



Northeast Coastal and Barrier Network Geomorphological Monitoring Protocol

Part II — Coastal Topography, Version 2

Natural Resource Report NPS/NCBN/NRR—2024/2618



ON THE COVER

Talisman, Fire Island National Seashore, New York.

NORBERT P. PSUTY

Northeast Coastal and Barrier Network Geomorphological Monitoring Protocol

Part II — Coastal Topography, Version 2

Natural Resource Report NPS/NCBN/NRR—2024/2618

Dr. Norbert P. Psuty¹, Tanya M. Silveira¹, Andrea Habeck¹, Dennis Skidds², Sara Stevens², Katy Ames¹, Glenn Liu¹

¹ New Jersey Agricultural Experiment Station
Rutgers, The State University of New Jersey
Sandy Hook Cooperative Research Program
130 Great Bay Boulevard
Tuckerton, NJ 08087

² National Park Service
Northeast Coastal and Barrier Network
University of Rhode Island
Kingston, RI 02881

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Executive Summary

Coastal topography was ranked as one of the most important variables for monitoring following a review of potential vital signs in the coastal parks of the Northeast Coastal and Barrier Network (NCBN). Changes in coastal topography, whether caused by erosion or accretion, vary both spatially and temporally. Understanding these variations is key to early recognition of potential problems affecting natural and cultural resources in coastal parks. For managers, understanding spatial and temporal patterns of geomorphologic change is basic to optimal management of any coastal park because the interface of marine and land systems 1) is highly dynamic and driven by multiple forcing mechanisms, 2) results in alterations to resource patterns and dynamics at habitat and ecosystem levels, and 3) can eventually result in the loss of static resources.

The establishment of local, long-term monitoring programs help us to understand the processes that are driving coastal change of beaches, dunes, and bluffs within the parks. This Coastal Topography Monitoring Protocol has been developed for use in the Northeast Coastal and Barrier Network parks. Monitoring is accomplished with survey-grade Global Positioning System (GPS)/Global Navigation Satellite Systems (GNSS) equipment that collects topographic data along pre-established transects spaced at regular intervals, augmented by more intense data-collection in areas of special concern to the parks. A network of high-quality survey control monuments (often referred to as benchmarks), used as accuracy assessment reference is located within each of the NCBN parks, providing a robust basis for long-term monitoring. Spring and/or fall surveys conducted in accordance with standard operating procedures generate coastal topography datasets that are organized and assembled by the NCBN data manager into a database for analysis and archival purposes. Dimensional parameters are measured to describe the beach-dune-bluff system, and attributes are compared and analyzed in a cross-shore and alongshore perspective, providing information about the temporal and spatial changes on beach-dune-bluff morphologies in the parks. The overall goal is to create a replicable means of data gathering that is efficient, adheres to scientific principles, and meets the management needs of the coastal parks.

Acknowledgments

As with other projects that are very broad in scope, many people have assisted in the compilation of information and testing of the protocol. Others assisted in providing support to the theme of the project and in sharing their experiences. Their contributions have been very helpful in bringing forth this document. Special appreciation is extended to the following in the National Park Service: Sara Stevens Nerone, Program Manager of the Northeast Coastal and Barrier Network, Robin Baranowski, Northeast Coastal and Barrier Network Science Communicator; Courtney Schupp, Neil Winn of the Assateague Island National Seashore; Mark Adams and Megan Tyrrell of the Cape Cod National Seashore; Mike Bilecki of the Fire Island National Seashore; Dave Avrin, Bruce Lane, Mark Christiano, Jeanne McArthur, Kathy Mellander, Hollis Provins, Chris Olijnyk, and Tony Luscombe of the Gateway National Recreation Area. In addition, recognition is extended to: Graham Giese and Mark Borrelli of the Provincetown Center for Coastal Studies; Keith Noonan, Phil Karrber, Joe Petrocelli, and Gary Conk of the State of New Jersey Howard Lab crew; and members of the Rutgers team over the years consisting of Dan Soda, Paul Zarella, Peter Dennehy, Peter Shipton, Barry Shafer, Mario Resina, Aaron Love, William Hudacek, Jake McDermott, and John Gagnon.

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Background and Objectives

Introduction

A major issue in all coastal parks is the amount of sediment being moved along the coast through time (sediment budget), and how that affects the beach and dune topography of the parks. Sediment budget affects the quality of the natural and cultural resources as well as the general infrastructure present in the coastal parks. It is among the most basic of concerns related to being at the shore. Bird (1985) indicates that at least 70 % of the world's sandy shorelines are eroding and the percentage is expected to increase because of sea level rise and sediment manipulation by human actions. Recent estimates by the Working Groups within the Intergovernmental Panel on Climate Change suggest that sea level will rise from 18 to 77 cm during the present century (IPCC Working Group I 2021). This forecast is accompanied by analyses of coastal change that will be an immediate consequence of this inundation (IPCC Working Group II 2022). Coastal geomorphological models exist that consider the effects of sea level rise on shoreline change and landform evolution (Davidson-Arnott 2005, Psuty and Silveira 2010, Carapuco et al. 2016). They are both a guide to the potential effects of continuing global change and a plea to gather data appropriate to the testing and calibration of the models. They are harbingers of the concern and interest in the quality of the coastal system, in the shepherding of coastal resources, and in the datasets describing these resources (Van der Lee 2009).

The Northeast Coastal and Barrier Network (NCBN) was created by the National Park Service (NPS), as part of the congressionally mandated Natural Resource Challenge, to ensure the systematic collection and use of scientific data in managing the nation's parks (NPS NCBN 2003). Within this structure, the NCBN has developed a series of scientific monitoring protocols to address a variety of natural resource issues appropriate to coastal locations. This document represents the second protocol in a series of three, developed for geomorphological monitoring in four of the eight parks that comprise the NPS NCBN (Figure 1). The initial protocol (*Part I—Ocean Shoreline Position*) focuses on the collection and analysis of the ocean shoreline position and is available at: [DataStore - Project - \(Code: 2192968\) \(nps.gov\)](#). This second protocol (*Part II—Coastal Topography*) focuses on the collection and analysis of two-dimensional coastal topography as a means to characterize beach, dune, and bluff systems.

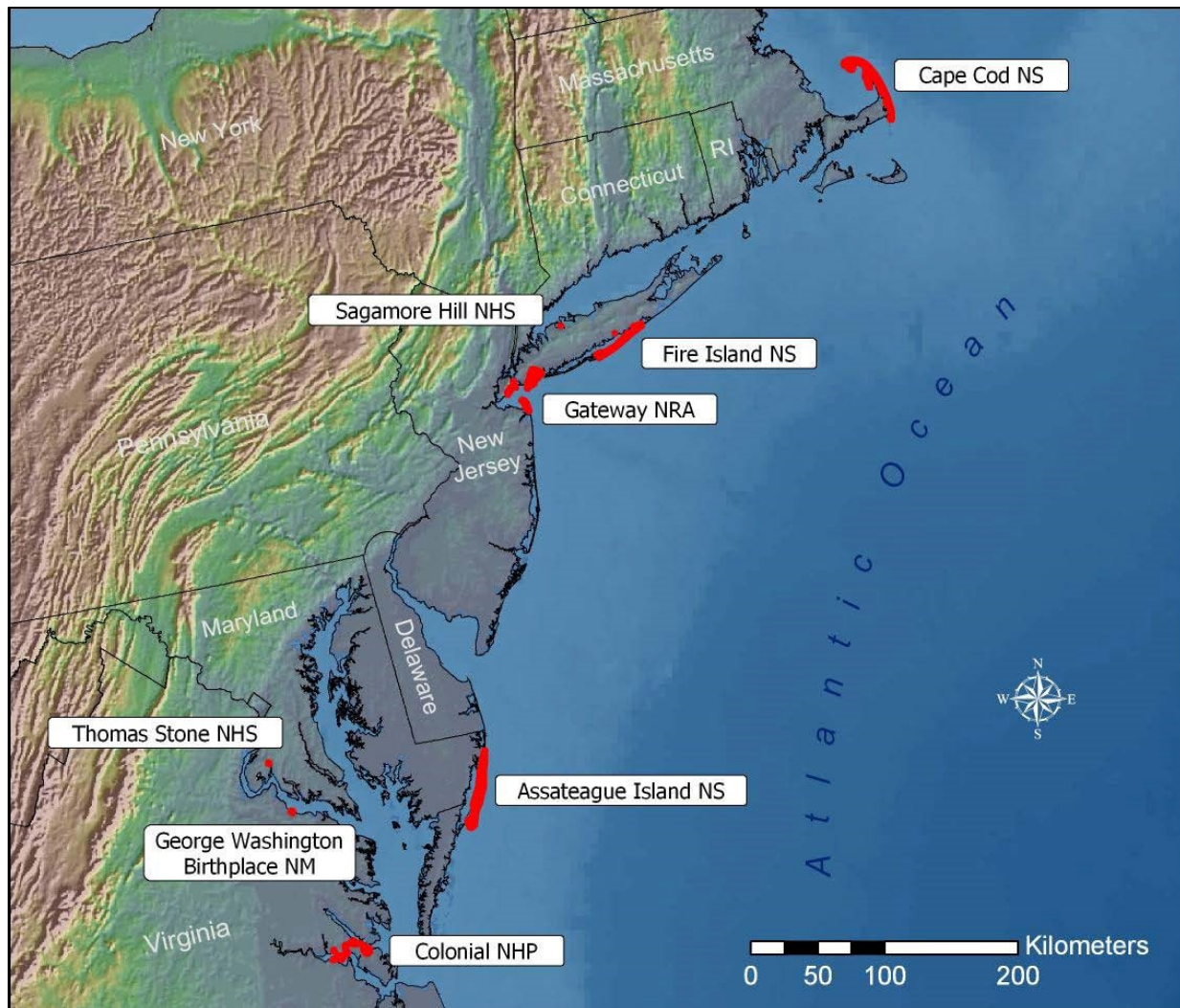


Figure 1. Locations of the eight National Park Service units in the Inventory and Monitoring Northeast Coastal and Barrier Network (Stevens et al. 2005), The Coastal Topography Protocol was developed for use in Assateague Island National Seashore, Gateway National Recreation Area, Fire Island National Seashore, and Cape Cod National Seashore.

Goal and Objective

A primary goal of the NCBN coastal geomorphological program is to provide information to park managers and to improve the understanding of the dynamic nature of park coastlines, including the temporal and spatial patterns of change that describe the condition of marine and coastal areas and support informed management decisions. The specific objective of this protocol is to characterize the variability in beach, dune, and bluff topographical characteristics and determine trends along the coastline in four NCBN parks (Assateague Island National Seashore (ASIS), Cape Cod National Seashore (CACO), Fire Island National Seashore (FIIS), and Gateway National Recreation Area (GATE)) over seasonal, annual, and long-term (five years or more) scales. Although this protocol was developed so that it could be used for monitoring in four of the NCBN parks with extensive beach and dune systems, implementation is based on NCBN staffing levels and expertise and

financial feasibility that also includes travel and equipment. This protocol requires support from each park in staff time, logistics, and access to the beach and dune areas as well as vehicles for access. In addition, the funding capacity of the NCBN must be significant enough to maintain data collection once the protocol is implemented. All these factors drive the decision and planning for implementation in a park. See *SOP 1: Monitoring Design Background and Justification for Northeast Coastal and Barrier Network Parks* to review current implementation by park for the NCBN.

The NCBN coastal geomorphology monitoring program and its protocols are based upon three underlying principles:

1. All protocols developed by the NCBN must have a scientific foundation. Collaboration with the scientific community will ensure that all geomorphological monitoring protocols are based on well-established scientific principles of coastal characterization, processes, and response. Because coastal geomorphology is a complex subject, valid interpretation of the data will require the active involvement of knowledgeable coastal scientists. All measurements are in the International System of Units (SI) (meters).
2. Data must address significant park management issues. Park managers and natural resource staff were active participants in the planning and scoping process in the development phase of the geomorphological monitoring protocols. The objectives identified in this protocol reflect a consensus of issues considered relevant at the park level. This protocol focuses on recording and assembling the geomorphological dataset to enable better-informed management decisions.
3. All protocols and their components must be feasible and sustainable to implement at the Network level. Although the scientific and management value of the monitoring data were both critical factors in determining which vital signs or indicators were selected for monitoring, the practicality and feasibility of implementation across the NCBN were also important.

Compared to shoreline position, landscape features and patterns at the inland reach of wave domination (upper beach, dunes, and bluffs) are less variable indicators of changes in coastal morphology. As a result, significant changes and trends associated with these features are more easily detected and applied to park management decision making. Beach, dune, and bluff erosion and migration often involve direct threats to natural and cultural resources, park infrastructure, and even to human safety and are a major management issue in many parks. This monitoring program provides crucial information to the scientific understanding of the evolution of park coastal geomorphology, and it contributes to the scientific foundation for resource-management decision-making. Among the information identified by coastal scientists and park managers as being of greatest potential use are:

- Changes in dimension and location of coastal topographic features that may indicate changes in habitat that, in turn, require management action.
- Sediment budget calculations that provide information on the amount of sediment available to the upper portion of the beach, acting as a buffer to park infrastructure.

The Coastal Topography Monitoring Protocol includes a number of highly detailed standard operating procedures (SOPs) included in one main [SOP Document](#) (Psuty et al. 2023). They are intended to ensure the consistency and repeatability essential to any long-term monitoring program. The SOP document, that includes all the SOPs associated with this protocol, will be modified and revised as technology improves and better methods for monitoring coastal geomorphological change are developed. In addition to the SOP document, a [Protocol Safety Plan](#) and [Quality Assurance Plan](#) are available.

The Oceanside Coastal Ecosystem

The basis for the Coastal Topography Monitoring Protocol is the beach-dune conceptual model (modified from Roman and Barrett 1999) that relates the physical processes and cultural impacts (agents of change) to the vectors of change (stressors) and to the responses of the coastal ecosystem (Figure 2). Fundamental to the model is an awareness that the coastal system is dynamic and that it is interacting at a variety of geographical and temporal scales. The model consists of an assemblage of natural and cultural agents and processes that generate characteristics of the coastal landscape. As the relative magnitude of the agents and processes varies, they cause alterations to the hydrology and sediment budget and consequently to the landscape.

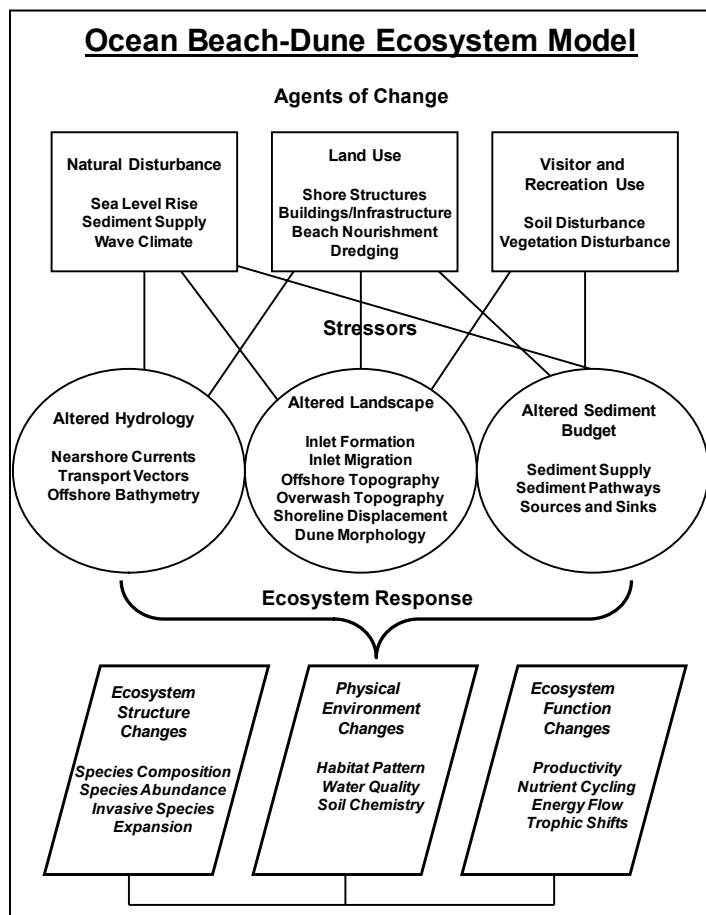


Figure 2. The Ocean Beach-Dune Ecosystem Model illustrates the relationships among the agents of change, stressors, and ecosystem response (after Roman and Barrett, 1999).

Furthermore, there is continuous interaction and feedback among the evolving components that drives additional changes and alterations. A primary manifestation of the alteration in the coastal system is a shift in shoreline position and modification of the beach, dune, and bluff topography. These coastal geomorphological changes result in an ecosystem response that incorporates changes in the physical environment and in the community structure and function (Figure 2).

The primary natural disturbances that drive geomorphological change are sea level rise, sediment supply, and wave climate. These natural factors influence the coastal geomorphological response at different temporal scales including individual events (storms), cyclic variations (seasonal), and annual and multi-year (long-term) trends (Carter 1988, Psuty and Ofiara 2002, Walker et al. 2017). One of the effects of sea level rise is inland displacement of the shoreline and alteration of the coastal profile. When coupled with erosion produced by a prevailing sediment deficit, the rate of inland shoreline displacement is increased (National Research Council 1987, Warrick et al. 1993, Rangel-Buitrago et al. 2015), and the elements of coastal topography evolve (Nicholls et al. 2007, Psuty and Silveira 2010). Whereas sea level rise and sediment supply are the primary factors causing the change, wave climate is responsible for the nearshore processes of waves and currents that steer the local sediment transport and consequently control the site-specific coastal configuration (Trenhaile 1997, Basasan and Guner 2021).

Local conditions such as the underlying geologic framework, bathymetry, offshore topography, and sediment sources and sinks interact with the primary factors and the coastal processes to influence the characteristics and the rates and direction of the coastal system alterations (Carter 1988, Honeycutt and Krantz 2003, Kirkpatrick 2018). In addition to natural causes, coastal changes are often accelerated by human-produced perturbations such as dredging and channel relocation, groins and jetties, and beach and dune manipulation (Walker 1990, Nordstrom 2000, Neal 2010, Duarte de Almeida 2021). These human influences can cause alterations to waves, currents, and availability and mobility of sediment. The combinations of natural processes and anthropogenic modifications interact to cause significant morphological change, affecting cultural and natural resources. Particularly, displacement of the coastal topography as well as changes in the width and/or volume of the beach, may result in the destruction of cultural resources, facilities, and other infrastructure (Stevens et al. 2005, Griggs 2021).

Coastal ecosystem response may consist of adjustments to resource patterns and dynamics, and it may eventually lead to the loss of fixed natural resources (Roman and Nordstrom 1988, Fischer 2018). These responses often elicit secondary changes in ecosystem structure or function. Structural changes in species composition or competitive interactions generally reflect landscape-level alterations in the quantity and quality of specific habitats. Similarly, functional changes in productivity or nutrient cycling may occur as a product of storm events and the associated reduction in habitat complexity. More subtle physical changes also include alterations in geo-chemical and hydrological conditions, such as groundwater quality and quantity. The magnitude and scope of the resultant coastal ecosystem response is complex, highly variable, and can often be cumulative. At the extreme, this includes the alteration of habitats and of core ecosystem processes. For example,

erosion of an existing coast may create new aquatic habitat, or overwash fans may fill in a wetland environment to create new terrestrial habitat.

The Process of Evaluating Vital Signs

Geomorphological change is important to the evolution of the coastal ecosystem, and in some cases, when it affects natural and cultural resources, recreational features, and facilities or infrastructure, the change presents complex challenges to park management. In order to address the full range of scientific and management concerns, multiple scoping workshops were convened to identify issues of general importance and to make specific recommendations for monitoring. Throughout the scoping process, the lack of adequate data to track and respond to geomorphological change was consistently identified as a high priority management issue for the NCBN parks.

Demonstrating the complexity of the coastal geomorphological process, twenty-nine potential monitoring variables (vital signs) of geomorphological change were identified as part of the scoping workshops (NPS NCBN 2003). The indicators were evaluated and ranked for data value and feasibility of implementation across multiple parks, and shoreline position and elements of the coastal topography were consistently identified as of high information value and capable of monitoring with existing methods (Table 1).

Table 1. The fourteen Vital Signs identified during the Northeast Coastal and Barrier Network Geomorphological Change Workshops; they are ranked for data value and feasibility of implementation at the network level (NPS NCBN 2003).

Geomorphological Change	Vital Sign	Monitoring Methods	Feasibility	Data Value
Ocean Shoreline Position	Ocean shoreline position	1D & 2D GPS, 2D & 3D Survey, Aerial Photography, LIDAR	High	High
Coastal Topography	Dune, beach, bluff, bluff morphology	LIDAR, Aerial Photography, 2D & 3D Survey	High	High
	Edge of vegetation	LIDAR, 1D, 2D GPS, Aerial Photography	High	High
	Landcover	LIDAR, 2D & 3D Survey	High	High
	Overwash fans/flood plains	LIDAR, 1D & 2D GPS, 2D & 3D Survey, Aerial Photography	Medium	High
	Shore type	Aerial Photography, 2D & 3D GPS, 2D & 3D Survey	Medium	Medium
Anthropogenic Modifications	Locations of structures and disturbances	Aerial Photography, 1D & 2D GPS, 2D & 3D Survey	Medium	High
Marine Geomorphology	Sediment quantity Sediment size	Terrestrial & Marine Sediment Samples	Medium	Medium
	Geologic framework	Acoustic Survey, Seismic Survey, Core Samples	Low	High

Table 1 (continued). The fourteen Vital Signs identified during the Northeast Coastal and Barrier Network Geomorphological Change Workshops; they are ranked for data value and feasibility of implementation at the network level (NPS NCBN 2003).

Geomorphological Change	Vital Sign	Monitoring Methods	Feasibility	Data Value
Marine Geomorphology (continued)	Depths	Acoustic Survey, Bathymetric LIDAR, Sled Survey	Low	Medium
	Migrating shoals & bodies	Acoustic Survey, Bathymetric LIDAR	Low	High
Marine Hydrography	Tide range	Local & Regional Tide Gauge	High	High
	Relative sea level position	Water Level Gauge	High	High
	Wave and current characteristics	Local Gauge - Regional Gauge	Low	High

The Components of Coastal Topography

Detailed knowledge of the hydrodynamic forcing of sediment mobilization, transport, and deposition and measurements of morphologic change and ecosystem response at the park level are key to understanding the coastal geomorphology of parks (Allen 2000). Coastal topography is a response of the system that can be effectively measured and monitored, providing high value datasets across time and space that can be used to address park management issues.

The beach is an accumulation of unconsolidated material that is being transported and redistributed in response to the hydrodynamic forcing agents (Short 1999, Brand, 2020). The result is a process/response interaction that extends from the dune area, across the exposed beach, and into the water out to a depth where little or no sediment is being transported (Komar 1998, Anthony 2020). Depending on the direction of the waves reaching the beach, sediment can be transported both across the beach (cross-shore), as well as along the coast (alongshore), resulting in a complex littoral transport system and a variety of beach morphologies (Figure 3).

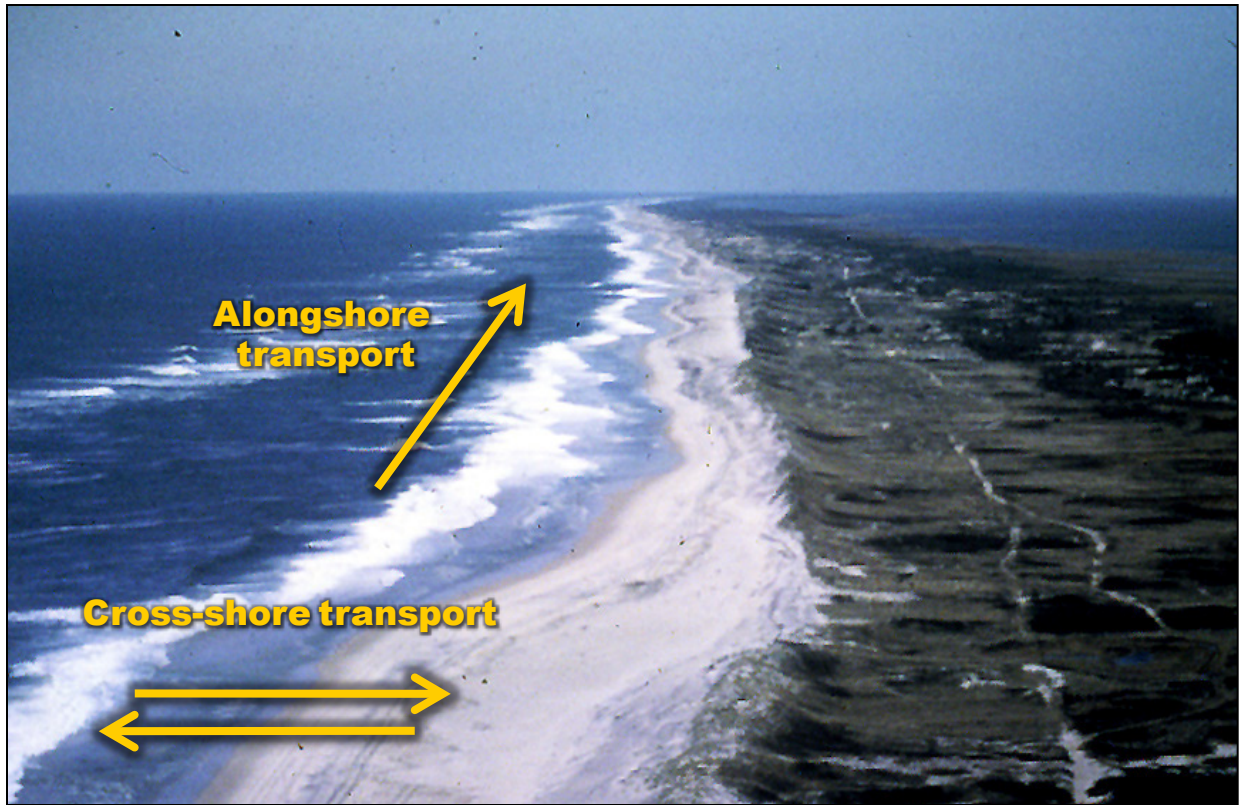


Figure 3. Aerial view of Fire Island National Seashore showing the shoreline variation due to the alongshore and cross-shore sediment transport acting upon the coast. (Source: Photo by Dr. James R. Allen, September 1988)

Components of the Coastal Profile

The major beach features develop parallel to the shore over large areal expanses (Figure 3). Beach profiles illustrate these major features by providing shore-normal cross-sections (Figure 4). The portion of the beach that is permanently underwater is mainly acted upon by waves and currents. This area is usually flat with the presence of one or more submerged bars. The intertidal portion of the beach is known as the beach face. This is the sloping part of the beach that is subjected to the periodic incursion of water by the tides, and it is acted upon by the currents and waves, and their wash and backwash processes. The area above the effect of the tide is the subaerial portion of the beach, which includes the presence of berms and dune or bluff features and is only affected by waves during extreme storm events.

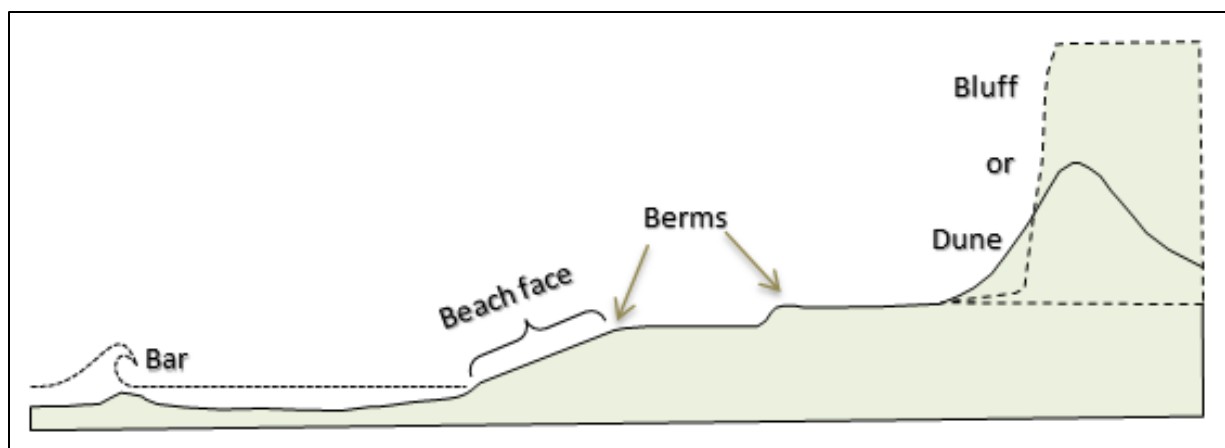


Figure 4. Beach-dune-bluff profile morphology.

The different portions of the beach have different dynamics because they are subjected to different processes at different timescales. These differences are represented by the morphological features present in each portion of the beach. The areas that are constantly or intermittently submerged are the most variable portions of the beach because they are acted upon by waves and currents. The ocean shoreline position reflects the changes occurring at the beach face level. The beach face width and slope change in response to the high-frequency tidal-cycle oscillations, as well as to the episodic storm events. The subaerial area, on the other hand, is less changeable, and the major changes of the landscape features, such as the berms, dunes, and bluffs, respond to lower-frequency events and embody the longer-term evolution in coastal morphology.

Major Geomorphological Features

The overall morphology of the beach is a product of the physical processes of waves, winds, and currents acting upon the beach, the composition of its sediments, and the sediment transport vectors that occur (Komar 1998, Davidson-Arnott et al. 2019). In response to the characteristics of the waves, the local physical settings, and the sediment type and availability, the beaches will exhibit different morphologies and features, as well as different spatial magnitudes. Thus, the dimensions and form of the major geomorphological features provide a direct measure of the coastal system condition and trends. The major geomorphological beach features that will be monitored through this protocol are:

- Beach face – the beach face corresponds to the sloping intertidal portion of the beach profile. It is a highly dynamic feature that changes with the variation in wave conditions, the sediment size, and the water levels. In general, the slope of the beach face is a measure of the wave energy. Storm conditions will flatten the beach face, whereas calmer wave conditions will promote a steeper one.
- Beach berm – the beach berm is the nearly horizontal portion of the beach that lies above the mean high tide elevation, and therefore it is only acted upon by the highest waves that reach above that elevation. Some beaches have more than one beach berm (incorporating a storm berm), and some beaches have no berm. Its width varies with the amount of sediment available to the beach-dune system. The berm will widen if onshore sediment transport is

dominant (usually during milder wave activity), and it will narrow if offshore sediment transport is dominant (usually during storms).

- **Foredune** – the foredune is a shore-parallel sand ridge that is located immediately inland of the beach berm. It develops where pioneer vegetation traps the sand that is transported inland from the beach berm and beach face, primarily by wind action. Foredunes are sites of sediment accumulation and storage, and their position, height, width, and volume are measures of the amount of sediment available to the overall beach system. The foredune is the least variable feature of the beach profile, and its characteristics and position are altered primarily under extreme events when waves reach above the beach berm. Its position in the beach profile is much more conservative than any other feature; therefore its variation is a measure of the longer-term coastal evolution.
- **Bluff** – bluffs exist along coasts that consist of bare rock, consolidated sediment, or unconsolidated sediment and that are also retreating under the attack of waves. The marine erosion produces a vertical face that may or not be separated from the surf by a narrow beach. The rates of retreat depend on the composition and resistance of the bluff material, and bluffs of unconsolidated sediments show the most rapid erosion. Extreme wave action during storms promotes undercutting of the bluff and subsequent landslides and slumping. In other cases, landslides may be caused by other processes (e.g., rainfall, faults), and waves transport the accumulated debris at the base of the bluff. Bluff recession is episodic and often shows high spatial variability.

Sediment Budget

Sediment budget is a very important variable in the maintenance of coastal morphology and the dynamics of sediment transfers in the beach-dune sand-sharing system (Psuty and Silveira 2010, Radar et al. 2018). For a beach to be maintained in place, the sources of sediment must be equal to the losses through a specified time, corresponding to a balanced sediment budget. Accretional coastal features are associated with a positive sediment budget, whereas erosional coastal features occur with a negative sediment budget.

Accretional coastal features

If the quantities of sediment input are greater than the losses, then the sediment budget is positive, the shoreline will be displaced seaward, and the beach berm will widen and create space for a new foredune to be established. A positive sediment budget will promote a wide beach profile, with topographical features that reflect the accretionary trend of that area: a wide beach berm and well-developed multiple dune ridges (Figure 5). This is the case of the beaches at the downdrift ends of the parks where sediment is being accumulated, such as the beaches at the western end of Breezy Point (GATE) or the beaches in areas of positive sediment input at Assateague Island.

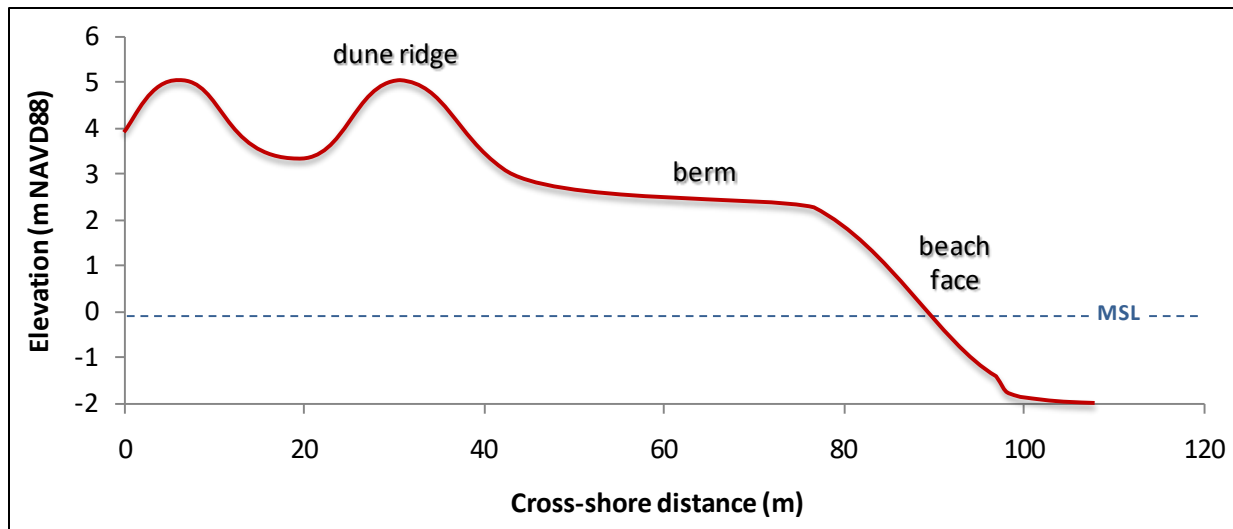


Figure 5. Typical beach profile associated with a positive sediment budget, incorporating multiple dune ridges and wide beach berm.

Erosional coastal features

If sediment input is less than the losses, then there is a negative sediment budget and the shoreline and beach-dune morphology will be displaced inland. Under a situation of negative sediment budget, a net inland displacement of the beach-dune system will occur, and the topography of the beach will retain its dimensions and features while shifting in space (Psuty and Silveira 2010, Psuty et al. 2018). However, the existence of accommodation space is necessary for this inland migration and morphological evolution to occur. The lack of accommodation space under a negative budget scenario will result in losses of dimension and form, with narrow beaches having little or no space for dune development. In some cases, an extreme negative sediment budget scenario may result in coastal bluffs (Figure 6). This is the case of the beaches that constitute the central part of Cape Cod, and of the beaches at the eastern end of the Great Kills area of GATE.

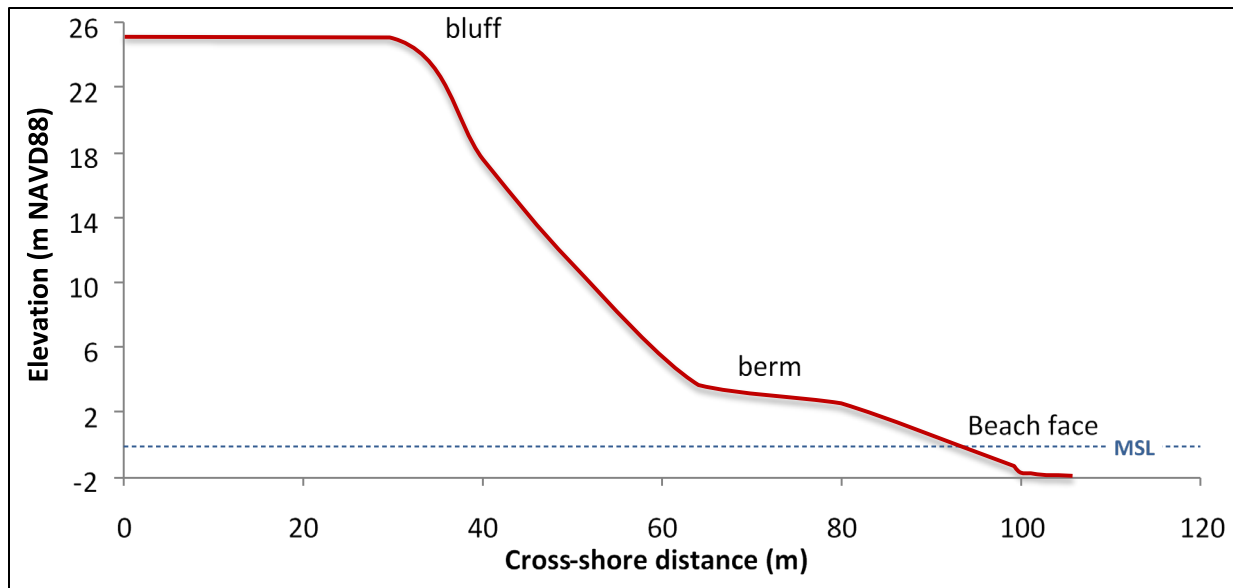


Figure 6. Typical beach profile at a coastal bluff, where the deficit of incoming sediment promotes a very narrow beach and the presence of a retreating bluff.

Geotemporal Elements of Sediment Budget

Early recognition of the importance of sediment input is seen in the coastal classification of Valentin (1952) that describes geomorphological outcomes related to sediment budget in a spatial context. The theme of temporal variation in morphological evolution is added by Bloom (1965), with the incorporation of sea level rise as another factor influencing the creation of topographical components at the local and regional scales. As described in Finkl (2004), the combination of spatial (alongshore) and temporal variables associated with sediment supply and sediment budget drives the evolution of coastal topography. This geotemporal relationship is at the core of periodic monitoring because measurements of topography depict the outcomes of sediment budget at a site and permit a comparison of alongshore sites. It is the combination of vectors of change in the spatial and temporal context (geospatial) that fuels the 2-D monitoring program and brings the sequence of process-response geomorphological features to the fore.

In areas of variable sediment supply, there will be an alongshore variation in the characteristics of the coastal topography and the beach-dune system. These transitions are usually easily identified, and they can be grouped into geomorphological units with similar beach profile dimensions and forms. Variations in the wave regime (direction and height) acting upon and along the coast, presence of inlets or headlands, as well as the presence of engineered structures such as jetties and groins influence the alongshore sediment pathway and may be used to identify these geomorphological units (Figure 7). In the case of CACO, the nature of the substrate, the variation in wave regime and sediment supply result in at least three units that undergo changes at different scales and frequencies. The central part of Cape Cod consists of high bluffs, whereas the southern and northern ends of Cape Cod are low-lying coasts composed of dune and beach systems (Figure 8). GATE is a fairly large geographical area with considerable variety in processes and forms. The cultural manipulation of the sediment supply and the resulting spatial variation in sediment budget cause the existence of a variety

of geomorphological units defined by updrift erosion and consequent downdrift accumulation (Psuty et al., 2010).



Figure 7. Groin between the Neponsit & Belle Harbor communities and Jacob Riis Park, both part of Gateway National Recreation Area, causing sediment accumulation on the updrift side and erosion and inland beach displacement on the downdrift side. Aerial image accessed February 2010. (Source: bing.com/maps/)



Figure 8. Oblique aerial imagery of a portion of Cape Cod National Seashore, at the northern margin of Nauset Bay, showing the alongshore variation and transition between two very different geomorphological units: A) the sand barrier and marshland to the south, and B) the bluffs to the north. Aerial image from USGS, Data Series 946 flown on May 19, 2009. (Source: Morgan et al. 2015)

Monitoring Objectives

Ultimately, a full understanding of how the beach morphology is changing over time, and at each given location, depends on our knowledge of the processes of cross-shore and alongshore sediment transport. The sediment input from one stretch of shore to the next and the sediment exchanges within the beach-dune or beach-bluff system create localized suites of resulting coastal features that can be measured and characterized through the acquisition of beach profiles. The collection of beach profiles provides a cross-shore visualization of the beach topography, generating information on the two-dimensional aspect of the morphological components: form, elevation, and extent. The systematic collection of beach profiles at specific locations, and related to established field monuments, fosters the analysis of these morphological features through time and space.

The wide range of physical settings along and among the NCBN parks results in a variety of different typical beach profiles between, and even within, parks. Different morphologies at different elevations may be found depending on exposure to waves, sediment availability, presence of human manipulations and structures, etc. Throughout the spectrum of environmental conditions and the beach morphodynamical states found along the parks, a number of coastal features can be measured and compared through time, resulting in a characterization of the coastal topography and its evolution through time (seasonal and long-term) as well as space (alongshore comparison) (Short and Trembanis 2004, Ruggiero et al. 2005). The key diagnostic topographical features of beach profiles include the dune or bluff, the beach berm, and the beach face.

Understanding the dynamics of changes in these features over time, through standardized data collection, will provide a scientific basis for informed resource management (National Research Council 1995). Some of the NCBN parks have long records of historical geomorphological datasets that can be used for long-term comparison to support decisions on infrastructure protection as well as resource management (e.g., Psuty and Pace 2009, Rogers et al. 2009, Rodriguez 2004). The assemblage of reliable and consistent data enables robust statistical analysis, yielding a better understanding of episodes, cycles, and trends (Colwell and Thom 1994, Dolan and Hayden 1983).

Monitoring coastal topography on a park-wide scale provides knowledge of the spatial and temporal variation in sediment transfers and sediment budget and creates a fundamental database for use in park management. The collection of coastal topography data twice a year, in the early spring (the fully developed winter beach) and the early fall (the fully developed summer beach), leads to the accumulation of a time series of seasonal beach states that represents the annual theoretical maximum and minimum configurations of the beach-dune profile. Each annual dataset portrays the magnitude of variation caused by the changes in the seasonal wave climate acting on the beach sediment supply. Monitoring of the seasonal variation contributes an understanding of the range of changes that occur in the morphology and the positive and negative displacements that relate to the contrast of higher energy and lower energy conditions. Additionally, seasonal contrasts offer a dimension of the range of changes that are not available at the annual scale. Longer-term comparisons of beach topography reveal changes created by differences in sediment availability and intensity of formational processes. Furthermore, the creation of a spatial network of beach profiles distributed along the park's shoreline provides information on the alongshore variation, and characterization of the park's geomorphological units.

The objective of the NCBN Coastal Topography Monitoring Protocol is to identify the seasonal, annual, and long-term (five-years or more of protocol-derived data sets) trends and variability in time and space of beach/dune/bluff morphology in the NCBN parks. Meeting this objective will address the following questions:

- What are the seasonal dimensions of the coastal features?
- What are the annual dimensions of the coastal features?
- What are the long-term, five years or more, dimensions of the coastal features?
- What are the directional displacements of the coastal features?
- What are the spatial and temporal trends in the displacement of the coastal features?

Measuring Coastal Topography

Measurement of coastal topography is accomplished through the collection of topographical data along beach transects that extend perpendicular to the shoreline. A matrix of geo-referenced control points provides the mechanism for the systematic tracking of the variations of the beach transect, and standard state-of-the-art practices of surveying are used to assure consistency in data collection. The systematic and repeated collection of topographical data starting at a fixed location and along pre-defined transect lines allows for tracking of the long-term variation of the beach/dune/bluff morphology.

Basics of Topography

Acquisition of topographical data involves measurements of the earth's surface in its spatial location, as well as its elevation. The spatial location is measured in terms of coordinates—distances from a starting point measured along two axes: longitude and latitude, also known as easting and northing, or X and Y (Figure 9). The elevation component adds the third dimension, known as Z, needed to portray the 3-dimensional aspect of the earth's surface.

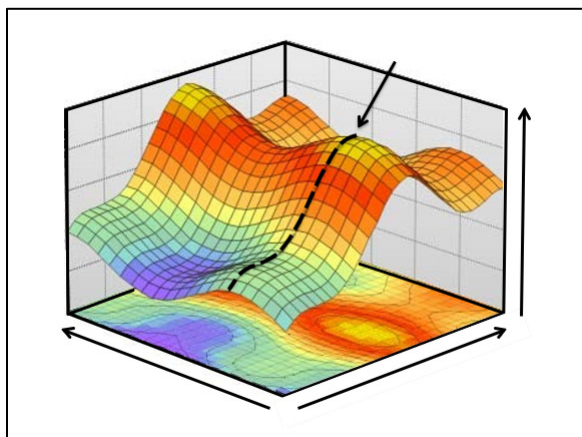


Figure 9. Three-dimensional characteristics of coastal topography.

For the purpose of the present protocol, easting and northing are measured in meters relative to the Universal Transverse Mercator (UTM) projection and grid system. All the parks of the NCBN are located in Zone 18 North, except for Cape Cod National Seashore, which is located on Zone 19 North. The North American Datum of 1983, 2011 realization, epoch 2010.0 – NAD83 2011 (2010.0) – is the horizontal datum applied.

The elevation is measured relative to a base elevation, known as a vertical datum. The North American Vertical Datum of 1988 (NAVD 88) is the most recent and most commonly used in the US. NAVD 88 is a fixed datum, determined by geodetic leveling, established relative to a specific zero point that does not change through time. Before NAVD88 was established in 1991, the National Geodetic Vertical Datum of 1929 (NGVD29) was the vertical control datum widely used in the US.

Another type of vertical datum is the tidal datum, expressed relative to a mean water level obtained from tide observations conducted through the National Ocean Service over a 19-year time period that includes all of the tidal variations caused by earth-sun-moon relationships and sea level change, referred to as a National Tidal Datum Epoch. Tidal datums change with every tidal epoch, and the most common tidal datums used are listed and described in Table 2. An example of the relationship between the 1983–2001 tidal epoch tidal datums and the NAVD88 and NGVD29 geodetic datums is represented on a typical beach profile, using the tide gauge measurements at Sandy Hook, NJ (Figure 10 and Table 3).

Table 2. Tidal datums as defined by the [National Oceanic and Atmospheric Administration Tides & Currents Glossary](#).

Tidal Datum	Description
MHHW (mean higher high water)	Average of the higher high-water height of each tidal day observed over the Tidal Epoch
MHW (mean high water)	Average of all the high-water heights observed over the Tidal Epoch
MSL (mean sea level)	Arithmetic mean of hourly heights observed over the Tidal Epoch
MLW (mean low water)	Average of all the low water heights observed over the Tidal Epoch
MLLW (mean lower low water)	Average of the lower low water height of each tidal day observed over the Tidal Epoch

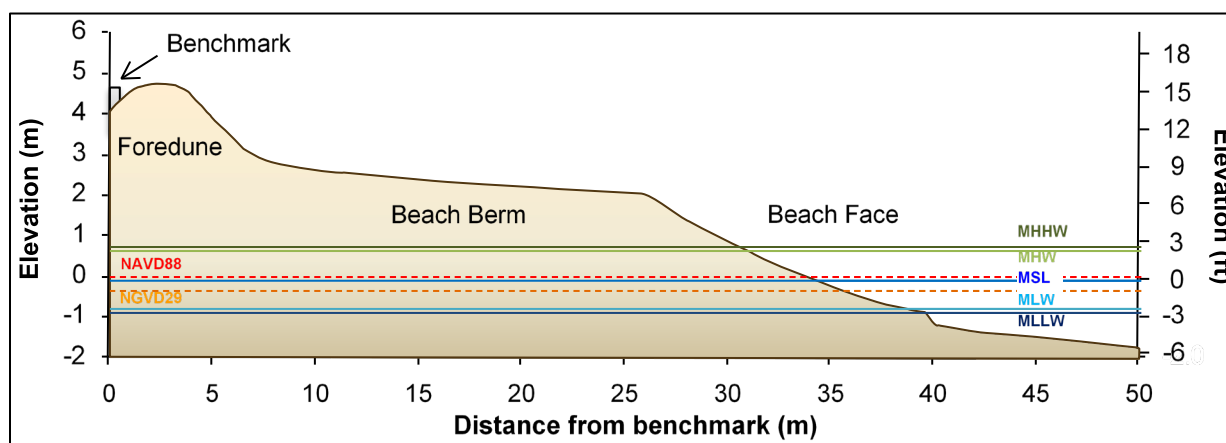


Figure 10. Typical beach profile showing the relationship between the 1983–2001 tidal epoch tidal datums, NGVD29 and NAVD88. (Source: NOAA tide gauge at Sandy Hook, NJ)

Table 3. Relationship of 1983–2001 Tidal Epoch water levels to NAVD88 and NGVD29. (Source: NOAA tide gauge at Sandy Hook, New Jersey).

Elevation of tidal datums and NGVD29 relative to NAVD88	Meters	Feet
MHHW (mean higher high water)	0.734	2.41
MHW (mean high water)	0.634	2.08
NAVD88 (North American Vertical Datum of 1988)	0.000	0.00
MSL (mean sea level)	−0.073	−0.23
NGVD29 (National Geodetic Vertical Datum of 1929)	−0.332	−1.09
MLW (mean low water)	−0.800	−2.62
MLLW (mean lower low water)	−0.858	−2.81

Note: The National Spatial Reference System (NSRS) is the spatial standard used to locate the coastal topography in this protocol. As technology progresses, the spatial reference system undergoes periodic updates related to datum realizations, thereby causing adjustments in the coordinates of the surveyed points. The NOAA National Geodetic Survey (NGS) releases these updates for the US. As the NSRS is updated, shifts in position will occur depending on location and will produce offsets in horizontal and vertical coordinates. The current geodetic datum used for this protocol is NAD83 2011 (2010.0). In 2022 NGS will replace NAD 83 and NAVD 88 with a new reference frame and geopotential datum based on GPS/GNSS and a gravimetric geoid model. Specific attention needs to be paid to the datum the survey control monuments are referencing in order that comparison to previous realizations may be accommodated. To remain current and maximize comparability through time, visit the National Geodetic Survey website at: <http://www.ngs.noaa.gov>.

Survey Monuments

The rationale for collecting topographic data along transects relies on creating a line that can be re-surveyed, thereby providing topographies that can be compared. No matter the method of data collection, the changes in elevation along the individual transect can always be compared if the data are measured relative to the same control point or monument. Each park can have up to three types of monuments:

1. Survey Control Monuments (also referred to as benchmarks): These are survey control points established with centimeter-level accuracy, computed through the National Oceanic and Atmospheric Administration (NOAA) Online Positioning User Service (OPUS) or established and maintained by the National Geodetic Survey (NGS). They are used to set up the GPS/GNSS base receiver needed for Real-time kinematic positioning (RTK) surveying or for the pre- and post-survey accuracy assessment check-ins.
2. Physical Transect Monuments: These monuments mark the location of the starting point of the transect to be surveyed. These are highly accurate topographical points, established with a GPS/GNSS system.
3. Virtual Transect Monuments: These monuments are sets of coordinates for a point falling exactly on the transect. Coordinates are generated in GIS and stored on the survey controller unit. Virtual monuments can be used to replace a lost physical transect monument and may be especially useful for transects where maintaining a physical monument is difficult or unfeasible. An example is at FIIS, where continual inland transgression of the system makes the maintenance of physical monuments difficult. Virtual monuments can also be used when

establishing new transects to implement this protocol rather than installing new, physical monuments.

Where possible, physical structures should be used to mark transect locations in the field, helping the field technicians re-locate and re-survey the same transect lines. Both survey control monuments and physical transect monuments are established to be long-lasting structures that provide a robust basis for long-term monitoring using this protocol. Therefore, they are established inland, far from the reach of the wave activity, usually behind the foredune or far from the bluff's edge. In cases such as sandy, barrier islands, physical transect monuments can be difficult to establish and maintain, so virtual transects can be established instead.

Physical transect monuments may correspond to pre-existing structures, such as fire hydrants or corners of curbs, or they can be established by the field technicians. There are different types and ways of establishing transect monuments. The field technicians may use rods, wooden stakes, or PVC pipes driven into the ground to mark the location of the transect lines.

For survey control monuments, needed for all surveys as accuracy assessment points whether using physical or virtual transects, the most sophisticated are stamped metal disks set into concrete or rock, or attached to long stainless-steel rods driven into the ground. These are typical of the monuments (benchmarks/survey marks) used by the National Geodetic Survey (NGS) and the US Army Corps of Engineers (USACE) (Figure 11a). They usually exhibit their ID and date of installation. In areas of loose sand, where the marker could be easily buried, there is usually a sign (witness post) marking its location (Figure 11b). Information on the NGS survey control monuments (including description, coordinates and elevation, and directions to the monument) is available on the Internet through an interactive map viewer. Some of the USACE survey control monuments information has been integrated into the NGS database.



Figure 11. Examples of a) metal disks survey monuments and b) witness post label, established by the US Army Corps of Engineers (USACE) and the National Geodetic Survey (NGS).

Besides these being used as physical transect monuments to mark the location of the transects to be surveyed for coastal topography analysis, they also can be used as survey control monuments to establish base stations for RTK GPS/GNSS surveys. These monuments may also serve as high quality reference points and can be used to check for accuracy assessment during surveys. Each park contains a network of either physical or virtual transect monuments established along the shoreline, as well as several high-accuracy survey control monuments needed for Real-time Kinematic surveying and accuracy assessment (see *SOP 3: Establishment of Monuments, Transects, and Geodatabases*).

Beach Profile Collection

Successive measurements of the elevations of the beach surface are taken along the pre-established profile line or transect at some distance interval, or whenever there is a change or inflection in the slope of the beach surface (Figure 12). The measurements of XYZ points are then portrayed in terms of elevations of the beach surface along the extent of the transect, providing a cross-sectional representation of the beach, referred to as the beach profile (Figure 12).

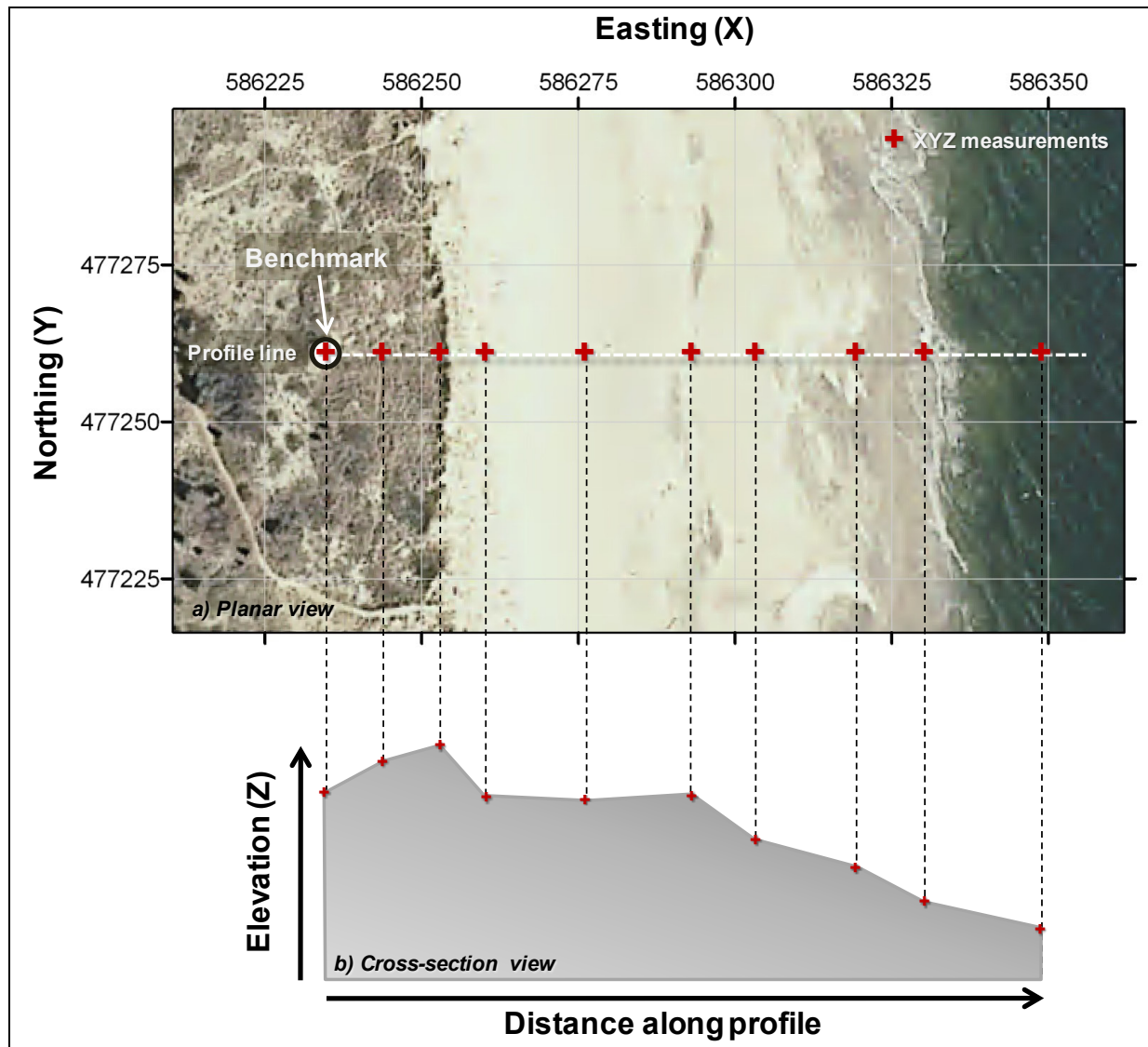


Figure 12. Collection of measurements of beach topography: a) planar view showing some of the XYZ measurements along a transect line perpendicular to the general trend of the shoreline, b) cross-section view of the collected data portrayed as elevations along the transect is considered the beach profile.

Field Methods and Equipment

There are several types of field equipment that can be used to collect beach profile topography field data. The simplest tools are used in the leveling techniques that involve a fixed initial reference point, with a known elevation, from which horizontal and vertical distances are measured. Some of the methods that involve this technique are the “hand level method”, the “horizon method” (Emery 1961), and the water level method (Andrade and Ferreira 2006). These tools are simple and easy to use, but are time consuming in their measurement and recording, and they provide a maximum of 1-2 cm of accuracy in elevation change at each measured point, resulting in cumulative errors.

Other methods involve the use of optical techniques and include the use of instruments (electronic or not) such as dumpy levels, automatic levels, theodolites, and total stations (Ghilani and Wolf 2008).

Electronic devices allow for data storage in data loggers, making it easier for field data gathering and processing. The total station is the most precise method to measure topography, providing XYZ data with accuracies on the order of millimeters over the length of a beach profile. The only limitation is that the method requires the total station to be established and maintained at a known point, and that it is always in line-of-sight of the reflecting prism.

Topographic data acquisition using positions from global satellite systems has become increasingly important in geomorphological and morphodynamic studies (Baptista et al. 2008, Matthues et al. 2022). A number of Global Navigation Satellite Systems (GNSS), such as the Russian GLONASS, have joined the original US Global Positioning System (GPS) and greatly increased the data-collection efficiency and attainable accuracy of such data collection equipment. GPS/GNSS methods rely on the broadcast of signals from a constellation of satellites that orbit the earth, controlled by a network of ground stations. Four satellites are sufficient to provide real-time XYZ positions to an accuracy that ranges from several meters to centimeters, depending on the equipment. The most sophisticated GPS/GNSS equipment, referred to as survey grade or geodetic, can measure a position to within 1-2 cm in the horizontal dimension, and 2-4 cm in the vertical, and does not have the problem of cumulative error. Combined with a RTK survey style that captures points in very short times and requires no post-processing, the RTK approach involves the use of two GPS/GNSS receivers (base and rover) in constant radio communication with each other. The base receiver works as the reference station, established at a point with known coordinates and elevation, sending real-time corrections to the rover receiver as it occupies successive points along a profile. The rover can be used freely within a 20 km range from the base station, allowing for coverage of large areas for surveying. However, measurement accuracy drops approximately 1 cm per each 10 km distance from the base. Also, terrain, buildings, and tree canopy can obstruct the satellite signal and make it difficult for the rover to acquire positions.

A relatively recent advancement for measuring coastal topography includes airborne methods that collect a very dense grid of XYZ points acquired by LiDAR (Light Detection And Ranging) systems (Brock et al., 2002). LiDAR acquires data automatically from an airborne platform and relies on an active sensory system that uses an infrared laser to measure distances to the ground and thereby calculates positions and elevations. It provides for the collection of large topographical datasets over wide areas in a very short time period, but the elevation data have an accuracy of about 15 cm. LiDAR surveys are being acquired when available for the NCBN parks, providing supplemental topographic datasets of the beach/dune systems in the NCBN's coastal parks.

Geodetic GPS/GNSS Unit

For the purpose of this protocol, which is directed to establishing seasonal and annual variation as its basic temporal consideration, the geodetic or “survey-grade” GPS/GNSS unit was selected as the most suitable equipment and RTK as the survey style to best collect coastal topography data (Figure 13). RTK is preferred over post-processing kinematic (PPK) style, for example, because it is one less step in the procedure and because it allows for a real-time quality check and accurate field data collection along pre-established profile lines.



Figure 13. Trimble R8 GPS/GNSS unit (base receiver on tripod, and rover receiver on pole) used for conducting topographical surveys at Gateway National Recreation Area, Sandy Hook Unit.

The geodetic GPS/GNSS equipment offers the best compromise between cost and quality of data provided. Although not as accurate as the total station, combining the GPS/GNSS unit and the RTK survey style (hereafter referred to collectively as GNSS-RTK) is a very time-efficient method of topographic data collection when compared with the other ground survey methods. It is less expensive and allows for better temporal programmability when compared to LiDAR. The equipment is highly portable, and the survey method allows access to remote areas without much constraint. The level of accuracy attained with the GNSS-RTK approach is adequate for the analysis that is performed on the topographical datasets, because variations of the beach surface and volumes at a seasonal scale are on the order of meters. Furthermore, the GPS field survey controller (a handheld field computer) allows for easy data collection and storage and provides the advantage of displaying results in real time. Importantly, the controller can display background layer files with the location of all monuments and profiles, allowing field verification crucial to the field data collection in this protocol. Therefore, the combination of speed of conducting the survey, the real-time calculation and storage of highly accurate data points, and the field views and verification of the survey profiles supports the GNSS-RTK approach.

The RTK system can and should also be used to acquire survey-quality positions for transect monuments and survey control monuments in the field. The NGS Online Positioning User Service ([OPUS](#)) provides free processing of GPS data files (measured according to guidelines) to provide coordinates that are highly accurate.

The RTK system offers a number of advantages because it can be set up and operated in a variety of ways, depending on the equipment and personnel available, the area to be covered, and the local constraints:

- Base + rover setup: Uses one base station that is temporarily erected in the field at a known location and is sending corrections to the rover via a radio link. This setup is adequate to survey profiles within a 5 km distance radius from the base station (20 km with external radio). As the distance increases, the atmospheric conditions at the rover and base station will become increasingly different, resulting in a decrease in accuracy.
- Multiple Bases + rover setup: Used when multiple base receivers are available and two (or more) reference stations can be established, each operating independently. This is useful for surveying large areas (>20 km distance radius from the base station) because the field technicians can select the reference station that is closest to its location and continue surveying, without the need to stop the survey.
- Base (single or multiple) + multiple rovers: Used when more than one rover can be in communication with one reference station at the same time. The existence of several rover units in the parks allows for teams of users to survey different profile lines at the same time, increasing the time efficiency of the data collection.
- Rover + correction services: An increasingly popular alternative to the base and rover setup is the use of commercially or publicly available correction services to access a network of reference stations (such as the National Geodetic Survey's Continuously Operating Reference Stations or "CORS" network (Continuously Operating Reference Stations) for real time correction. This is particularly useful in cases where communication between the rover and base is not possible (e.g., due to the presence of obstacles such as high bluffs). Internet-based Networked Transport of RTCM via Internet Protocol (NTRIP) services offer corrections over cellular or wi-fi connections. This option can have cell phone associated costs and require a plan with a carrier that supports the type of data connection that is necessary. The use of rovers and cellular-based NTRIP correction services has become the primary setup at some NCBN parks, such as Gateway National Recreation Area. Other services such as Precise Point Positioning (PPP) can similarly deliver such corrections via satellite. All such services eliminate the need for field staff to set up and employ a local base-station.

Additionally, a radio repeater may be setup and used to pick up the base station radio signal and broadcast the signal farther within the survey area. The NCBN parks have a number of TRIMMARK™ 3 radio modems that can be used for this purpose.

Monitoring Design

Establishment of the Survey Transects

This protocol focuses on the collection of data that tracks and measures site specific and alongshore variability of the topographical changes. Transects are surveyed from an established network of transect monuments, either virtual or physical, that have been created along the entire length of the ocean beach at each of the parks. The distribution of the transects and their associated monuments were selected according to the following criteria:

- Representation of the park's geomorphological units
- Representation of areas of special concern
- Distribution and quality of previously-established transects
- Ease of access

Monitoring coastal topographies and their vectors of change is especially important in areas where cultural and natural resources are of special concern to the park. Transects may be spaced evenly throughout the park or adjusted to capture the characteristic areas of concern. This is ultimately a decision that is left to the discretion of local management based on their monitoring priorities. Pre-existing transect/monuments networks established by the NPS or other institutions were analyzed and subjected to quality evaluation, such as confirmation of their location in the field and verification of their coordinates. Further, the incorporation of pre-existing monuments used for acquiring coastal topographical data extends the opportunity for comparison between the data acquired with this protocol and previously acquired topographical data. Whenever there is the need for installation of new transects and survey control monuments in the spatial network, the establishment should follow the guidelines and requirements described in *SOP 3: Establishment of Monuments, Transects, and Geodatabases*. The new transect monuments' coordinates and elevations will be acquired with a survey-grade GPS/GNSS unit and will be registered to NAD83 (2011) 2010.0 and NAVD88, in meters.

The information on the network of survey transects within each park, including description of the locations and attributes of each survey physical or virtual monument, is stored in GIS files maintained by the Project Lead and the NCBN Data Manager. Additionally, field booklets are created for each park with a brief description of each monument and transect location, including aerial photos of the site, ground photos, and coordinates and elevation information, when the protocol is implemented in a park. Data storage and creation of the field booklets are both described in *SOP 3: Establishment of Monuments, Transects, and Geodatabases*.

Each monument has an associated transect line, along which, measurements are collected (Figure 12). This line feature is initially established in the office with a GIS and normally begins at the transect monument and is directed toward the shoreline. When this is not logistically possible (e.g., when the beach or dune have migrated significantly), a virtual monument may be established anywhere along the transect line. The line is drawn orthogonal to the general trend of the shoreline and has an associated azimuth. The line features are stored in GIS files associated with the

monuments' files, which are documented in park field booklets. The guidelines and procedures to create and store the transect lines are described in *SOP 3: Establishment of Monuments, Transects, and Geodatabases*

Survey Frequency and Timing

The morphology of the full beach-dune system profile changes with the seasonal variations in the wave-energy levels (Komar 1983, Biaisque and Senechal 2019). Commonly, winter storms produce higher and more energetic wave conditions leading to mobilization of the sediments in the beach face, berm, and dune and promoting the transfer of the sediment to a high berm (storm berm) adjacent to the foredune and to the subaerial portion of the beach, which is stored in the form of sand bars. At an extreme condition, the high berm is completely eroded and the foredune base is scarped. This offshore transfer profile configuration is referred to as the winter profile (Figure 14). During the summer, waves are smaller and less energetic, and the sediment is transported back to the intertidal and subaerial portions of the beach, leading to the widening of the beach berm and recovery of the dune. This profile configuration is referred to as the summer profile (Figure 14).

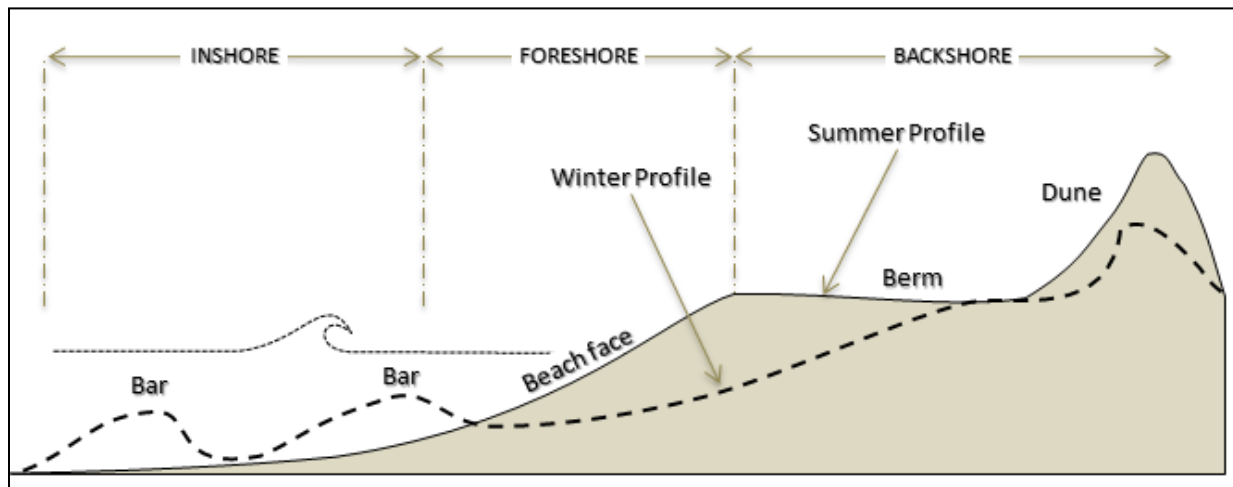


Figure 14. Changes in beach profile morphology, associated with seasonality of coastal energetics.

Bluff coastlines behave in a different manner. Because they are inherently erosional coastal features, bluffs respond to seasonal variations in the wave-energy levels by retreating at different rates. Bluff recession is usually accelerated during winter when severe storms with higher wave energy impact the coast and promote scouring and slumping of the bluff face. The beach that may or may not exist at the base of the bluff will also change with the seasonal variability in the wave regime. The beach will be narrower during the winter and wider in the summer.

The configurations of the winter and summer profiles typically reach their peak expression around the end of the winter and summer seasons, respectively. Likewise, bluff retreat and beach loss are maximized around the end of the storm season. To track this seasonal variation, beach profile surveys are conducted twice per year and timed to capture the general occurrence of the maximum seasonal

(winter/summer) state. The winter profile is surveyed in mid-March to late April and the summer profile in mid-September to late October (*SOP 5: Survey Timing and GPS/GNSS Mission Planning*).

It is suggested that field surveys be conducted around the lowest of the low tide levels that are reached during spring tides. Conducting the survey during this condition promotes maximum exposure of the beach profile, and it provides the opportunity to collect more data during the span of time that the beach face is exposed. The survey should be accomplished during the 6 hours around low tide, 3 hours before and 3 hours after the predicted time of low tide.

The topographical survey should be conducted when minimum satellite availability and satellite geometry specifications are met (*SOP 5: Survey Timing and GPS/GNSS Mission Planning* and *SOP 6: Basic GPS/GNSS Requirements for Coastal Topography Data Collection*). Timing of the surveys may also be affected by park specific issues such as the presence of species of concern or public activities that constrain the conducting of the topographical survey. Park management should always be consulted in advance when planning the survey. Details for timing and mission planning are provided in *SOP 5: Survey Timing and GPS/GNSS Mission Planning*.

The topographical surveys will provide information that describes the beach and dune characteristics and their seasonal variation (Figure 14), as well as their alongshore spatial variability. Further, supplemental beach transects may also be measured after a major storm event, providing information on the magnitude of short-term variations of the beach (Forbes et al. 2004). This information can be of great value to both park managers and coastal scientists. The protocol can and should be applied in pre-and-post-storm beach profile surveys, whenever possible. Because numerous storms of varying intensity and duration are expected to affect a given park in a typical year, the decision of when to conduct these additional surveys is problematic. Local observation and judgment must be exercised in making the determination whether to conduct the supplemental surveys.

Field Methods

Field Season Preparations and Mission Planning

In the beginning of the year, the two seasonal survey windows should be identified according to the monitoring design (*SOP 5: Survey Timing and GPS/GNSS Mission Planning*). Tide prediction tables from the NOAA Tides & Currents website should be consulted and a list of potential survey dates and times should be established and prioritized. Satellite availability and satellite geometry predictions, available from the Internet, should also be considered in the survey window selection.

Prior to the survey, the field team should check the field equipment to make sure all the items are working properly and that all batteries are charging (*SOP 2: Equipment and Supplies*). All the survey background files (*SOP 3: Establishment of Monuments, Transects, and Geodatabases*) must be uploaded into the field survey controller (*SOP 6: Basic GPS/GNSS Requirements for Coastal Topography Data Collection*). The field team must check the time of low tide for the days of the survey and notify park personnel and neighbors of the activity (*SOP 5: Survey Timing and GPS/GNSS Mission Planning*). Prior to the field season the protocol lead must review and make any necessary updates to the [Coastal Topography Monitoring Safety Plan](#), and each member of the field team must read and review the Coastal Topography Monitoring Safety Plan before going into the field.

Conducting the Topographic Survey

Prior to the beginning of the survey, the GPS/GNSS equipment must be set up to assure that all rovers are receiving correction signals (whether via radio from base station or over cell service) over the entire area being surveyed. Depending on the method used, more than one base station might have to be set up, or repeaters might have to be used to extend the range of the radio signal. When creating the survey “job” profile, verify that the correct coordinate system, datum, and geoid is used (*SOP 6: Basic GPS/GNSS Requirements for Coastal Topography Data Collection*). Once the GPS/GNSS system is configured and working, the team of field technicians (each with a rover unit) will perform a pre-survey survey control monument check-in or accuracy assessment for quality control purposes. After this check-in, they will make use of the field booklet and the field survey controller to locate either virtual or physical monuments that mark the locations of the transects.

For quality-control purposes, the first measurement at the transect is on the monument location. The rover is then positioned on the transect line shown as a background file in the screen of the field survey controller. Data are collected with the GPS/GNSS rover receiver along the pre-established transect line, starting at the monument and following the established azimuth that is running perpendicular to the general trend of the shoreline. Point measurements (XYZ) are taken at some distance interval (no more than 5 m), or whenever there is a change or inflection in the slope of the beach surface and continuing seaward until at least the elevation of 0 m NAVD88, defining a position low on the beach face, is reached. *Note: most applicable equipment is not designed to be immersed.*

In areas with bluffs, the survey may have to be divided into two parts. For ease of access and to take advantage of the low tide, the field technicians may have to survey the upper part of the bluff at one

time, and then survey the beach area at the low tide time, producing an interrupted dataset of points for the same transect line. In this case, a specific nomenclature is used to ID the survey points (*SOP 7: Conducting the GPS/GNSS Coastal Topography Survey*).

At least one photograph is taken at each transect to capture the general aspect of the dune/bluff feature present. Before closing the survey, a post-survey control monument check-in/accuracy assessment is performed. Additional details are included in *SOP 7: Conducting the GPS/GNSS Coastal Topography Survey*.

Post-survey Data Download and Initial QA/QC

Immediately upon completion of the survey and return to the office, the survey job is downloaded from the field survey controller to a computer hard-drive and a backup copy created. The data should be retained on the field survey controller until quality checks can be made. If using the Trimble platform, the downloaded job is imported into the Trimble Business Center (TBC) software (or similar), and the data are exported and converted into ESRI geodatabase feature classes. The transects' data are plotted in ArcGIS and the coordinates of the starting point at each profile line, as well as the general alignment between the collected points and the pre-established transect lines, are checked for accuracy. Two auxiliary files representing monuments and geodatabase (*SOP 3: Establishment of Monuments, Transects, and Geodatabases*).

The photographs are transferred into the computer and renamed to reflect each transect's ID and date of the survey to which they refer. The field data form is completed and reviewed. Following all the quality control procedures and creation of metadata, the final dataset of the surveyed transects (e.g., job files, TBC project, exported files, feature classes, field data forms, and photographs) will be sent to the NCBN Data Manager. Additional details are included in *SOP 8: Initial Post-Survey Processing*.

Data Management

Data storage and retrieval are vital elements of the NCBN Coastal Topography Monitoring effort. The program generates a variety of data products that are archived in a central SQL Server database, overseen and controlled by the NCBN Data Manager (*SOP 11: Data Management*). These products are retrievable for broad-based usage and analysis. To better understand the structure of the archiving system and the type of information available, a Database User's Guide has been produced, which describes the elements of the data input and the categories of coastal topography data. The Database User's Guide also describes the procedures for retrieving information. In addition, a Quality Assurance Plan (QAP) has been developed, documenting all aspects used during preparation for data collection, implementation, and data handling, to assure that all activities associated with the guidelines in this protocol, are identified and carried out. This helps to ensure and verify that data meet specific data-quality objectives throughout the Data Lifecycle.

Field Data Forms

To ensure that datasets remain as complete, accurate, and up to date as possible, it is imperative that all field data are recorded on appropriate field data forms during each sampling event (*SOP 7: Conducting the GPS/GNSS Coastal Topography Survey*). The field data form contains sections that capture important data that should be entered before (e.g., date of last storm event) and during a survey event. Any edits, changes, or corrections to the data are noted on the field form and include the date and initials of the person making the change.

Data Entry and Verification

Data should be entered into the NCBN Coastal Topography SQL Server Monitoring Database as soon as possible after returning from the field (*SOP 8: Initial Post-Survey Processing*). The database has been designed to reduce errors associated with data entry by using features such as drop-down lists and acceptable value ranges to reduce errors due to spelling, etc. It is the responsibility of the NCBN Data Manager and Protocol Lead to ensure that individuals responsible for data entry have been properly trained to use the database and have the most recent version of the Database User's Guide. Data entry is verified by staff other than the person entering the data. All records are exported from the database and a visual review and comparison with the original field data forms are conducted. Errors are marked and corrected as soon as possible.

Data Archiving

At the end of the field season, electronic scans of all field data forms are archived as Adobe pdf files as described in *SOP 11: Data Management*. A copy of the data contained in the NCBN Coastal Topography Monitoring Database is archived annually, and all certified data are posted on the Integrated Resource Management Applications (IRMA) website.

Change Calculation, Data Analysis, and Reporting

Generation of Beach Profile Cross-section, and Calculation of Dimensional Parameters

The topographical data collected in the field in the form of horizontal coordinates and elevation (XYZ) will be portrayed as elevations of the beach surface along the extent of the transect, providing a cross-sectional profile of the beach (Figure 12). *SOP 9: Change Calculation and Data Analysis* describes the procedure for manipulating the profile data and includes the step-by-step methodology for plotting and analyzing the beach profiles. *SOP 10: Coastal Topography Reporting* describes the development of annual reports if requested by a park, or the trend reports that are produced every five years providing not only the trends within a five-year period and the full record of data collection. The NCBN Protocol Lead oversees reporting.

Construction of the profiles utilizes 2D Analyst, a Microsoft Excel application created for this Protocol to generate the profile cross-sections and calculate the dimensional parameters of each profile. A step-by-step description is presented in *SOP 9: Change Calculation and Data Analysis* on how to use 2D Analyst and derive the dimensional parameters according to the type of morphology present.

For beach profiles with foredune features:

- Cross-section area above NAVD88 = total area of the beach profile
- NAVD88 distance from transect monument = measure of the beach width
- Foredune crest height
- Foredune crest distance from transect monument

For beach profiles with bluff features:

- Cross-section area above NAVD88 = total area of the beach profile
- NAVD88 distance from transect monument = measure of the beach width
- Bluff's edge elevation
- Bluff's edge distance from transect monument

Optional metrics may be derived from the datasets using 2D Analyst, such as the bluff base or dune toe position and elevation, or the cross-sectional area of selected geomorphological features (e.g., subaerial beach, dune, or bluff area).

Data Analysis and Reports

The dimensional parameters generated from the analysis of each beach profile are compared and analyzed in a tabular and graphic portrayal, providing information about the temporal and spatial changes on beach morphology in the parks (*SOP 10: Coastal Topography Reporting*).

A suite of summary statistics (mean, maximum, minimum, and standard deviation values) are calculated for each of the parks and profiles, describing the dimensions of the change in the cross-

section beach area, the NAVD88 contour position, and in the dune and bluff features. Site specific patterns of accretion/erosion and migration of components of the profiles are accessed through this cross-shore analysis.

A calculation for profile uncertainty was developed for the annual reports in 2017 and has been applied to all reports thereafter. The total uncertainty, as well as the value for each feature (beach and dune), should be calculated for all profiles using 2D Analyst. Further information on the methodology is provided in *SOP 10: Coastal Topography Reporting*.

The dimensions of change calculated for each profile will be compared spatially along the park to assess the alongshore variability of the beach morphology. The spatial relationship between profiles may be quantified and correlated to assess patterns of alongshore transport.

Personnel Requirements and Training

Roles and Responsibilities

NCBN staff are responsible for the development, implementation, reporting and updates to the protocol. The NCBN Program Manager and Protocol Lead are responsible for coordinating protocol development, necessary revisions, as well as an implementation plan. The Protocol Lead is in charge of developing the sampling schedule for each of the NCBN parks where the protocol is implemented.

This protocol is designed to utilize trained park staff for field data collection when possible. The data collection is improved through the use of personnel who have a basic understanding and working knowledge of the park and its resources. Because of their familiarity with its appearance, park personnel are much better situated to perform periodic observations of the beach. Their participation enhances the accurate and consistent collection of data along the transects to reflect the major topographic beach features. The use of park staff also limits or prevents the problem of schedule overlap, where NCBN staff might be expected to work in multiple parks at or around the same time. Consistent feature identification and measurement is important, and assignment of data collection to a single or small number of NCBN or park trained field technicians is highly recommended.

The data management aspect of the monitoring effort is the shared responsibility of the field technician, the Protocol Lead, and the NCBN Data Manager. The field technician is responsible for field data collection, initial data download, and initial QA/QC. The field technician should work closely with the NCBN and/or park GIS specialist for additional post-processing, data verification and data validation, preliminary data editing, and export to the designated GIS format. The Protocol Lead is responsible for data documentation (metadata), data summary, and basic analysis and reporting. Ultimately, the Protocol Lead has the responsibility to see that adequate QA/QC procedures are built into the database management system and that appropriate data handling procedures are followed.

Qualifications and Training

The Protocol Lead needs to be knowledgeable in the data gathering methodology and is responsible for developing and delivering a training program to provide a scientific and technical foundation for consistent and accurate data collection. An essential component in the collection of coastal topography data means having knowledgeable, competent, and attentive field technicians. They must be able to identify the major topographic features along the beach profile and to consistently collect points that will reflect and portray those features. The field technician should have:

- A basic understanding of coastal processes and familiarity with the resource and appearance of the major coastal features
- Competence and experience in the operation of all equipment being used in the survey
- Competence and experience in following accuracy assessment and quality assurance procedures
- Competence in following NCBN and park-based safety procedures

Frequency of the Training Sessions

Training shall be conducted prior to initial implementation of the protocol and thereafter at a minimum interval of once every two years, or as needed due to staff or procedural changes. Safety review and training will occur annually.

Target Audiences

Whenever possible, the NCBN shall provide training for local field technicians to establish a core of competent and qualified personnel with local knowledge, while also helping to reduce problems related to staffing or scheduling.

More details on roles, responsibilities, qualifications, and training can be found in *SOP 4: Training for Field Data Collection*.

Operational Requirements

Annual Workload and Field Schedule

Coastal topographic monitoring surveys are conducted in early spring (mid-March to late April) and early fall (mid-September to late October), a period that coincides with the peak expression of seasonal beach variability in the NCBN ocean parks. The unpredictability of extreme tide and weather events precludes the scheduling of surveys to specific annual dates. More details on the survey window can be found in *SOP 5: Survey Timing and GPS/GNSS Mission Planning*.

The surveys require two field technicians. Tide oscillation is a constraint to the acquisition of the data, limiting the daily survey time to the 6 hours around the predicted time of low tide. The NCBN parks will present different workloads because they have different spatial networks of transects, with a varying number of beach transects to be surveyed. Additionally, site-specific constraints that have to do with access to transects and survey control monuments limit the number of transects that can be surveyed in one day. For example, GATE's network covers six coastal areas spread throughout the three Units (Sandy Hook, Jamaica Bay, and Staten Island), which are between 10 and 70 kms apart. In the case of CACO, the combined bluff and beach profiles cannot be surveyed continuously, requiring that the field technicians visit the same profile line twice. Equipment availability is also a constraint. If only a single base station is used for corrections, the area that can be surveyed by the rover unit is limited to a 20 km radius, and frequently to a shorter distance because of obstacles and/or absence of a powerful radio signal transmitter communicating with the receiver. Due to these potential constraints, additional base station setups are required to cover the entire park's spatial network of profiles.

In general, it is estimated that one transect takes approximately 20-30 minutes to be surveyed (collection of points and photograph). Given the time to travel between survey control monuments and additional equipment setup, 5-10 beach transects can be surveyed in one day, depending on the park and the number of field technicians. Considering the spatial network of transects established for each park, the estimated workload is outlined in Table 4. All parks are different, and time is variable for data collection among them.

Table 4. General workload for coastal topography monitoring surveys for each Northeast Coastal and Barrier Network park.

Park	GPS/GNSS Device	Transects	Survey Time
Assateague Island National Seashore	1 GPS/GNSS unit	33 beach transects	5 days
Cape Cod National Seashore	1 GPS/GNSS unit	22 beach transects	4 days
Fire Island National Seashore	1 GPS/GNSS unit	38 beach transects	5 days
Gateway National Recreation Area	2 GPS/GNSS units	48 beach transects	6 days

The pre- and post-survey workload is similar for all the parks. Survey preparations and mission planning should take one workday to accomplish, and post-processing should take two to three days.

Facility and Equipment Needs

The minimum equipment needed for the coastal topographic monitoring surveys consists of a survey-grade GPS\GNSS receiver, a field survey controller, and some source of correction data (e.g., a local base station set up over a known survey control monument, a RTK network accessed over cellular connection, etc.). If more than two field technicians work simultaneously, field equipment requirements will increase accordingly. Should a park lack the proper equipment, the NCBN will attempt to arrange access to the items necessary to conduct the survey.

A computer and peripheral devices with appropriate ports and cables, RTK jobs processing software (e.g., Trimble Business Center) for download, initial QA/QC, and export to ESRI GIS format are required to complete the initial tasks. The GIS component consists of the ESRI ArcGIS or similar software. Office computing needs and other equipment items are detailed in *SOP 2: Equipment and Supplies*.

Procedure for Revising the Protocol

Following operational and science reviews, revisions to both the protocol document and associated standard operating procedure (SOP) document are to be expected. The rationale for having two separate documents, the protocol, or general protocol overview document, and one SOP document, that includes all procedural guidelines (individual SOPs) is that the Protocol document provides the general overview along with the history and justification for the monitoring and an overview of the sampling methods, but it does not provide all of the procedural details. The protocol document is only revised if major procedural changes are made that affect the sampling design and data analysis. The SOP document in contrast, provides very specific step-by-step instructions for performing a given task, and is expected to be revised more frequently due to individual SOP updates within the main SOP document such as equipment, software, and other relevant changes. When procedures are revised, in most cases, because they do not affect the data itself, or associated analysis, it is not necessary to revise the main Protocol document to reflect general changes made. The SOP document, on the other hand may be revised as often as annually.

For details on versioning procedures, see *SOP 13: Protocol and SOP Versioning*.

Protocol Revision History Log

The following table lists all changes that have been made to this document since the original publication date. Versioning guidelines can be found in the separate [Standard Operating Procedure \(SOP\) document](#) associated with this document. For complete instructions, please refer to *SOP 13: Protocol and SOP Versioning*.

Revision Log. Add new rows and information as required for update.

Protocol Version #	Revision Date	Author (full name, title, affiliation)	Location in Document and Description of Change	Reason for Change
1.0	4/12/2013	Dennis Skidds, NCBN Data Manager	NA	Initial Protocol
2	8/29/2023	Glenn Liu, Geoscientist-in-the-Parks (GIP), Rutgers, Dennis Skidds, Scott Rasmussen and Sara Stevens Nerone, NCBN	- Updated/changed figures, updated text, and hyperlinks. - SOPs separated and published separately from the main protocol document. - Extended survey window—Decision made by the Technical Steering Committee - Added workflows and methodologies to allow for different types of GPS/GNSS technologies. - Added language on the use of virtual transect monuments - Additional recent references were added.	Full Protocol update prescribed by Technical Steering Committee

Literature Cited

- Allen, J. R. 2000. Vital signs of northeast coastal park resource change: Shoreline monitoring group report. National Park Service Internal Report.
- Andrade, F., and M. A. Ferreira. 2006. A simple method of measuring beach profiles. *Journal of Coastal Research* 22(4):995-999.
- Anthony, E. J., and T. Aagaard. 2020. The lower shoreface: Morphodynamics and sediment connectivity with the upper shoreface and beach. *Earth-Science Reviews*. 210.
- Baptista, P., L. Bastos, C. Bernardes, T. Cunha, and J. Dias. 2008. Monitoring sandy shores morphologies by DGPS - A practical tool to generate digital elevation models. *Journal of Coastal Research* 24(6):1516–1528.
- Başaran, B., and H. A. A. Güner. 2021. Effect of wave climate change on longshore sediment transport in Southwestern Black Sea. *Estuarine, Coastal and Shelf Science*. 258.
- Biausque, M., and N. Senechal. 2019. Seasonal morphological response of an open sandy beach to winter wave conditions: The example of Biscarrosse beach, SW France. *Geomorphology* 332:157-169.
- Bird, E. C. F. 1985. *Coastal Changes: A Global Review*. John Wiley & Sons, London.
- Bloom, A. L. 1965. The explanatory description of coasts. *Zeitschrift für Geomorphologie NF* 9:422-436.
- Brand, E., A. L. Montreuil, R. Houthuys, and M. Chen. 2020. Relating hydrodynamic forcing and topographic response for tide-dominated sandy beaches. *Journal of Marine Science and Engineering* 8(3):151.
- Brock, J. C., C. W. Wright, A. H. Sallenger, W. B. Krabill, and R. N. Swift. 2002. Basis and methods of NASA Airborne Topographic Mapper Lidar surveys for coastal studies. *Journal of Coastal Research* 18(1):1-13.
- Carapuco, Mafalda M., R. Taborda, T. M. Silveira, N. P. Psuty, C. Andrade, M. C. Freitas, 2016. Coastal geoindicators: Towards the establishment of a common framework for sandy coastal environments. *Earth-Science Reviews* 154:183-190.
- Carter, R. W. G. 1988. *Coastal environments: An introduction to the physical, ecological and cultural systems of coastlines*. Academic Press, London, 617 p.
- Colwell, P. J., and B. G. Thom. 1994. Morphodynamics of coastal evolution. Pages 33-86 in: Carter, R. W. G., and C. D. Woodroffe, editors. *Coastal evolution: Late quaternary shoreline morphodynamics*. Cambridge University Press, Cambridge, United Kingdom.

- Davidson-Arnott, R. 2005. Conceptual model of the effects of sea level rise on sandy coasts. *Journal of Coastal Research* 21(6):1166–1172.
- Davidson-Arnott, R., B. Bauer, and C. Houser. 2019. *Introduction to coastal processes and geomorphology*. Cambridge university press.
- Dolan, R., and B. Hayden. 1983. Patterns and prediction of shoreline change. Pages 123-150 in: Komar, P. D., editor. *Handbook of coastal processes and erosion*. CRC Press, Boca Raton, FL.
- Duarte de Almeida, I., and A. Silva. 2021. Coastal erosion: from coastal natural resources loss to territorial imbalances and social impacts. (4).
- Emery, K. O. 1961. A simple method of measuring beach profiles. *Limnology and Oceanography* 6(1):90-93.
- Finkl, C. W. 2004. Coastal classification: Systematic approaches to consider in the development of a comprehensive scheme. *Journal of Coastal Research* 20(1):166-213.
- Fischer, A. P. 2018. Pathways of adaptation to external stressors in coastal natural-resource-dependent communities: Implications for climate change. *World Development* 108:235-248.
- Forbes D. L., G. S. Parkes, G. K. Manson, and L. A. Ketch. 2004. Storms and shoreline retreat in the southern Gulf of St. Lawrence. *Marine Geology* 210:169-204.
- Griggs, G., and B. G. Reguero. 2021. Coastal adaptation to climate change and sea-level rise. *Water* 13(16):2151.
- Ghilani, C. D., and P. R. Wolf. 2008. *Elementary surveying: An introduction to geomatics*. 12th Edition. Pearson Prentice Hall, NJ.
- Honeycutt, M. C., and D. E. Krantz. 2003. Influence of the geologic framework on spatial variability in long-term shoreline change, Cape Henlopen to Rehoboth Beach, Delaware. *Journal of Coastal Research Special Issue* 38.
- IPCC. 2021. *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY.

- IPCC. 2022. Summary for Policymakers. H.-O. Pörtner, D.C. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem (eds.)). In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [H.-O. Pörtner, D.C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY.
- Kirkpatrick, L. H., and A. N. Green. 2018. Antecedent geologic control on nearshore morphological development: The wave dominated, high sediment supply shoreface of southern Namibia. *Marine Geology* 403:34-47.
- Komar, P. D. Editor. 1983. *Handbook of Coastal Processes and Erosion*. CRC Press, Boca Raton, FL.
- Komar, P. D. 1998. *Beach processes and sedimentation*, Second Edition. Prentice Hall, Upper Saddle River, NJ.
- Mattheus, C. R., K. N. Braun, E. J. Theuerkauf, and J. A. Santoro. 2022. Urban pocket-beach morphodynamics along the wave-dominated southwest coast of Lake Michigan: An analysis of shoreline and sand volumetric changes. *Journal of Great Lakes Research* 48(1):52-67.
- Morang, A. 2002. Atlantic coast of New York monitoring program: Cross-shore profiles, quality-control procedures, monumentation and data archiving. TR-02-16. U.S. Army Corps of Engineers Coastal Hydraulics Laboratory, Vicksburg, MS.
- Morgan, K. L. M., C. J. Hapke, and E. A. Himmelstoss. 2015. Baseline coastal oblique aerial photographs collected from Owls Head, Maine, to the Virginia/North Carolina border, May 19-22, 2009: U.S. Geological Survey Data Series 946. Available at: <https://dx.doi.org/10.3133/ds946> (accessed 29 October 2019).
- National Research Council. 1987. *Responding to changes in sea level: Engineering implications*. National Academy Press, Washington, D.C.
- National Research Council. 1995. *Beach nourishment and protection*. National Academy Press, Washington, D.C.
- Neal, W. J. 2010. Coastal topography, human impact on. *Marine Policy & Economics*. p.424.
- Nicholls R. J., P. P. Wong, V. R. Burkett, J. O. Codignotto, J. E. Hay, R. F. McLean, S. Ragoonaden, and C. D. Woodroffe. 2007. Coastal systems and low-lying areas. Pages 315-356 in: Parry, M. L., O. F. Canziani, J. P. Palutikof, P. J. van der Linden, C. E. Hanson, editors. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK.

- Nordstrom, K. F. 2000. Beaches and dunes of developed coasts. Cambridge University Press, Cambridge, UK.
- NPS NCBN - National Park Service Northeast Coastal and Barrier Network. 2003. Geomorphological monitoring workshops Report. NPS Internal Report.
- Psuty, N. P., K. Ames, A. Habeck, and G. Liu. 2018. Sediment budget and geomorphological evolution of the estuarine dune-beach system on three nourished beaches, Delaware Bay, New Jersey. *Geosciences* 9(1):16.
- Psuty, N. P., P. Dennehy, T. Silveira, and N. Apostolou. 2010b. 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. National Park Service, Fort Collins, CO.
- Psuty, N. P., M. Duffy, J. F. Pace, D. E. Skidds, and T. M. Silveira. 2010a. Northeast Coastal and Barrier Network geomorphological monitoring protocol: Part I—ocean shoreline position. Natural Resource Report NPS/NCBN/NRR—2010/185. National Park Service, Fort Collins, Colorado.
- Psuty, N. P., and D. D. Ofiara. 2002. Coastal hazard management: Lessons and future directions from New Jersey. Rutgers University Press, New Brunswick, NJ.
- Psuty, N. P., and J. P. Pace. 2009. Sediment management at Sandy Hook, NJ: An interaction of science and public policy. *Geomorphology* 104:12-21.
- Psuty, N. P., and T. M. Silveira. 2010. Global climate change: An opportunity for coastal dunes? *Journal of Coastal Conservation* 14(2):153-160.
- Psuty, N. P., T. M. Silveira, A. J. Spahn, D. Skidds, K. Ames, and G. Liu. 2022. Northeast Coastal and Barrier Network geomorphological monitoring protocol: Part II—coastal topography, standard operating procedures version 2.00. Northeast Coastal and Barrier Network, National Park Service, Kingston, RI. Available at: <https://irma.nps.gov/DataStore/Reference/Profile/2293040> (accessed 18 March 2022).
- Rader, A. M., A. J. Pickart, I. J. Walker, P. A. Hesp, and B. O. Bauer. 2018. Foredune morphodynamics and sediment budgets at seasonal to decadal scales: Humboldt Bay National Wildlife Refuge, California, USA. *Geomorphology* 318:69-87.
- Rangel-Buitrago, N. G., G. Anfuso, and A. T. Williams. 2015. Coastal erosion along the Caribbean coast of Colombia: Magnitudes, causes, and management. *Ocean & Coastal Management* 114:129-144.
- Rodriguez, A. H. 2004. Needs assessment, creation, and utilization of the coastal geotoolbox. Masters Thesis. University of Rhode Island, Department of Natural Resources Science.

- Rogers, S. S., G. Giese, and M. Adams. 2009. Anomalous accretion along outer Cape Cod shoreline possibly linked with eolian transport associated with parabolic dune field. *Geological Society of America Abstracts with Programs* 41(3):85.
- Roman, C. T., and K. F. Nordstrom. 1988. The effect of erosion rate on vegetation patterns of an East Coast barrier island. *Estuarine, Coastal and Shelf Science* 26:233-242.
- Roman, C. T., and N. E. Barrett. 1999. Conceptual framework for the development of long term monitoring protocols at Cape Cod National Seashore. USGS Patuxent Wildlife Research Center. Cooperative National Park Service Studies Unit, Narragansett, RI.
- Ruggiero, P., G. M. Kaminsky, G. Gelfenbaum, and B. Voigt. 2005. Seasonal to interannual morphodynamics along a high-energy dissipative littoral cell. *Journal of Coastal Research* 21(3):553-578.
- Short, A. D. Editor. 1999. *Handbook of beach and shoreface morphodynamics*. Wiley and Sons, New York, NY.
- Short, A. D. and A. C. Trembanis. 2004. Decadal scale patterns in beach oscillation and rotation, Narrabeen Beach, Australia - time series, PCA and wavelet analysis. *Journal of Coastal Research* 20(2):523-532.
- Stevens, S., B. Milstead, M. Albert, and G. Entsminger. 2005. Northeast Coastal and Barrier Network Vital Signs Monitoring Plan. Technical Report NPS/NER/NRTR—2005/025. National Park Service. Boston, MA.
- Taylor, Wiseman, and Taylor. 1993. GPS Survey Report. Taylor, Wiseman and Taylor Engineering Company, Mount Laurel, NJ.
- Trenhaile, A. S. 1997. *Coastal dynamics and landforms*. Oxford University Press, New York, NY.
- Valentin, H. 1952. Die Küstern der Erde. *Petermanns Geographische Mitteilungen, Ergänzungsheft* Nr. 246.
- Van der Lee, W. T. B. 2009. Practical experiences in monitoring and dynamic preservation of the Dutch coast: A case study. Pages 85-94 in: Pye, K. and W. Ritchie, Eds. *The measurement of coastal change. Proceedings of the St. Fergus Symposium*. Aberdeen Institute for Coastal Science and Management, Aberdeen, UK.
- Walker, H. J. 1990. The coastal zone. Pages 271-294 in: Turner, B. L., editor. *The Earth as transformed by human action*. Cambridge University Press, Cambridge, UK.
- Walker, I. J., R. Davidson-Arnott, B. Bauer, P. Hesp, I. Delgado-Fernandez, J. Ollerhead, and T. Smyth. 2017. Scale-dependent perspectives on the geomorphology and evolution of beach-dune systems. *Earth Science Reviews* 171:220-253.

Warrick, R. A., E. M. Barrow, and T. M. L. Wigley, editors. 1993. Climate and sea level change: observations, projections and implications. Cambridge University Press, Cambridge, UK.

Zeigler, J. M., H. J. Tasha, and G. S. Giese. 1964. Erosion of the cliffs of outer Cape Cod: Tables and graphs. Woods Hole Oceanographic Institution, No. 64-21. Woods Hole, MA.

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

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1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525