOE/CPE 94 USACOE 1954
14 Sept 1944	H	1.67 1.98	Battery Sandy Hook	USACOE/CPE 94 Pore & Barrientos 1976
25 Nov 1950	NE	1.95 2.04	Battery Sandy Hook	USACOE/CPE 94 USACOE 1954
6-7 Nov 1953	NE	2.07 2.62	Battery Sandy Hook	USACOE/CPE 94 USACOE 1954
31 Aug 1954 (Carol)	H	1.58 1.61	Battery Sandy Hook	Govs Task Force 1994 Pore & Barrientos 1976
14-16 Oct 1955	NE	1.58	Battery	USACOE/CPE 94
12 Sept 1960 (Donna)	H	2.22 2.28 2.29 2.28	Battery Ft. Hamilton Sandy Hook Sandy Hook	USACOE/CPE 94 USACOE 1992 USACOE SPM 1973 Pore & Barrientos 1976
6-8 March 1962	NE	1.89	Battery	USACOE/CPE 94
23 January 1966	NE	1.46 no datum	Sandy Hook	Pore & Barrientos 1976
12 Nov 1968	NE	1.40 no datum	Sandy Hook	Pore & Barrientos 1976
3 Feb 1972	NE	1.16 no datum	Sandy Hook	Pore & Barrientos 1976
19 Feb 1972	NE	1.22 no datum	Sandy Hook	Pore & Barrientos 1976
6 Aug 1976 (Belle)	H			
6 Feb 1978	NE			Govs Task Force 1994
6 Sep 1979 (David)	H	1.41	Sandy Hook	NOAA ¹
28-29 March 1984	NE	1.83	Sandy Hook	USACOE/CPE 94
27 Sept 1985 (Gloria)	H	1.67	Battery	USACOE/CPE 94
31 Oct 1991	NE	1.75	Sandy Hook	Govs Task Force 1994 NOAA
11 Dec 1992	NE	2.31 2.10	Sandy Hook Battery	Schubert & Busciolano 1994 Schubert & Busciolano 1994
NOAA data				
March 2001	NE	1.41	Sandy Hook	NOAA ¹
25 Dec 2002	NE	1.61	Sandy Hook	NOAA ¹
3 Jan 2003	NE	1.50	Sandy Hook	NOAA ¹
10 Dec 2004	NE	1.41	Sandy Hook	NOAA ¹
25 May 2005	NE	1.42	Sandy Hook	NOAA ¹
31 Jan 2006	NE	1.56	Sandy Hook	NOAA ¹
16 April 2007	NE	1.61	Sandy Hook	NOAA ¹
12 Dec 2008	NE	1.50	Sandy Hook	NOAA ¹

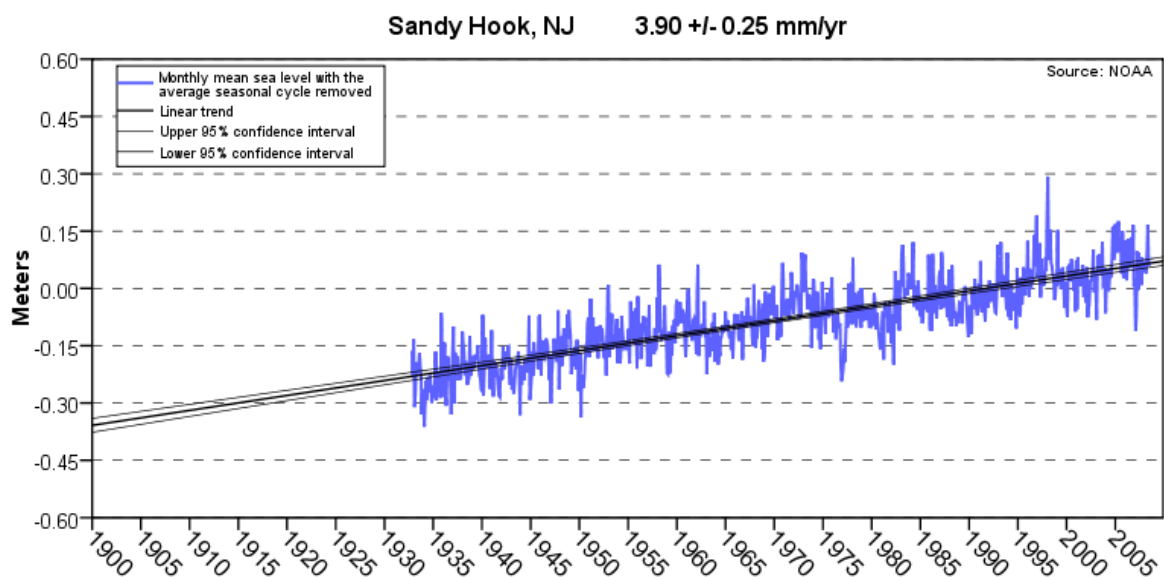


Figure 4. The mean sea level trend is 3.90 millimeters/year with a 95% confidence interval of +/- 0.25 mm/yr based on monthly mean sea level data from 1932 to 2006, equivalent to a change of 0.39 m (1.28 ft) in 100 years. The vertical datum base value is MSL, 1995. NOAA, 2009.

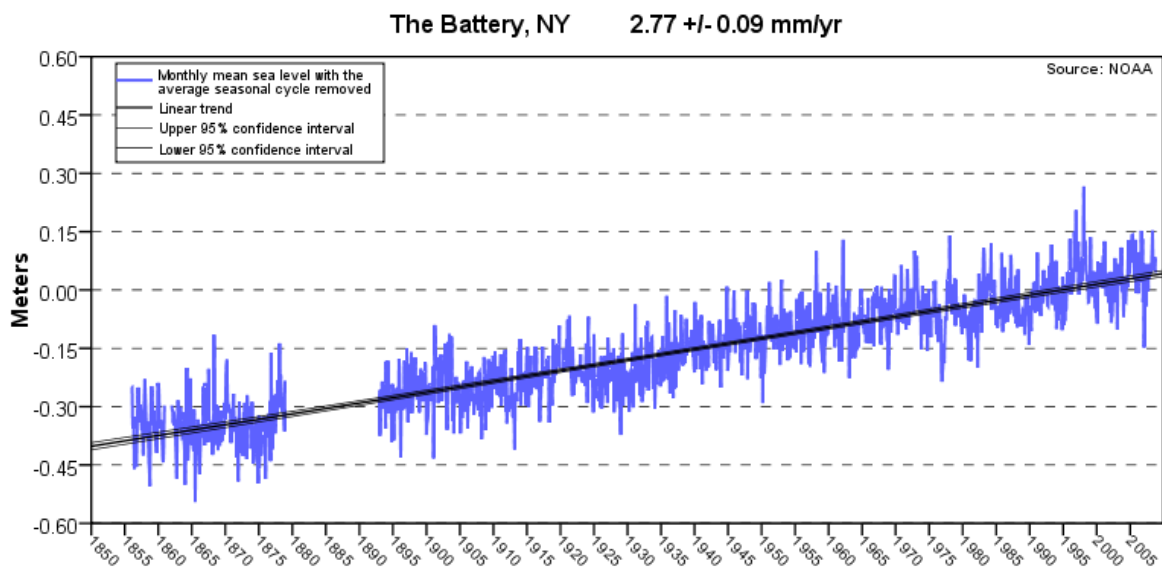


Figure 5. The mean sea level trend is 2.77 millimeters/year with a 95% confidence interval of +/- 0.09 mm/yr based on monthly mean sea level data from 1856 to 2006, equivalent to a change of 0.28 m (0.91 ft) in 100 years. The vertical datum base value is MSL, 1995. NOAA, 2009.

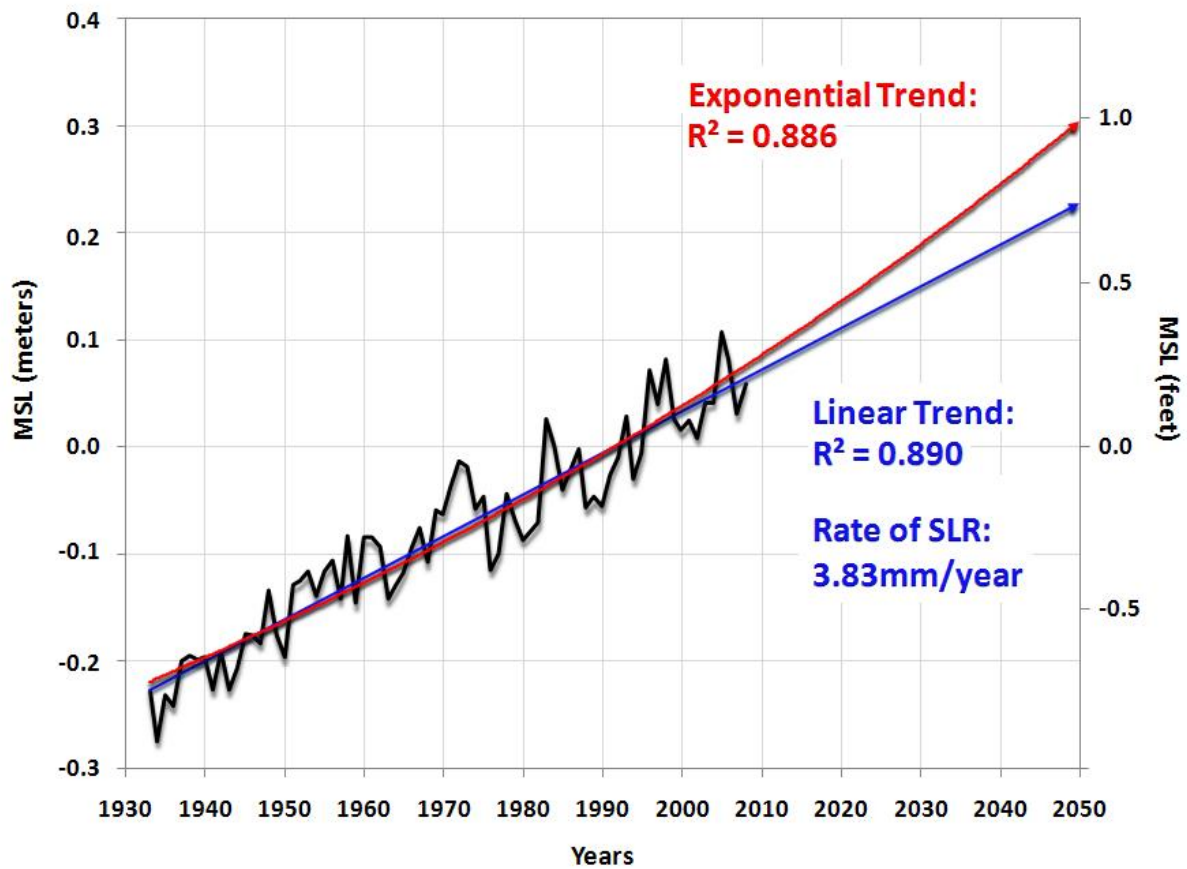


Figure 6. Statistical comparison of linear rate of SLR to exponential rate, derived from Sandy Hook tide gauge data, 1933-2008. The correlation value (R^2) assigned to the exponential increase is nearly identical to the correlation value assigned to the linear increase. The base value for the vertical scale is MSL, 1995. NOAA, 2009.

Sediment Budget

Whether a shoreline erodes or builds seaward is a function of the local sediment budget, a comparison of the amount of incoming sediment compared to the outflows of sediment. It does not matter if the sediment is lost to an offshore sink, inland to a bay, or whether it is transported to the next unit downdrift. It is a comparative measure that applies to a geographical area for some duration of time. Usually, sediment budget is expressed in terms of some volume of sand per year. As an example, Plumb Beach in the Jamaica Bay Unit may have a negative sediment budget of $-1,000 \text{ m}^3/\text{yr}$. However, that value may be composed of some parts of Plumb Beach losing $2,000 \text{ m}^3/\text{yr}$ and another part gaining $1,000 \text{ m}^3/\text{yr}$. At Plumb Beach, as well as at other coastal portions of GNRA, there is an alongshore compartmentalization of the shoreline that incorporates gradations of sediment budget that often passes from zones of negative sediment budget to positive sediment budget, each with their characteristic features and vectors of change. In a general application of the concept, most of GNRA is undergoing a long-term negative sediment budget. However, there are gradients of sediment availability that affect local sediment budgets and their characteristics and trends. Thus, portions of Gateway may be accreting and extending laterally while, in general, the units are experiencing net loss. Further, there is a cultural component to the sediment budget because of the physical emplacement of sediment on the beaches by dredging or trucking. In the short-term, the cultural contribution to sediment availability affects the sediment budget.

The natural configuration of the topography at the shoreline is a broad free-sand beach backed by a vegetated foredune-ridge (Fig. 7). With adequate sand, the beach and dune system will exchange sediment with the offshore during seasonal variations in wave energy, and the form will continue to be present, although with episodic changes in dimension (Fig. 3). Under conditions of long-term positive sediment budget, the shoreline will migrate seaward and the topography will be composed of a series of stranded foredune ridges, each abandoned ridge representing a former shoreline position. Under a negative sediment budget, the dune-beach system will be displaced landward as sand is eroded and transported downdrift, causing the barrier island to narrow. Under a persistent negative sediment budget, the foredune may be lost to the profile and the beach may terminate against an eroding bluff, or some infrastructure, or the site may be a location of overwash and transfer of sediment from the ocean side to the bay side of the barrier. This is a condition that occurs toward the end of the life of part of a barrier island. It signals the time of redistribution of much of the remaining sand constituting that part of the barrier and the displacement of the barrier system as well as the displacement of the beach-dune components. Under extreme negative sediment budgets, the beach and portions of the barrier island will be lost if there is no human intervention. Importantly, the issue of sediment supply to beach systems and sediment budget will take on additional meaning as sea level continues to rise. Stability of the shoreline position and continuity of the habitat characteristics will require an increasing amount of sediment to maintain an equilibrium sediment budget.

Human Manipulation

There are few portions of the Gateway shoreline that are in a natural state (Nordstrom, et al., 1975; Smith, et al., 1985; Wolff, 1989; Psuty, 2008). Most of the coastal topography has been altered by the presence of engineering structures (groins, jetties, and seawalls) that are changing the rates and quantities of alongshore transport as well as the locations of sediment accumulation

and/or loss, summarized in the National Shoreline Study (USACOE, 1971). Further, dredging of navigation channels at inlets and entrances to harbors has moved great quantities of sediment and has affected the local sediment supply and budget. And, there have been several instances of beach nourishment that have created local accumulations, displacing the shorelines from tens to a hundred meters. Some episodes of the beach nourishment have been practiced within GNRA, whereas some have been in an updrift location that have subsequently migrated into the Park. Together, the human imprint dominates large portions of the GNRA shoreline and influences the evolution of topographical development.



Figure 7. Natural beach-dune configuration with adequate sediment budget, incorporating a foredune, an upper berm reached during storm conditions, and a lower surface that is affected by the normal tidal variations and incident waves. May 22, 2007

Landform Responses

The two major landform components of GNRA are the coastal barrier spits that compose Sandy Hook on the NJ coast and Riis Park – Breezy Point on the NY coast (Fig. 1). They are both products of the alongshore transport of sediment that have extended the two barrier features toward Lower New York Bay. Each of the coastal barriers retains a series of accretionary dune ridges that represent stages in the downdrift extension of the landform. Some of the dunal ridge forms are natural, whereas others are the product of human influences. In other parts of Gateway, Plumb Beach is formed on a remnant of the easterly terminus of the Coney Island barrier. Great Kills is located on a remnant of a barrier spit that formerly extended southwesterly along the ocean-facing margin of Staten Island. Each of the components has a suite of beach and foredune associations produced by local natural and cultural conditions.

Sandy Hook

The Sandy Hook Unit occupies the distal end of the Sandy Hook barrier spit that extends northward (downdrift) for 18 km from its origin at the coastal headland in Monmouth Beach. In the past, the barrier spit evolved by accumulating sediment at its northern portion and episodically building to the north-northwest. Several old shoreline positions are preserved as stranded foredune lines in the topography (Fig. 8). However, there is a very limited natural source of sediment to support the basal portion of the barrier spit, and the historical record (Moss, 1990) recounts periods of inlet formation opposite the Navesink and Shrewsbury drainage basins. During the historical period of 1733-1900, Sandy Hook has at times been an island detached from any part of the mainland, it has been connected to the mainland at the Highlands, and it has been connected at Long Branch, as now (Moss, 1990). Human alterations of Sandy Hook have interacted with the natural processes to harden the shoreline, to displace sites of localized erosion with emplaced sediment, and to focus erosional effects caused by structures (Nordstrom, et al., 1977; Allen, 1981; Psuty and Namikas, 1991).

The former inlet breaches in the basal portion of Sandy Hook probably allowed a net sediment transport from the drainage systems into the coastal alongshore flows for some temporal span. However, a quest for coastal stability led to the construction of a 12 km long seawall during the period of 1900-1926, with numerous groins, that extended from the contact of the barrier spit with the headland, at the southern margin of Monmouth Beach, to a position currently within the Park (Fig. 8). The seawall and its impacts are now prime determinants for coastal features along most of the Park's ocean shoreline at Sandy Hook.

Caldwell (1966) estimated the volume of sand transported along the Sandy Hook ocean shoreline at about 382,000 m³/yr (500,000 yds³/yr) on the basis of the incident wave energy (magnitude and direction). The material is derived entirely from local sources (McMaster, 1954; Minard, 1969). Allen (1981) described Sandy Hook as composed of three segments related to sediment budget and sediment transport. He indicated that the southern portion (Segment 1), nearly north-south in orientation, is marked by erosion because there is no adequate source of sand to buffer the continuous loss, creating a negative sediment budget. That erosional portion continues until about halfway into the Park, where there is a change in orientation of the shoreline toward the



Figure 8. Coastal topography and engineering structures on the Sandy Hook Unit. The natural dune-beach system is divided into the active units and those which have been stranded inland as the spit has evolved.

north-northwest. Allen suggests that this mid portion (Segment 2) of Sandy Hook is a zone of sediment transport with little net gain or loss, a balanced sediment budget because of lower wave energy and the input of eroded sediment from the south. After about 2.5 km, the orientation changes again, almost due northwest, resulting in additional lowering of the incident wave energy. This portion of Sandy Hook (Segment 3) shows evidence of sediment accumulation, a positive sediment budget, and a northerly extension of the Hook.

A major change in sediment availability and shoreline change historically occurred beyond the northerly limit of the seawall. As is common in locations downdrift from a shoreline composed of hard structures, accelerated erosion developed beyond the limit of the seawall. Sherman, et al. (1977) referred to this location as the Critical Zone and determined that the erosion downdrift of the seawall began after 1950 and accelerated through 1976. Despite several attempts to stabilize the shoreline (Nakashima, et al., 1983), Psuty and Namikas (1991) measured a loss rate that peaked at 176,000 m³/yr (ca. 230,200 yds³/yr), including periods of beach nourishment.

Whereas the incident energy arriving at Sandy Hook has probably not changed during the past several decades, the shoreline displacement downdrift of the end of the seawall has been altered by the several episodes of beach nourishment in the Park, and, more importantly, by the beach nourishment projects updrift of the Park. Major inputs of sediment seaward of the seawall (Fig. 9) have contributed to the local sediment budget and have displaced the shoreline position seaward while contributing great quantities of material to downdrift transport. Approximately 9,815,000 m³ (12,838,000 yds³) have been placed updrift of the park since 1985 (Psuty and Ofiara, 2002; Corps web site). The Park has placed 4,822,000 m³ (ca. 6,300,000 yds³) of sediment in the vicinity of the Critical Zone over the span of 1975-2002 (Psuty and Ofiara, 2002). The result of the massive nourishment projects updrift of the park and within the Critical Zone is a relatively low rate of net sediment loss in the location immediately downdrift of the end of the seawall in recent years, on the order of 20,000-40,000 m³/yr (ca. 26,000-52,000 yds³/yr) (Psuty and Pace, 2009). 201,000 m³ (263,000 yds³) of sediment was pumped into the Critical zone in late 2002. Most of that remains onsite (Psuty, et al., 2009). Meanwhile, the sediment transportation zone (Segment 2) in the middle portion of Sandy Hook is recording a modest gain, 30,000 m³ /yr (ca. 39,000 yds³), and the northern portion (Segment 3) is building due north under a positive sediment budget. A large shoreline projection is both widening and elevating the northernmost portion of Sandy Hook (Fig. 10). Sediment is also transported beyond the northern tip of the Hook into the adjacent navigation channel, from where it has been dredged and emplaced at the Critical Zone on several occasions (Zammit and Slezak, 1987).

Elements of the natural beach-dune geomorphology occur at several locations on the oceanside of Sandy Hook. Natural refers to the products of the ambient wave and currents mobilizing sediments to build parts of the beach-dune topography described earlier, distanced from the artificial structures and not created by human action. At Sandy Hook, there is a natural beach-dune topography that begins near the northern margin of the Critical Zone and continues to the northerly point of the Hook (Fig. 8 and 10). There are a number of stranded foredune ridges that exist in the topography. They represent stages in the accretional history of Sandy Hook (Fig. 8 and 10). There are several parallel foredune ridges in Segment 3 that represent episodes of northerly accretion, but they are truncated both to the east and the west, representative of a narrowing of the distal end of Sandy Hook. The dune-beach system seaward of the seawall and at the Critical Zone is largely an engineered feature and is not part of the current sand-exchange

Beach Fill 1995-1996



Figure 9. The artificially wide beach following beach nourishment at the Park entrance.

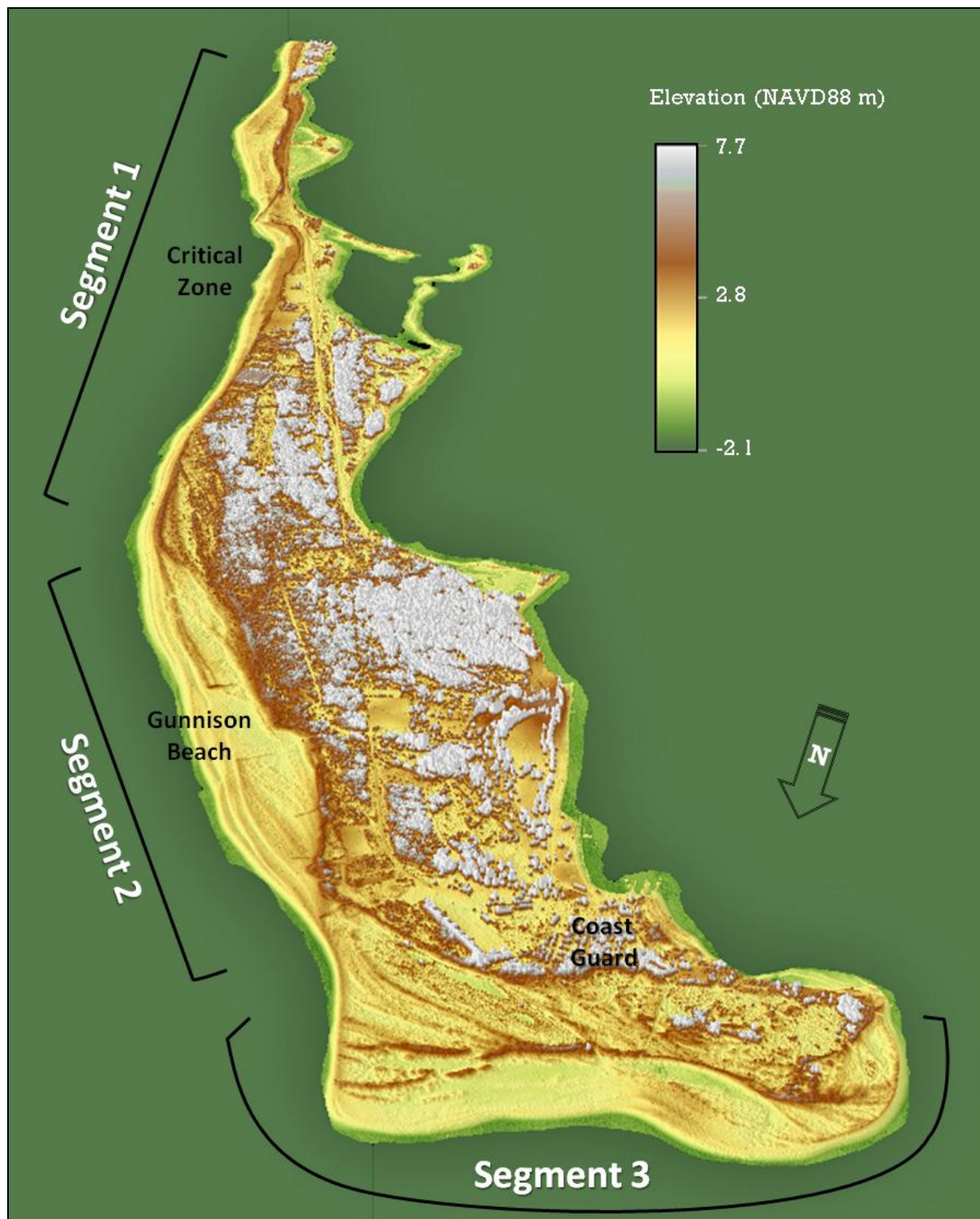


Figure 10. Coastal topography of Sandy Hook derived from first-return LiDAR data. Elevation measurements were collected in 2005 using the NASA Experimental Advanced Airborne Research LiDAR (EAARL); part of a collaborative effort among the USGS, NASA, and NPS. The surface characteristics of the three segments display the recent evolutionary development of the Hook culminating in the multitude of accretionary ridges in Segment 3

topography described in Figure 3.

The dominant engineering structure external to the Park as well as within the Park is the massive seawall at its southern margin. The seawall was constructed in stages from 1898 through 1921 (Sherman, et al., 1977). It has a general elevation of 5.1 m (NAVD88) and a width of 3.7 m. There are five groins on the seaward face of the seawall in the park. They do not presently alter the alongshore transport of sand at the beach. They are low rock and timber groins that are exposed usually only at low tide after a storm. With the exception of the rock groin immediately updrift from the northern end of the seawall, none of the existing groins associated with the seawall create a downdrift offset in the shoreline (Fig. 11).

There is a lengthy timber groin seaward of Battery Gunnison that is completely enveloped with sand. It was last seen in the 1980s. There are two rock groins near North Beach that are occasionally visible. There is a downdrift offset of the shoreline associated with these latter groins. They are low and permeable. They seem to be a factor in the shoreline response, but not the sole cause of the offset.

As with other coastal shorelines in GNRA, Sandy Hook contains a mix of natural and human-created features. The seawall at the southern margin of the Park is the primary factor for other elements of the coastal topography. It supports the connection with the mainland and it maintains the continuity of the shoreline. Episodes of beach nourishment along its seaward margin supply material to maintain the ocean shoreline beyond the downdrift terminus of the structure. At present, a small negative sediment budget at the end of the seawall creates a slow rate of inland shoreline displacement. Most of the remainder of the ocean shoreline is slowly eroding (Segment 1), stable (Segment 2), or accreting (Segment 3).

Staten Island

The three components of the Park shoreline on Staten Island (Fig. 1) share a similar natural history. They are situated at a site where Pleistocene glacial deposits are being re-worked by waves and currents operating at the modern sea level. However, very little of the natural topography remains. It has been modified by large amounts of beach nourishment, dredged sediment to create the existing Great Kills park, and a myriad of shore structures. Okulewicz and DiGuardia (1984) describe a persistent NE-SW alongshore transport direction that is eroding the available sediments and creating a depositional spit at Crooke's Point. They report that the ocean-facing Staten Island shoreline has been displaced inland an average of 38 m from 1836 to 1961. The rate of displacement has slowed with the application of beach nourishment and the construction of a multitude of groins.

Great Kills

Great Kills Park (Fig. 12) was constructed by huge excavations of sediment to create the boat basin of Great Kills Harbor and to build the surrounding upland (in 1935-1948, and in 1955). In part, the artificial upland re-established the connection from the mainland to Crooke's Point. However, the alongshore transport of sediment to the southwest was now interrupted by the construction of groins updrift of the Park location and the newly-created upland was a site of negative sediment budget and erosion. In addition to the retention of sediment updrift by the variety of engineering structures, a portion of the eastern coastal upland and its associated



.Figure 11. Inland offset of shoreline downdrift of terminus of seawall, the Critical Zone, September 11, 2008.

wetland (formerly inland of the barrier spit leading to Crooke's Point) now formed a projecting headland near Oakwood Beach and functioned as a further obstruction to alongshore processes. That is, wave diffraction altered the pattern of wave energy and accelerated the loss of sediment immediately downdrift of the headland (Smith, et al., 1985). In addition, Okulewicz and DiGuardia (1984) report that the rate of erosion at Great Kills more than doubled following the completion of the outfall pipe at the Oakwood sewage treatment pipe in 1975. The pipe serves as a very long groin and effectively stops any sediment from reaching Great Kills.

Beach nourishment was applied several times in the early 1970s, as well as in the period 1974-1982, to try to preserve the bathhouse (Niedoroda, et al., 1975; Smith et al., 1985; Nordstrom, 1987). Eventually, the sediment emplaced on the beach was eroded and the bathhouse was removed.

The Great Kills area is divided into four segments (modified after Smith, et al., 1985): 1) the riprap structure and wetlands at Oakwood Beach; 2) the projecting headland; 3) the cliffed coast downdrift of the headland; and 4) the stable or accreting shoreline at the distal portion of the barrier. The Oakwood Beach wetlands (Segment 1) were originally inland of a sandy barrier spit. Following complete erosion of the spit, the remaining peaty wetlands were eroded and now occupy a niche downdrift and inland of the structural combination of the sewage treatment plant outfall and a low riprap seawall. The topography consists of a narrow band of sand transgressing a peaty layer. It is not a foredune-beach system because it lacks the full range of features and it is not exchanging sediment as in Figure 3. Segment 2 consists of a peat layer bounded inland by a thick deposit of fill. The fill is scarped and has a bluff that reaches 3-4 m high in places. The combined fill and peat are less easily eroded and now project seaward of the general trend of the Great Kills shoreline (Fig.13). Toward the southwestern margin and beyond the peat outcrop, Segment 3 exhibits a cliffed coast that extends for about 1000 m (3280 ft) alongshore and is primarily retreating into fill material. A narrow beach face, about 10 m (33 ft) wide at mean water level, extends from the cliff to the water. The cliff is highest at the northeast portion, nearly 3 m (10 ft), and decreases in elevation to less than a meter to the southwest. The accreting Segment 4 has a low foredune, about 1.0-1.5 m (3-5 ft) high, and a beach width of 30 m (98 ft). The jetty at Crooke's Point (built in 1958) establishes the southwestern extent of the barrier spit. It is meant to assist in maintenance of the navigation channel, 3 m (10 ft) deep and 45 m (150 ft) wide, immediately southwest of the jetty. At present, the updrift side of the jetty is completely alluviated and sediment is being transported around the end of the jetty to build a narrow beach on the downdrift side, to move into the navigation channel, and to drift alongshore toward the entrance to the Great Kills boat basin.

A key element in the Great Kills shoreline evolution is the erosional trend in Segment 3 (Fig. 14). Smith, et al. (1985) calculated that the rate of erosion in the site of the former bathhouse reached 5 m/yr (16 ft/yr) because of the absence of an incoming sediment supply and the diffraction of wave energy around the peat outcrop. They describe the situation as a classic log-spiral erosional beach extending inland and expanding its erosional scarp downdrift. Subsequent evaluations of the site of maximum erosion rates produced similar displacements, around 5 m/yr (16 ft/yr) through 2006 (Mellander, pers. commun., 2007). In the absence of an incoming sediment supply, the negative sediment budget at this site will continue to cause removal of material from this location, displace the shoreline inland, and supply eroded sediment to the downdrift accreting shoreline.



Figure 12. Great Kills Park, Staten Island Unit, with mix of structures and topographical features.

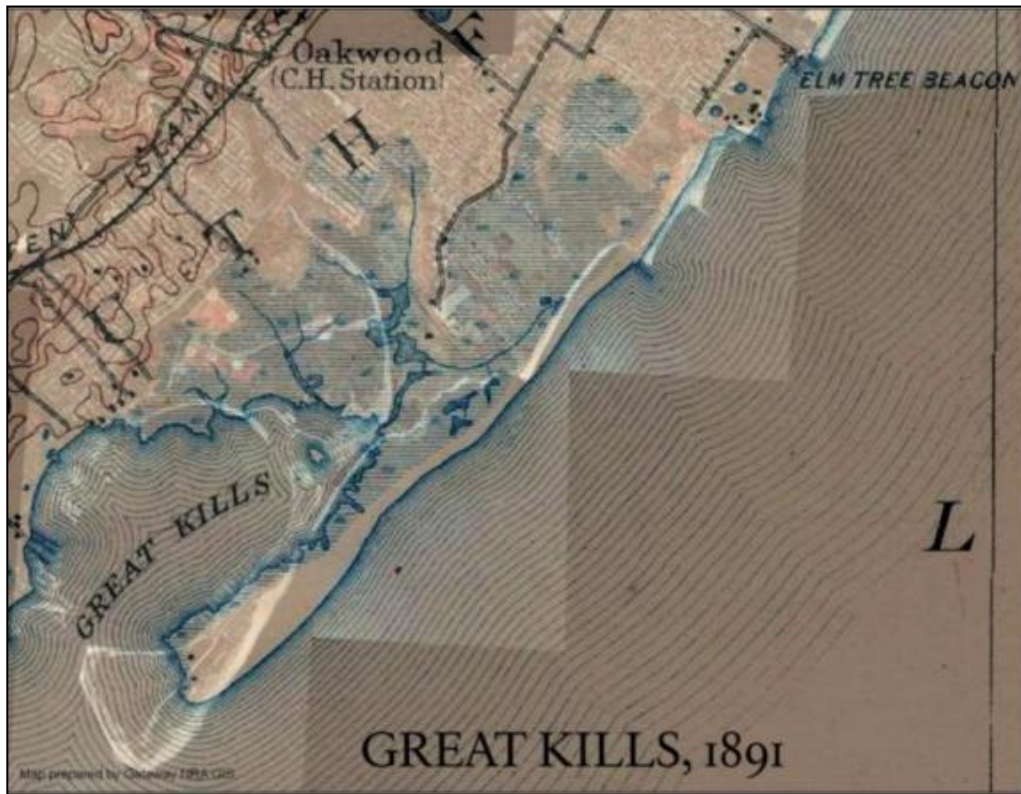


Figure 13. Comparison of topography from 1891 topographic map and location of existing park shoreline on 2002 aerial photograph at Great Kills (Mellander, 2007).

Miller Field

The shoreline at Miller Field extends between two groins for a distance of 630 m (2067 ft), of which 500 m (1640 ft) is within Gateway (Fig. 15). This shoreline is completely artificial and is totally manipulated by the emplacement of fill and the transport restrictions imposed by the two groins (Fig. 15). The sand supply to support this beach and its topography is derived from the fill placed within the groin compartment and updrift of the northern groin (USACOE, 1965b, 1995). The beach form has a gently-sloping beach seaward of a constructed dike in this setting (Fig. 16).

Fort Wadsworth

The beach on the seaward-facing side of Ft. Wadsworth is a product of fill placed in the mid 1950s (USACOE, 1965b, 1995). With the exception of the northern 75 m, which is lined by assorted riprap bounded by some sort of offshore breakwater, the beach form is a gently-sloping sand surface positioned against a sand dike (Figs. 17 and 18). There is no new sand being transported into this site. It is exposed to waves entering the bay between Sandy Hook and Breezy Point and thus sand mobilization will continue to remove some of the emplaced material and cause slow erosion. It was estimated that prior to a variety of forms of sand emplacement, the rate of erosion was on the order of 0.8 m (2.7 ft)/yr (USACOE, 1965b). However, that was a calculation applied to the time prior to the construction of groins and manipulation of the sediment supply.

Breezy Point

Breezy Point is the westerly extension of the Rockaway barrier island (Fig. 1). Historically, the barrier island was slowly eroding and being displaced inland as it was extending westward. The natural evolution of the western point was altered by the construction of a large jetty adjacent to the Rockaway Inlet navigation channel in 1933. Since that time, the migration of the western end of Rockaway barrier has ceased, to be replaced by accumulations updrift of the jetty.

This component of Gateway NRA includes Jacob Riis Park, Fort Tilden, the Breezy Point Cooperative, and the western terminus of the barrier, Breezy Point (Fig. 19). There are some elements of natural coastal topography in this portion of GNRA, but most reflect the impacts of human intervention of either the sediment supply or manipulation of the topography. Groin construction on the Rockaway barrier was primarily initiated in the period 1922-1927 (USACOE, 1965a) and was accompanied by more than 3.8 million m³ (5 million yrd³) of sediment placed on the beach (Kassner and Black, 1984). Eight stone groins and a stone bulkhead were constructed at Fort Tilden in 1943 (USACOE, 1965a).

Most of the Rockaway barrier is fronted by beach groins that are attempting to slow the alongshore transport of sediment to the west. There are 48 groins in the Jacob Riis Park – Fort Tilden shoreline. The groins in Jacob Riis Park are low stone and concrete structures that allow for sediment bypass and do not create major offsets in the shoreline or the beach form. However, eleven of the groins constructed at Fort Tilden are higher stone groins and they have a larger impact on the beach form and shoreline. They produce offsets in the beach from east to west and the foredune feature is often scarped at the inner margin of the groins. The beach narrows and the foredune is more impacted from east to west along the Fort Tilden shoreline.



Figure 14. Severe erosion downdrift of projecting headland. Pilings are at site of demolished bath house. March 31, 2009.



Figure 15. Miller Field, Staten Island Unit, with coastal features and structures.



Figure 16. Beach seaward of constructed sand dike at Miller Field, March 31, 2009.



Figure 17. Fort Wadsworth, Staten Island Unit, coastal topography and structures.



Figure 18. Beach-dune profile seaward of constructed sand dike, Fort Wadsworth. Glacial deposits are immediately inland of veneer of fill at this site. May 5, 2008.

The Rockaway barrier is at the far end of a sediment pathway that transport sediment along the south shore of Long Island, at a rate of about 344,000 m³/yr (450,000 yds³/yr) (Hess and Harris, 1987). Numerous inlets in the barrier chain are sites of interruption of the sediment pathway and a decreasing sediment supply to the west is accompanied by greater segmentation of the barrier island chain and greater dynamics of shoreline mobility (Taney, 1961). It is likely that impacts of erosion would be greater were it not for sediment transfers conducted at the inlets bordering some of the barrier islands. Sediment is supplied to the eastern end of the Rockaway barrier by routine dredging of Little Rockaway Inlet, approximately 153,000 m³ (200,000 yds³) every two years (USACOE records) and deposition of the sediment downdrift to nourish the beaches in the Rockaway communities. In addition, starting in 1975 and continuing to 2004, 13,000,000 m³ (17,000,000 yds³) of sediment have been dredged from the offshore to supply sand to the Rockaway beaches (Yasso and Hartman, 1976; Nersesian, 1977; NY District website). Kana (1999) reports that over 19 million m³ (25 million yds³) have been placed on the Rockaway beaches since 1920.

However, not all of that sand has reached western Rockaway. A long and high groin at the eastern end of Jacob Riis Park, enlarged in 1982, currently intercepts the alongshore transport of this nourishment and has the effect of widening the beach in the updrift community while producing a negative offset in the shoreline in the park. One outcome of this deficit sediment supply immediately downdrift is a highly mobile beach profile that occasionally narrows to the

point that the water is nearly at the base of the park's infrastructure, preventing the development of a foredune in the beach profile. Some measure of coastal stability is reached in the Fort Tilden area where the foredune feature has some continuity in form and survives the seasonal variation in beach width. Foredune topography continues throughout Fort Tilden, even though there is a riprap and wooden bulkhead along this entire length (Fig. 20). The foredune is interrupted seaward of the Breezy Point Cooperative, but exists as the primary dune and stranded foredunes west of the Cooperative (Figs. 19 and 21).

Construction of the 2550 m (8,400 ft) jetty at Breezy Point in 1933 changed the condition of sediment transport at this location. The jetty terminated western elongation of the barrier island and reduced alongshore transport to support maintenance of the navigation channel and accumulation at its updrift margin. A huge zone of accumulation occurred that displaced the shoreline seaward in the form of accretionary ridges (foredune features) that extended for a distance of 4.5 km (2.8 miles). At present, there may be a slightly-negative sediment budget in the eastern portion of this part of the park that will cause the zone of accumulation to retreat a bit and the junction of accumulation with the former shoreline will be erosional. As the negative budget continues and the deficit increases, the contact of the accumulation will shift to the west, exacerbating the erosional offset at this contact.

The far western margin of the sediment accumulation has a series of natural foredune ridges as the shoreline was accreting under the impetus of the local positive sediment budget. The accumulation has reached its maximum. The area updrift of the jetty is full and sand is being transported around the jetty. Some of the sand accumulates as an attenuated beach deposit on the downdrift and inland side. Most of the sediment transported beyond the jetty is presently accumulating in the Rockaway Inlet navigation channel, necessitating routine dredging to maintain channel dimensions. The ocean shoreline at Breezy Point should not change position

much because it is constrained by the end of the jetty. However, the foredune in this western area could continue to increase in height and breadth because it is at the site of sediment transfer from the beach to an inland position. If the beach position is constant, the site of this eolian sediment transport and accumulation will also be relatively constant and will spur localized foredune growth.

Plumb Beach

Plumb Beach is a remnant of the eastern end of the Coney Island barrier island and its associated tidal inlet delta. This location was isolated from the general barrier evolution by the westerly extension of Rockaway barrier island during the past several centuries (Taney, 1961) that shielded it from direct interaction with ocean waves (Fig. 22). Initially separated from the developed portions of Coney Island by 1902, the remnant coastal feature was effectively isolated from any alongshore sediment supply by the later dredging of the navigation channel into Sheepshead Bay. As a result of the absence of sediment input caused by the navigation channel, the remnant barrier migrated inland as a narrow beach/dune topographic form transgressing the wetland and shoal to its interior. Creation of the Belt Parkway (late 1930s) resulted in a large amount of fill placed on the shoal inland of Plumb Beach and the establishment of a re-formed shoreline at the seaward margin of the fill. Because there was no natural source of sand coming to this area, net erosion displaced the shoreline inland toward the Belt Parkway. Although the record is incomplete, there is aerial photo evidence of several episodes of beach nourishment and riprap placement in the central portion of Plumb Beach. Severe erosion in 1984-85 resulted in loss of the existing pathway and its subsequent reconstruction atop a variety of construction debris. In 1992, a major beach nourishment project was conducted by placing 192,000 yds³ of sand dredged from the Rockaway navigation channel onto this site (Bohlen, 1990; USACOE and CEP, 1994; Psuty, 2008).

The existing coastal topography at Plumb Beach derives from the combination of emplacement of fill and the subsequent erosion and transport of the fill in this location at the eastern terminus of the Coney Island barrier island. The central area of Plumb Beach is an erosional zone that has a small escarpment (bluff) eroding back into the fill (Fig. 22). Minimal transport of the eroded sediment to the west has created narrow beach and low dune topography. The greater transport is to the east and it has created a spit-like beach-dune topography that is extending easterly as sediment is entrained by the nearshore currents (Fig. 22). Because the incident wave energy is primarily arriving via the Rockaway Inlet, the locus of major erosion, about 1,900 m³ (2,500 yrd³) annually (USACOE and CEP, 1994) and the direction of alongshore transport will not vary much. The central area will be the zone of loss of sediment and the major transport direction will be to the east. The erosion zone will expand both to the east and to the west. The eroded sediment will add to the distal end of the eastward extending spit and will both broaden the small foredune ridge and shift it inland over the adjacent wetland.

The easterly extending spit has elements of beach-dune topography that are natural products of a positive sediment budget. There is an equilibrium beach width, height, and slope that are related to the availability of sediment transported into the location. The foredune feature is highest and broadest east of the comfort station. It has a relatively constant height and width for about 350 m (1,148 ft) (pre-1992), then a much lower and narrower foredune for the next 150 m (492 ft) (1992-2002), and a very low foredune for the distal 50 m (164 ft). The post-1992 foredune is slowly shifting inland and encroaching on the wetland habitat that is occupying the



Figure 19. Ocean coast extends from the jettied Rockaway Inlet updrift to the eastern margin of Riis Park. The offset at the western portion of Fort Tilden follows the trend of the shoreline before construction of the Breezy Point jetty in 1933.



Figure 20. Portions of the wooden bulkhead and riprap wall exposed at base of foredune in Ft. Tilden. March 31, 2009.



Figure 21. Coastal topography of Breezy Point spit, derived from first-return measurements collected in 2005 using the NASA Experimental Advanced Airborne Research LiDAR (EAARL); part of a collaborative effort among the USGS, NASA, and NPS. This data set provides metrics of the topographical elements of this site.

backmarsh/shoal location of the ancestral Plumb Beach barrier island (Figs. 23 and 24).

In addition to the great volumes of fill emplaced in the Plumb Beach area, there are a few other indications of human modifications that are affecting the coastal topography. The western margin consists of a bulkhead structure that functions as a groin and there is a slight seaward

displacement of the shoreline adjacent to the structure (built in early 1950s). In 1980-1983, an offshore breakwater of old tires was constructed to intercept the incident waves and reduce the energy reaching the beach (Nordstrom, 1987; USACOE and CPE, 1994) (Fig. 22). Remnants of the breakwater are exposed at the low water position during spring tides. There is little indication of geomorphological impact of this feature at present. In the same time as the breakwater, tires were used to construct five groins to the west of the comfort station (Fig. 22). No remnants of the groins are seen today. A further impact to the geomorphological evolution is the presence of sizeable rip-rap material emerging at the eroding margin in central Plumb Beach (Figs. 22 and 25) (related to the response following the March 1984 storm, repairs to bike path, and construction of a loose rubble revetment, USACOE and CPE, 1994). This coarse material will function as a bulkhead and will slow the inland displacement of the shoreline, but will extend the erosional zone to the east and to the west.



Figure 22. Topography and structures at Plumb Beach.

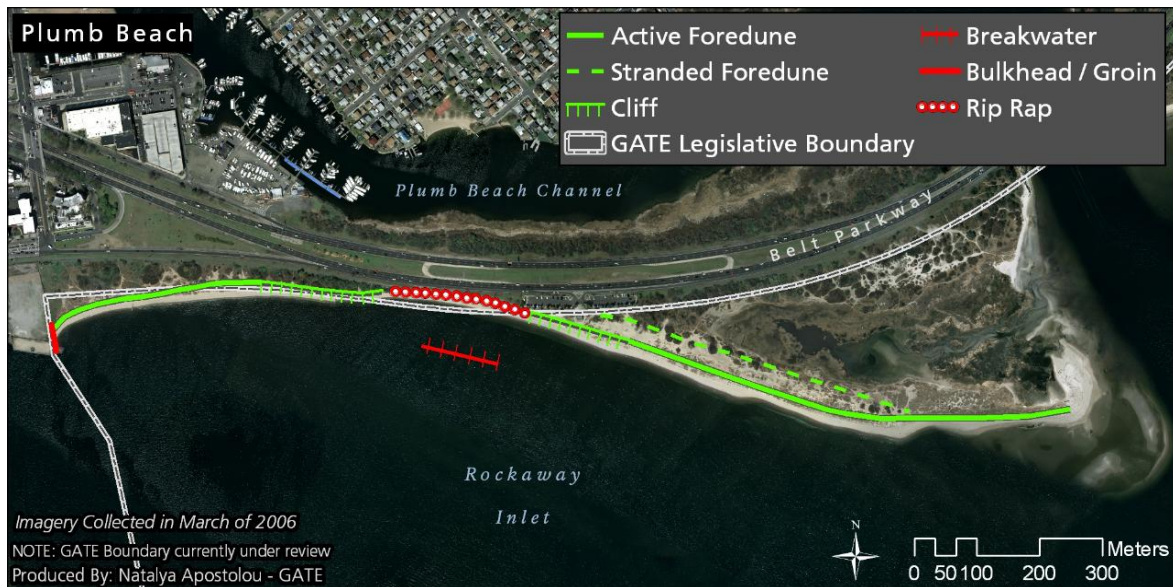


Figure 23. Small foredune developing at eastern margin of Plumb Beach, migrating inland over wetland and tidal channel. April 10, 2008.

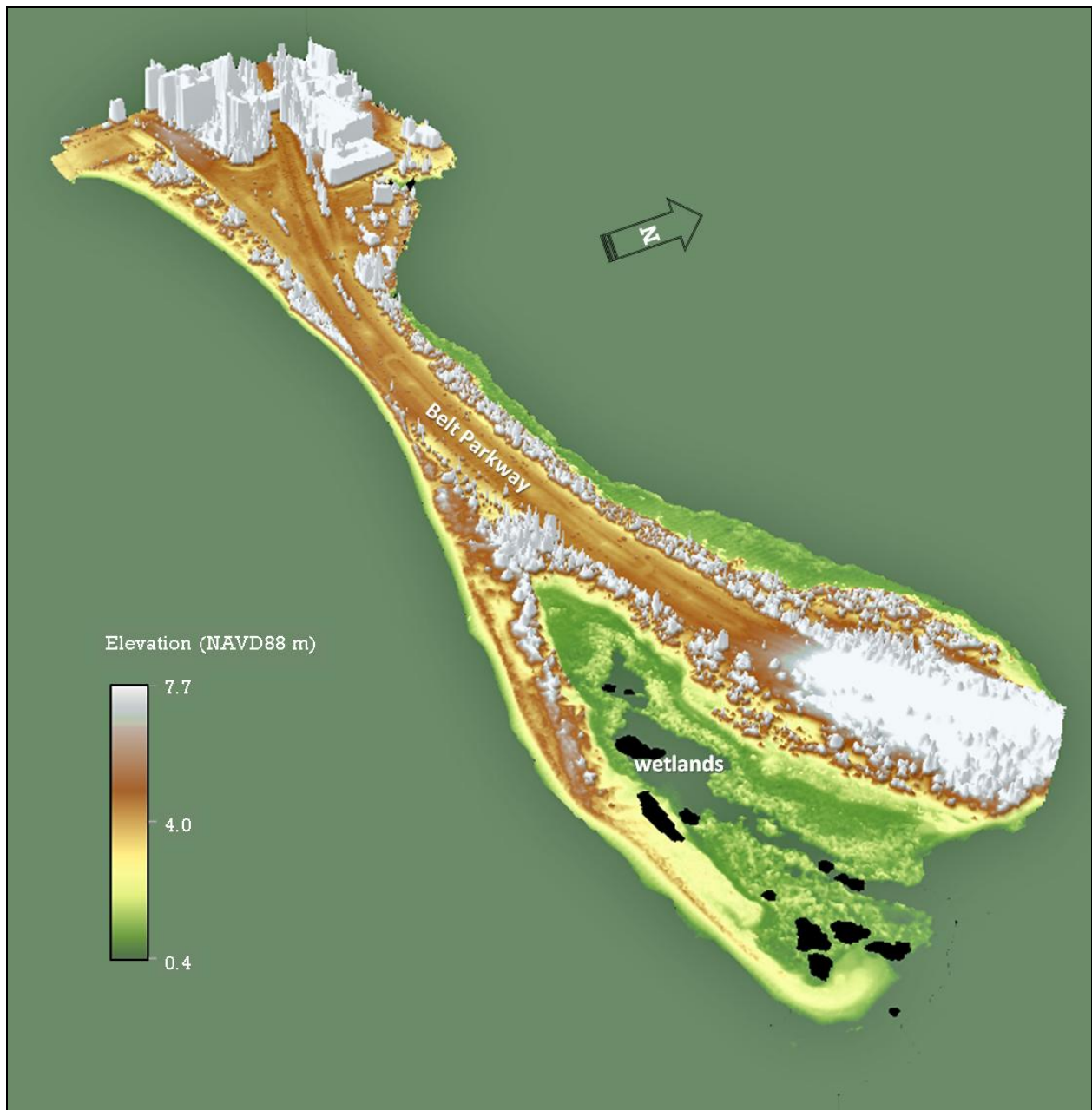


Figure 24. Coastal topography of Plumb Beach, derived from first-return measurements collected in 2005 using the NASA Experimental Advanced Airborne Research LiDAR (EAARL); part of a collaborative effort among the USGS, NASA, and NPS. This data set provides metrics of the topographical elements of this site.



Figure 25. Riprap exposed at eroding sector, central Plumb Beach, March 31, 2009

Sediment Management

The ocean shoreline conditions in most of GNRA are driven by a cultural manipulation of the sediment supply and the resulting spatial variation in sediment budget along a barrier spit topographical system. Most of the park's ocean shoreline is affected by conditions updrift of the Park's boundary and the effects of structures at or near the boundary. In nearly every case, there is a negative impact to the sediment budget and a consequent erosional situation that is mobilizing sediment near the boundary and displacing the shoreline toward existing infrastructure within the Park. Further, in many instances, there is an additional downdrift effect of the local erosion that is causing accumulation and impacts on habitat and navigation channels. The combination of impacts of erosion at one site followed by impacts of accumulation at a downdrift site pleads for sediment management so as to reduce the impacts at both locations. Sediment management is not easy. It involves some sort of reduction of mobilization at the site of erosion and/or manipulation of the sites of accumulation. Furthermore, global climate change and increasing sea level rise present an additional challenge by changing and promoting an increase in the effects of storms upon the shoreline. Adaptation to the changing geomorphological controls and conditions must be taken into consideration in any sediment management plan, in order to guarantee a long-term solution in dealing with the changing coast.

The Park's history has shown that quick solutions often fail to incorporate the temporal and spatial aspects of the sediment-morphology system, aiming only to fix the sediment deficit at very local scales. These are not solutions for a long-term sediment management of the Parks' shorelines.

In a system-wide approach, with a potential adaptation to the changing conditions, sediment management may involve a physical transfer of sediment from the zone of accumulation to the zone of erosion, a recycling of the material in transport. Sandy Hook is the first of the Gateway units to embark on such a program of sediment recycling that transports sediment from the zone of accumulation to the zone of erosion via a slurry pipeline. This is an effective approach to sizeable quantities of sediment transfers. Plumb Beach and Great Kills have much lower quantities of sediment being transported and may not need the infrastructure of a pipeline. Riis Park could be the beneficiary of sediment recycling. However, it could also be assisted by improved alongshore sediment mobility at its eastern boundary.

Areas for Future Inquiry

- The acquisition of shoreline position data and topographical analysis are essential ingredients to the understanding of the vectors of change and the impacts of natural and cultural modifications to the coast. The implementation of the coastal monitoring effort undertaken through the NPS Inventory and Monitoring Program provides a consistent and coherent data set to track and to investigate the dimensions of these changes and their evolution under issues of sediment availability and sea-level rise. The one-dimensional, two-dimensional, and three-dimensional monitoring of beaches and dunes will be tracking the geotemporal vectors and will track the variety of responses to the constraints operating in the coastal system. These data are fundamental and will serve as a guide to future management decisions.
- There are several CODAR HF radar units gathering wave and current data in Gateway NRA (<http://marine.rutgers.edu/cool/codar.html>, and <http://hudson.dl.stevens-tech.edu/maritimeforecast/>). There is the potential to incorporate the spatial characteristics of these data sets and apply them to vectors of shoreline change. This type of information is unavailable through other means and the data are being collected now.
- There is a need for models that can describe the shoreline evolution with different combinations of natural processes and human manipulation. The presence and/or absence of structures and the sediment transfers by dredging and emplacement have short-term and long-term impacts. A modeling effort could help to weigh and evaluate options in sediment management and modification of structures.

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NPS 646/101463, March 2010

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