



Inventory of Coastal Engineering Projects in Cape Hatteras National Seashore

Natural Resource Technical Report NPS/NRSS/GRD/NRTR—2013/713



ON THE COVER

Hatteras Island, Cape Hatteras National Seashore, NC

Photograph by: Kate Dallas

Inventory of Coastal Engineering Projects in Cape Hatteras National Seashore

Natural Resource Technical Report NPS/NRSS/GRD/NRTR—2013/713

Kate Dallas

Oregon State University
104 CEOAS Administration Building
Corvallis, OR 97331

Michael Berry, Peter Ruggiero

Oregon State University
104 CEOAS Administration Building
Corvallis, OR 97331

March 2013

U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado publishes a range of reports that address natural resource topics of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Technical Report Series is used to disseminate results of scientific studies in the physical, biological, and social sciences for both the advancement of science and the achievement of the National Park Service mission. The series provides contributors with a forum for displaying comprehensive data that are often deleted from journals because of page limitations.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner. This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

Views, statements, findings, conclusions, recommendations, and data in this report do not necessarily reflect views and policies of the National Park Service, U.S. Department of the Interior. Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the U.S. Government.

This report is available from the Geologic Resources Division and the Natural Resource Publications Management website (<http://www.nature.nps.gov/publications/nrpm/>). The report and accompanying Geographic Information System (GIS) project can also be accessed through the Integrated Resource Management Applications Portal website (<http://irma.nps.gov>).

Please cite this publication as:

Dallas, K., M. Berry, and P. Ruggiero. 2013. Inventory of coastal engineering projects in Cape Hatteras National Seashore. Natural Resource Technical Report NPS/NRSS/GRD/NRTR—2013/713. National Park Service, Fort Collins, Colorado.

Contents

	Page
Figures.....	v
Tables.....	vii
Appendices.....	vii
Abstract.....	ix
Acknowledgments.....	xi
Introduction.....	1
Maintenance of Natural Processes.....	2
Restoration of Natural Processes.....	2
Construction of Facilities.....	2
Replacement of Facilities.....	3
Cooperative Conservation.....	3
Methods.....	5
Results.....	7
Background.....	8
Setting.....	9
Dune Construction.....	10
Bodie Island.....	12
Nags Head.....	12
Oregon Inlet.....	16
Hatteras Island.....	17
Pea Island.....	17
Rodanthe & Avon.....	19
Buxton, Cape Hatteras Lighthouse, and Frisco.....	21

Contents (continued)

	Page
Hatteras Village	23
Ocracoke Island	25
Impacts	28
Artificial Dune Construction	28
Oregon Inlet	31
Cape Hatteras Lighthouse Area	34
Discussion and Recommendations for Further Study and Management	36
Literature Cited	38

Figures

	Page
Figure 1. Percent of total structure length (by structure type) in and adjacent to CAHA.	7
Figure 2. Location map for CAHA with places mentioned in the report.....	8
Figure 3. Conceptual diagram illustrating barrier island migration.....	9
Figure 4. Installation of sand fencing in 1937.	11
Figure 5. Constructed dunes (seen here north of Rodanthe in March 2012) parallel Highway 12 nearly the entire length of CAHA.	11
Figure 6. Bodie Island and northern Pea Island structure map.	13
Figure 7. Timber pilings that act as a groin were built in 1960 to protect an outfall pipe at the northern boundary of CAHA.....	14
Figure 8. The soundside shoreline of Oregon Inlet Fishing Center (middle foreground) and U.S. Coast Guard Station (top right) (#5–23 Figure 9) has bulkheads, piers, and a revetment.	14
Figure 9. Oregon Inlet Fishing Center structure map.	15
Figure 10. The Herbert Bonner Bridge across Oregon Inlet and the northern end of Pea Island.....	16
Figure 11. Graph of sediment dredged from Oregon Inlet between 1960 and 2009.	17
Figure 12. Inlet on northern Pea Island that formed during Hurricane Irene in 2011.	18
Figure 13. The Hatteras Island Fishing Pier in Rodanthe.....	19
Figure 14. Southern Hatteras Island structure map.....	20
Figure 15. View from the top of the Cape Hatteras Lighthouse.....	22
Figure 16. Steel sheet-pile groin (that was built in 1969 to protect a Navy facility) at the former location of the Cape Hatteras Lighthouse (#31 Figure 14).	22
Figure 17. The Frisco Pier has been extensively damaged by storms and was closed in 2009 (#32 Figure 14).	23
Figure 18. Hatteras Island breach near Hatteras Village after Hurricane Isabel in 2003.....	23

Figures (continued)

Figure 19. The Hatteras Ferry Landing Marina and Hatteras Island U.S. Coast Guard Station.	24
Figure 20. Southern end of Hatteras Island and northern end of Ocracoke Island structure map.....	24
Figure 21. Ocracoke Ferry Landing (left) and Hatteras Ferry Landing Marina and Coast Guard Station (right) structure maps.	25
Figure 22. The ferry landing on northern Ocracoke Island (#43–48 Figure 21).	26
Figure 23. Ocracoke Harbor, known locally as Silver Lake.....	26
Figure 24. Typical cross sections of a (A) natural barrier island and (B) stabilized barrier island show how dune stabilization may effect island morphology.....	28
Figure 25. 1852 historic shoreline and subsequent Highway 12 locations in 1955, 1974, 1999 and 2003 in the Avon-Buxton area overlain on a 2003 aerial imagery.	29
Figure 26. Comparison of Ocracoke Island (left) and Portsmouth Island (right).	30
Figure 27. Map showing historic shorelines from 1849–1998.	31
Figure 28. Oregon Inlet (A) overview map (from Bing Maps 2012), (B) southern side (Pea Island) and (C) northern side (Bodie Island).	32
Figure 29. Oregon Inlet historic shorelines from 1949–2007.....	33
Figure 30. Cape Hatteras Lighthouse and groins.....	34
Figure 31. Historic shorelines from 1852 to 1980 around the Cape Hatteras Lighthouse.....	35
Figure 32. Photograph shows the proximity of the lighthouse to the ocean prior to relocation (circa 1990).	36

Tables

	Page
Table 1. Coastal structures in and adjacent to Cape Hatteras National Seashore.	7
Table 2. Timeline of shoreline protection measures in the Buxton/Cape Hatteras Lighthouse area.	21

Appendices

	Page
Appendix A: Glossary.....	44
Appendix B: Coastal Structure Data.....	46
Appendix C: Beach Nourishment & Dune Construction Data	48
Appendix D: Dune Renourishment (repair) Data	50
Appendix E: Dredging Data for Oregon Inlet.....	52
Appendix F: Dredged Sediment Placement Data for Pea Island	54

Abstract

A reconnaissance-level investigation, analysis and inventory of coastal engineering projects in eight coastal national parks were completed by Oregon State University with funding provided by the National Park Service Geologic Resources Division. The coastal national parks inventoried in this study include:

1. Cape Hatteras National Seashore
2. Colonial National Historical Park
3. Fort Matanzas National Monument
4. Fort Raleigh National Historic Site
5. Gateway National Recreation Area
6. Golden Gate National Recreation Area
7. Olympic National Park
8. San Francisco Maritime National Historical Park

This report includes information on coastal engineering projects identified in, or immediately adjacent to, Cape Hatteras National Seashore (CAHA). The report serves as a supplement to a Geographic Information Systems (GIS) database (the GIS data are available online: <http://irma.nps.gov>).

A total of 72 coastal engineering projects were identified in and adjacent to Cape Hatteras National Seashore (CAHA). Of the total, 48 are coastal structures, 17 are beach nourishment projects, 5 are dredging projects, and 2 are dune construction projects. Together the 48 coastal structures extend for 5,723 m (18,360 ft), armoring 1% of the park's ocean shoreline due primarily to the structure's soundside locations and the park's lengthy ocean shoreline.

Beach nourishment projects have emplaced over 7.8 million m³ (10.2 million yd³) of sediment on CAHA beaches from 1962 to 2011. Dredging at three inlets and two marinas has removed or bypassed an unknown, but likely significant, volume of material. At Oregon Inlet, nearly 9.2 million m³ (12 million yd³) of sediment was dredged from the inlet system between 1960 and 2012 (excludes sidecast dredging). Over 4.3 million m³ (5.7 million yd³) of this total was placed offshore from 1960–1989. The remaining 4.8 million m³ (6.3 million yd³) was deposited on northern Pea Island beaches and in the nearshore region from 1997–2010. In addition, artificial dunes built in the 1930s and 1950s extend the entire length of the park and are regularly maintained for limited purposes after storms.

Artificial dune construction has interfered with natural barrier island evolution processes (i.e. overwash and inlet formation), resulting in island width reduction, changes to beach

morphology, and habitat alterations. Coastal structures at Oregon Inlet have altered the natural inlet migration, contributing to the need for channel dredging and beach nourishment projects. Coastal structures that were installed to protect a former Navy facility near the Cape Hatteras Lighthouse have locally stabilized the shoreline and created a beach inflection point.

Acknowledgments

This project was funded by the National Park Service's Geologic Resources Division through the Pacific Northwest Cooperative Ecosystem Studies Unit Task Agreement (J8W07110009) to Oregon State University. Spencer Rogers, Thayer Broili, Courtney Schupp, Andy Coburn, and Linda York provided valuable peer reviews.

We would like to thank Randy Swilling, the Natural Resource Program Manager at Cape Hatteras, for helping us arrange a field visit to the park. Special thanks goes to pilot John Kimmel for taking us on an aerial tour of the park. Other park staff, including Thayer Broili, Doug Stover, Patrick Gamman and Laura Pickens, also provided assistance during our field visit and helped with acquisition of imagery. Dennis McGuiness (retired CAHA maintenance chief) provided a wealth of knowledge on the history of coastal structures in CAHA.

John Abel and Lancelot Winslow of the North Carolina Department of Transportation (NCDOT) helped with background information related to NCDOT structures and dredging operations. Dee Dee Fauser of the U.S. Army Corps of Engineers Wilmington District office provided dredging records for federal channels adjacent to CAHA for the last 10 years, which greatly improved the report.

Introduction

The Coastal Engineering Inventory (CEI) project aims to inventory, catalog and map coastal engineering projects in and adjacent to coastal units of the National Park Service (NPS). The primary projects that were inventoried include coastal structures, dredge and fill projects, and beach nourishment and dune construction projects. In this phase of the inventory coastal engineering projects were identified in eight coastal national parks. Prior to this study another report (Coburn et al. 2010) documented coastal engineering projects in ten additional coastal national parks. The report and GIS data are available online at <http://irma.nps.gov>.

In this phase of the NPS CEI project, a qualitative impacts analysis was also performed to help better understand the extent of human-altered coastal areas within each respective park. This section describes the impacts of coastal engineering projects and their influence on natural sediment transport processes. In addition to highlighting major engineering projects that are impacting local and regional sediment transport, we have also included related information pertaining to current park management concerns as expressed during the site visit.

Coastal engineering projects are usually motivated by a desire to protect the backshore environment from erosion or alter the coastal zone for a particular purpose (i.e. maintain a navigation channel, develop roadways, or restore wetlands). In order to fulfill project objectives, a suite of engineering solutions are available that are typically categorized into hard and soft engineering projects. Coastal engineering solutions often combine both hard and soft engineering approaches, such as when beaches are nourished following breakwater construction.

Hard engineering solutions include the construction of seawalls, revetments, breakwaters, sills, and bulkheads to protect the backshore from coastal erosion and sometimes flooding (see the Glossary in Appendix A for definitions). Jetties and groins are also classified as hard engineering projects and are used to alter the sediment transport regime by trapping sediment. Impacts from hard structures are highly site dependent, but may include the loss of sediment supplied to downdrift areas, localized scour in front of and at the downdrift end of structures, visual impacts, placement losses, reduction in beach access, and the alteration or reduction of habitat.

Soft engineering solutions include non-structural means of stabilizing the backshore or changing coastal environments through beach nourishment, dune construction, dredging, or filling. These methods add or redistribute sediment within the system and are used to widen sediment-starved beaches, maintain navigable waterways, protect coastal infrastructure, and restore wetlands. As with hard solutions, impacts vary significantly by project and location. Soft engineering projects may impact hydrodynamic and sediment transport processes, beach morphology, aquatic ecosystems, and/or beach habitats.

The overall goal of this project is to develop a greater understanding of the coastal engineering modifications in the National Park System. Along coastlines expected to be impacted by climate change, structurally modified shorelines will likely respond differently than natural coastlines, which may have a more dynamic response to coastal erosion and sea level rise. An inventory of coastal engineering modifications will provide information to allow resource managers to make better decisions about how to preserve NPS resources, establish baselines, develop desired future conditions, and balance the protection of historic resources and infrastructure with the

preservation of natural systems. All of these actions will improve the ability of the NPS to manage coastal park units in accordance with NPS policies. The main NPS policies relevant to coastal engineering projects are summarized below (see *NPS Management Policies 2006* for more detail).

Maintenance of Natural Processes

Generally, NPS policy requires that natural coastal processes in parks, such as erosion, shoreline migration, deposition, overwash, and inlet formation, be allowed to continue without interference (*NPS Management Policies* § 4.8.1.1 2006). The NPS may intervene in these processes only in limited circumstances, such as when there is no other feasible way to protect natural resources, park facilities, or historic properties (*NPS Management Policies* § 4.8.1 2006).

Restoration of Natural Processes

In parks where pre-existing or new activities or structures have altered and/or are currently altering coastal dynamics, ecosystems, tidal regimes, and sediment transport rates, the NPS policy is to investigate, in consultation with appropriate state and federal agencies, alternatives for mitigating the effects of such projects and for restoring natural conditions (*NPS Management Policies* § 4.8.1.1 2006). NPS restoration actions in human-disturbed areas seek to return the area to the natural conditions and processes characteristic of the ecological zone in which the damaged resources are situated, as called for by park management plans (*NPS Management Policies* § 4.1.5 and § 4.4.2.4 2006). An example would be the restoration of shoreline processes.

Park landscapes disturbed by natural events, such as hurricanes, are allowed to recover naturally unless manipulation is necessary to 1) mitigate for excessive disturbance caused by past human effects, 2) preserve cultural and historic resources as appropriate based on park planning documents, or 3) protect park developments or the safety of people. (*NPS Management Policies* § 4.1.5 and § 4.4.2.4 2006).

Construction of Facilities

Generally, the NPS must avoid the construction of buildings, roads, and other development that will cause unacceptable impacts on park resources and values (*NPS Management Policies* § 9.1 2006). Development will not compete with or dominate park features or interfere with natural processes (*NPS Management Policies* § 9.1.1.2 2006). In shoreline areas, this means that new developments will not be placed in areas subject to wave erosion or active shoreline processes unless 1) the development is required by law; or 2) the development is essential to meet the park's purposes, as defined by its establishing act or proclamation, and

- no practicable alternative locations are available;
- the development will be reasonably assured of surviving during its planned life span without the need for shoreline control measures; and
- steps will be taken to minimize safety hazards and harm to property and natural resources (*NPS Management Policies* § 4.8.1.1 2006).

Replacement of Facilities

Park development that is damaged or destroyed by a hazardous or catastrophic natural event will be thoroughly evaluated for relocation or replacement by new construction at a different location. If a decision is made to relocate or replace a severely damaged or destroyed facility, it will be placed, if practicable, in an area that is believed to be free from natural hazards (NPS *Management Policies* § 9.1.1.5 and § 4.1.5 2006).

Cooperative Conservation

Under NPS policy, park superintendents are required to monitor state government programs for managing state-owned submerged lands and resources within NPS units. When there is potential for such programs to adversely impact park resources or values, superintendents will make their concerns known to appropriate state government officials and encourage compatible land uses that avoid or mitigate potential adverse impacts. When federal acquisition of state-owned submerged lands and resources within NPS units is not feasible, NPS will seek to enter into cooperative agreements with state governments to ensure the adequate protection of park resources and values (NPS *Management Policies* §3.4 2006).

In addition, the NPS has the authority under 36 C.F.R. §1.2(a)(3) to apply general NPS regulations, such as special use permit requirements, on or in waters that are subject to the jurisdiction of the United States, or in areas within their ordinary reach up to the mean or ordinary high water line, even if the submerged lands are non-federally-owned and regardless of whether the park has exclusive, concurrent, or proprietary jurisdiction. Waters subject to the jurisdiction of the United States refers to three types of waters: (1) navigable (as defined in 33 C.F.R. § 2.36(a), (2) non-navigable but located on lands for which the U.S. has acquired title or control and has accepted or retained exclusive or concurrent jurisdiction, and (3) waters made subject to U.S. jurisdiction by certain international agreements and statutes (33 C.F.R. § 2.38).

Methods

Coastal engineering terminology was adapted from the NPS Coastal Engineering Inventory pilot project (Coburn et al. 2010) and through discussion with the NPS Geologic Resources Division. The NPS selected eight coastal national parks in which coastal engineering projects were identified, inventoried and mapped. Projects in the inventory include coastal structures, dredging, filling, beach nourishment, and dune construction.

A digital park boundary shapefile for all of the inventoried parks was downloaded from the NPS Integrated Resources Management Applications Portal (<https://irma.nps.gov>). Georeferenced digital orthophoto imagery was obtained from each park and added to ArcMap 10.0 to create a basemap.

A visual inspection of the orthophoto imagery was completed and locations of all discernible coastal structures were digitized using ArcMap. A site visit to the park, along with staff correspondence, was used to complement and confirm initial findings based on examination of the imagery and to identify other coastal engineering projects. A comprehensive online and hardcopy literature search was undertaken to obtain attribute data for each project (year of construction, material, year of maintenance, cost, lead construction agency, and volume). Unless otherwise specified, costs presented in the report are in project-year dollars.

A coastal engineering project was considered distinct if there was any discernible, physical separation between it and an adjacent engineering project. A series of bulkheads constructed by individual interests, for example, would be classified as one structure as long as no identifiable gaps were observed between them. Some projects, such as dredge projects that place dredge spoil on the beach, serve multiple purposes (i.e., dredging and beach nourishment). In these cases, the primary reason for the project was ascertained and the project was classified accordingly. Projects that occurred repeatedly in one place (e.g. inlet dredging) were counted as one project.

Overview statistics were calculated to summarize the coastal engineering projects within each park. The percentage of shoreline armored by coastal structures was found by totaling the length of bulkheads, breakwaters, groins, revetments, seawalls, and sills and dividing it by the total length of shoreline. Structure length and shoreline length were determined using ArcMap. The structure length used in calculating the percentage of shoreline armored for individual structures was merely the length of the structure. For groin fields (defined here as three or more groins) the length was set as the length of the groin field along the shoreline, while for jetties the width of the mouth of the inlet was used.

An ArcGIS 10.0 file geodatabase for each park was compiled using ArcMap. Each geodatabase includes a park boundary feature class and identified coastal engineering projects separated into three feature classes: 1) coastal structures 2) dredge and fill projects and 3) beach nourishment and dune construction projects. The GIS projects also contain an ArcMap document for data viewing (.mxd), data layer files (.lyr), FGDC-compliant metadata (.xml and .txt), FAQ metadata (.html), a table attribute file (.pdf), and a README file (.pdf). Location information for dredge, fill, beach nourishment, and dune construction projects was often non-existent or vague. Therefore, not all of these projects are included in the GIS data, and those that are included have only approximate locations.

Results

Seventy-two coastal engineering projects were identified in, and adjacent to, Cape Hatteras National Seashore (CAHA). Of this total, 48 are coastal structures that extend 5,723 m (18,360 ft) (Table 1 and Figure 1). Only 5 coastal structures (all of which are groins) are on the ocean side of the barrier islands. Together these groins armor nearly 1,400 m (4,600 ft) of shoreline, or roughly 1% of the approximately 125-kilometer (78 mi) long ocean shoreline in CAHA. However, since groins are shore-perpendicular, the length of shoreline impacted (i.e. armored) by them is likely to be greater. Impacts of the terminal groin at Oregon Inlet, for example, probably extend farther downdrift than the length of the groin. A summary of all of the structures within and adjacent to CAHA is presented in Appendix B.

Table 1. Coastal structures in and adjacent to Cape Hatteras National Seashore.

¹ Structures	Number	Length (m)
Bulkhead	8	2,073
Groin	5	1,377
Pier	31	1,586
Revetment	4	687
TOTAL	48	5,723

¹See the Glossary in Appendix A for structure definitions.

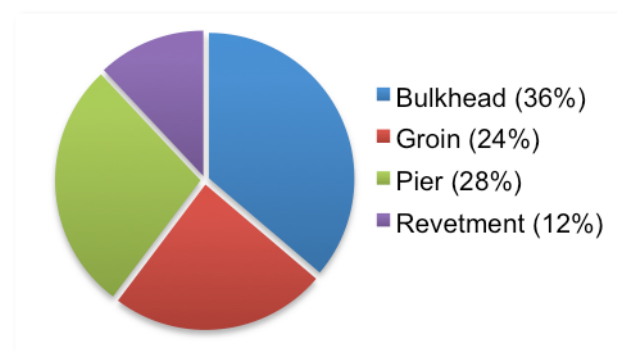


Figure 1. Percent of total structure length (by structure type) in and adjacent to CAHA.

Seventeen of the engineering projects are beach nourishment projects that have placed a minimum of 7.8 million m³ (10.2 million yd³) of sediment from 1962 to 2011 at a cost of over \$47 million. This total includes sediment placed for shoreline stabilization efforts and to close inlets, but does not include dredged sediment placed on beaches (these projects are classified as dredging since their primary purpose was dredging.). The total volume placed is a minimum value because some of the identified projects did not have volume information and there are likely additional nourishment projects that have occurred for which we were unable to find any documentation.

Artificial dunes built in the 1930s and 1950s extend the entire length of the park. Records were found for 10 episodes of dune repair from 1962 to 2005, and additional undocumented repairs have likely occurred, primarily after storms. See Appendices C and D for a summary of beach nourishment and dune construction/repair projects in CAHA and adjacent areas.

Dredging regularly occurs at Oregon Inlet, the Hatteras Ferry Landing Marina in Hatteras Village, Rollison Channel (near Hatteras Village), and Ocracoke Inlet (Figure 2). At Oregon Inlet, over 9.1 million m³ (12 million yd³) of sediment was dredged from the navigation channel and bar between 1960 and 2012 (does not include sidecasted sediment, see Appendix E for details). Prior to 1990, sediment dredged from the inlet system was placed offshore (total of 4.3 million m³ [5.7 million yd³]); since 1990, dredged sediment has been placed on northern Pea Island beaches and in the nearshore (total of 4.8 million m³ [6.3 million yd³]). An additional 3.1 million m³ (4.1 million yd³) was placed within the beach and nearshore between 1990 and 1997, with most of the sand dredged from the inlet system (Appendix F).

Background

Cape Hatteras National Seashore is part of the Outer Banks of North Carolina, a barrier island chain that stretches for more than 280 km (175 mi) along the Atlantic coast of North Carolina (Figure 2). CAHA was authorized in August 1937 as the nation's first national seashore to preserve the wild and primitive character of the dynamic barrier islands, and was officially established in January 1953 (Binkley 2007).



Figure 2. Location map for CAHA with places mentioned in the report. Yellow shading shows park property (image from ESRI Bing Maps basemap layer 2012).

CAHA contains 143 km² (35,400 ac) of land across three barrier islands: Bodie, Hatteras, and Ocracoke (Figure 2) (Gregory and Smith 2011). Most of the islands within the seashore are <400 m (<1,312 ft) wide, with the widest part being about 4 km (2.5 mi) between Buxton and Frisco (Figure 2) (Pendleton et al. 2004). The islands are connected by North Carolina State Highway 12, which was built in the 1950s (Riggs et al. 2009a), and by the Hatteras-Ocracoke ferry. Highway 12 passes through eight villages that lie within the boundary of the seashore, but are not managed by the NPS. The northern section of Hatteras Island between Oregon Inlet and the village of Rodanthe is the Pea Island National Wildlife Refuge (known locally as Pea Island) (Figure 2). Pea Island lies within the CAHA boundary, but is administered by the U.S. Fish and Wildlife Service.

Setting

Barrier islands are low-lying, dynamic landforms that are constantly evolving in response to storms, ocean currents, sea level changes, waves and wind. From 1945 to 1986 the Outer Banks ocean shoreline moved landward at an average rate of 1.4 m/yr (4.5 ft/yr) (Inman and Dolan 1989). Overwash and inlet formation, which typically occur due to significant storm surges, are the most important processes in the transgression, or landward migration, of the Outer Banks (Dolan and Lins 1985). Storm surges that carry water and sediment onto and across the island build back-barrier flood-tide deltas and deposit overwash fans, which contribute to landward barrier migration (Figure 3) and help to maintain island width and elevation (Dolan and Lins 1985, Mallinson et al. 2008, Riggs et al. 2009b).

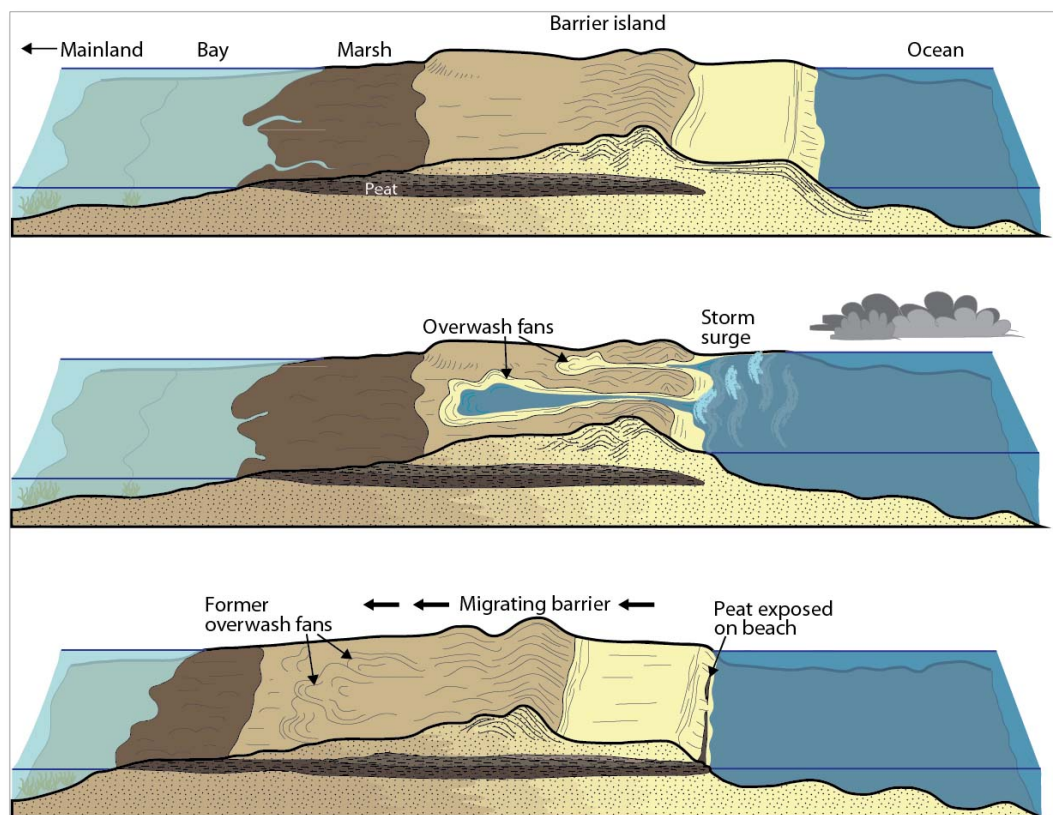


Figure 3. Conceptual diagram illustrating barrier island migration (graphic by Trista Thornberry-Ehrlich [Colorado State University]).

The barrier islands are also moving southward under the influence of wave driven sediment transport. The region around CAHA experiences the highest wave energy along the East Coast of the United States, with an annual average significant wave height of 1 m (3.2 ft) and peak wave period of 9 sec (NCCRC 2010a). This results in a very high net southerly-directed longshore transport, estimated to be 590,000 m³/yr (772,000 yd³/yr) (Inman and Dolan 1989). In the past 400 years more than 30 inlets have opened and closed along the Outer Banks (Dolan and Lins 1985, Mallinson et al. 2008). During the past 125 years only three inlets have remained opened continuously: Oregon Inlet, Hatteras Inlet, and Ocracoke Inlet (Figure 2) (Dolan and Lins 1985).

The geology of the Outer Banks reflects the rise and fall of relative sea level over time. Along the modern North Carolina barrier islands a thin layer of modern sands cover marsh peats, tidal flat muds, fluvial sands and gravels, bay-fill sands and muds, flood tidal delta sands, and inlet-fill sands and gravels (Riggs et al. 1995). A complex mix of marine, coastal, estuarine, fluvial, and other Coastal Plain deposits, including peat, mud, sands, gravels, and shell beds, underlies the modern barrier islands (Schupp and Thornberry-Ehrlich in press). For a detailed review of the park's geology see the CAHA Geologic Resources Inventory Report (Schupp and Thornberry-Ehrlich in press) and its associated geologic map (available at <http://www.nature.nps.gov/geology/inventory/>).

Nor'easters, tropical storms, and hurricanes have all caused extensive erosion and overwash at CAHA. The cumulative effect of high tide, storm surge, and large waves during these events can produce total water levels higher than the dunes, resulting in overwash, inlet formation, extensive infrastructure damage and potential loss of life (Dolan and Lins 1985). Hurricane Irene made landfall south of CAHA on August 27, 2011 and produced storm surges up to 2.4 m (8 ft) above normal tide level, creating five breaches across Hatteras Island (USGS 2011). Hurricane Sandy hit CAHA during late October 2012 and affected roughly 30% of the dunes within the park (with respect to their flood prevention function) (Thayer Broili, NPS, email, 2-13-13).

Tides in the region are semidiurnal with a mean range of 0.91 m (3.0 ft) at the Oregon Inlet tide gauge (NOAA 2012). The longest record of sea level data in the area is at the Duck, North Carolina tide gauge, located approximately 50 km (31 mi) northwest of Oregon Inlet. The Duck gauge shows a 4.59 ± 0.94 mm/yr (0.18 ± 0.04 in/yr) rise in sea level from 1978 to 2011 (NOAA 2012), a value that is significantly higher than the average rate of global sea level rise rate, 1.7 mm/yr (0.07 in/yr) for the 20th century (Church and White 2006). Rates of sea level rise along the North Carolina coast vary as a function of latitude, with higher rates of rise in the north, and lower rates in the south (Zervas 2004). More information on sea level trends for the State of North Carolina can be found in Zervas (2004) and the North Carolina Coastal Resource Commission's sea level rise assessment (NCCRC 2010b).

Dune Construction

In response to rapid erosion, the NPS, in collaboration with the Civilian Conservation Corps and Works Project Administration, began a massive sand fixation program in 1937 (Figure 4) (Binkley 2007). Sand fences were erected along 174 km (108 mi) of the North Carolina coast from the Virginia State Line to southern Hatteras Island, trapping windblown sand and forming barrier dunes (Figure 5). The dunes were then further stabilized with vegetation. By 1941 the project had installed 1,250 km (780 mi) of sand fencing, planted 26 km² (6,510 ac) of grass and over 3 million trees and shrubs, and built 120 km (75 mi) of dikes and jetties at a cost over \$1.7

million (Binkley 2007). Dune height ranged from 3–8 m (10–26 ft) and dune widths were 25–100 m (82–328 ft) (Birkemeier et al. 1984).



Figure 4. Installation of sand fencing in 1937 (NPS photo from Dolan 1985).



Figure 5. Constructed dunes (seen here north of Rodanthe in March 2012) parallel Highway 12 nearly the entire length of CAHA (image by Kate Dallas).

In October 1956 the NPS resumed dune construction, extending the artificial dunes to the southern tip of Ocracoke Island and rebuilding the 1930s dune system. After the Ash Wednesday storm destroyed portions of the dune on March 7, 1962, the dune line was completely restored along the entire length of the National Seashore (NPS 1963).

The constructed dunes have led to the artificial stabilization of the barrier islands, which has promoted coastal development and required the dunes to be rebuilt after each major storm at a significant cost (Riggs et al. 2009). The dunes impede the natural island-building processes of inlets and overwash that historically built island width and elevation. The net result is island narrowing and increased exposure to overwash and future inlet formation (Riggs et al. 2009a) (see Impacts section). Soundside erosion has also contributed to island narrowing.

Storms frequently cut through the dunes and deposit large volumes of sand on Highway 12. The North Carolina Department of Transportation (NCDOT) regularly rebuilds the dunes to protect the highway. CAHA does not allow or promote dune reconstruction, however. All of the

reconstruction activities occur within the highway right-of-way and are not regulated by the park (Randy Swilling, CAHA Natural Resource Program Manager, email, 10-19-12). The NCDOT has requested and permitted the relocation of various sections of the Highway 12 right-of-way as the location of the highway changes. Within Pea Island National Wildlife Refuge, the U.S. Fish and Wildlife Service has rejected these requests in recent years (Spencer Rogers, UNCW, email, 2-13-13).

Bodie Island

Nags Head

The Town of Nags Head has two large recreational piers, Jennette's Pier (#1 Figure 6) and the Nags Head Fishing Pier (#2 Figure 6), both located outside of the park. Jennette's Pier was the first pier built in the Outer Banks in 1939. The pier was rebuilt in 1947 and 1963, remodeled in 1996, and demolished in 2008 to be replaced by the current pier, which was completed in 2011. Nags Head Fishing Pier, located in southern Nags Head, was constructed in 1947, rebuilt after the Ash Wednesday Storm in 1963, and has been repaired many times (Village Realty, Inc. 2012).

The Town of Nags Head completed two beach nourishment projects in 2001 and 2011. The first was a small project that included placement of $152,911 \text{ m}^3$ ($200,000 \text{ yd}^3$) of sediment dredged from Roanoke Sound during two episodes in 2001–2002 (WCU 2012). The second was a large beach nourishment project from May to October 2011 (CSE 2011). The 2011 project placed $3,528,517 \text{ m}^3$ ($4,615,126 \text{ yd}^3$) of sediment along 16 km (10 mi) of the city's beaches at a cost of \$36 million (CSE 2011). The sediment used in the project was dredged from a borrow area located approximately 0.9–4.5 km (0.6–2.8 mi) offshore of southern Nags Head (CSE 2011). The project was initiated to restore the beach for a minimum of ten years and replace sand lost during the delay in the startup of the federal Dare County beach erosion control project.

The 50-year federal Dare County project calls for 16.3 km (10.1 mi) of shoreline along Nags Head to be nourished initially with roughly $6,150,000 \text{ m}^3$ ($8,040,000 \text{ million yd}^3$) of sand and periodically renourished with $2,168,000 \text{ m}^3$ ($2,835,000 \text{ yd}^3$) (CSE 2011). While this federal project has been authorized, it is currently unfunded and has yet to be constructed. Although outside of the park, sediment placed along the Nags Head shoreline may affect park beaches as it moves down coast through littoral transport.



Figure 6. Bodie Island and northern Pea Island structure map. Blue line shows park boundary. Area in red box is enlarged in Figure 9 (image from ESRI Bing Maps basemap layer 2012).

At the boundary between the Town of Nags Heads and CAHA is a NCDOT concrete stormwater outfall pipe that is protected by timber pilings (labeled as a groin, #3 Figure 6 & Figure 7). Plan drawings from the NCDOT show that the outfall and pilings were proposed in early 1960s and were likely built soon thereafter. The outfall and pilings have been repaired over time, including the most recent repair in 2003 (John Abel, NCDOT, phone conversation, 10-25-12). Throughout the developed areas of CAHA there are additional ocean outfalls that may function as groins (total number unknown). However, they are typically buried in the beach and since they were not visible in our aerial imagery, they were not included in this study.

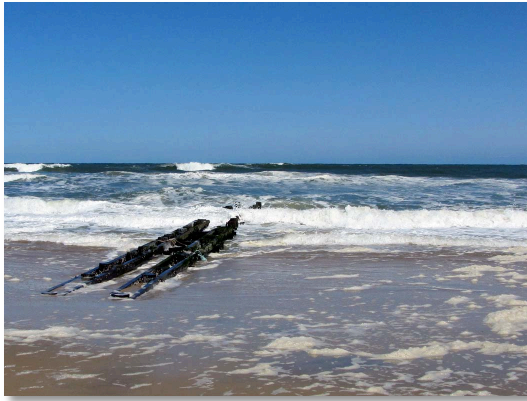


Figure 7. Timber pilings that act as a groin were built in 1960 to protect an outfall pipe at the northern boundary of CAHA (labeled as a groin, #3 Figure 6, image by Kate Dallas).

On the soundside of Bodie Island near the Bodie Lighthouse is a wooden pier used by the Off Island Hunting Club (#4 Figure 6). The hunting club formed in the early 1960s and the pier was originally built around the same time and has been repaired over time by the club, most recently after Hurricane Irene in 2011 (Dan Barker, President Off Island Gun Club, email, 10-23-12). Further south along the sound side of the island is the Oregon Inlet Fishing Center Marina and U.S. Coast Guard Oregon Inlet Station (Figure 8), which has bulkheads, piers, and a revetment.

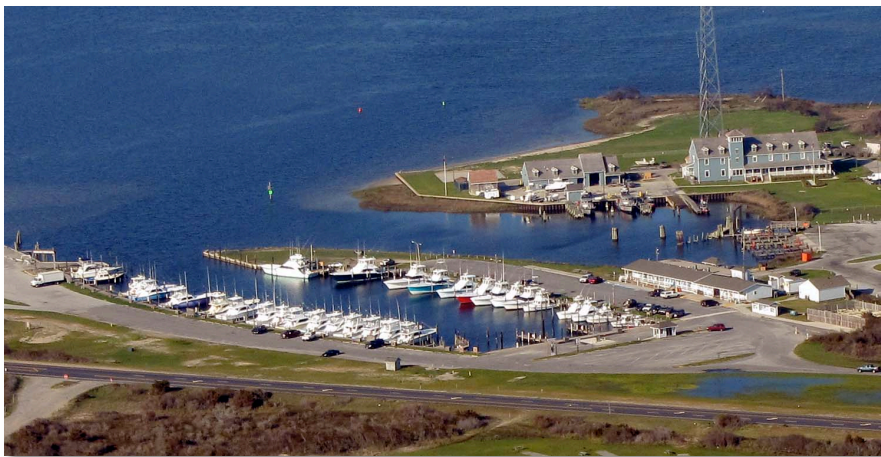


Figure 8. The soundside shoreline of Oregon Inlet Fishing Center (middle foreground) and U.S. Coast Guard Station (top right) (#5–23 Figure 9) has bulkheads, piers, and a revetment. View is to the southwest (image by Kate Dallas).

Before the Herbert Bonner Bridge (Figure 19) was built across Oregon Inlet, a ferry connected Bodie and Pea Islands. The ferry operated between the 1930s and 1964 and departed from what is now the Oregon Inlet Fishing Center basin (Dennis McGuiness, retired NPS, phone conversation, 10-25-12). The concrete ferry pier is still visible today (#11 Figure 9).

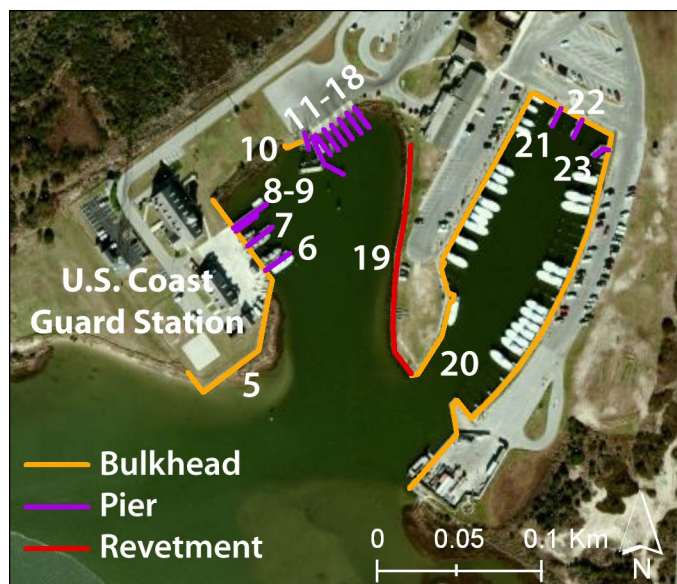


Figure 9. Oregon Inlet Fishing Center structure map (image from ESRI Bing Maps basemap layer 2012).

In 1953 a small marina was built on the site of the present day fishing center. Binkley (2007) reports that control over the fishing center and the southern end of Bodie Island were at the heart of the struggle to establish CAHA. In 1955 the land and marina were purchased by the NPS and the marina was subsequently leased to a private individual. Most of the original cement and timber bulkhead and the timber piers in the marina (#20–23 Figure 9) were built prior to December 1956 (Binkley 2007). The bulkhead has been repaired numerous times including repairs in 1966, 1979, and the mid 1980s (NPS 1966, NPS 1979, Binkley 2007). The rock revetment to the west of the marina was installed in the 1990s (#19 Figure 9) and the public docks (#11–18 Figure 9) were built in 1964 (FMSS database, accessed 12-19-12) and replaced in 2012 (Oregon Inlet Fishing Center staff, phone conversation, 10-5-12).

Storms have damaged structures in the basin, requiring repair or replacement. For example, all of the marina docks were replaced in 2011 following Hurricane Irene (Oregon Inlet Fishing Center staff, phone conversation, 10-5-12). No damage was reported in the basin following Hurricane Sandy in 2012 (Oregon Inlet Fishing Center staff, phone conversation, 1-3-13).

The Coast Guard station at Oregon Inlet is located in its fourth location since it began as a lifesaving station in 1883 (USCG 2012). The current station was built in 1990 for \$3.5 million (USCG 2012) and included construction of a concrete bulkhead on the eastern and southern shoreline, three timber piers, and a concrete boat ramp (#5–9 Figure 9) (Joseph Haskell, U.S. Coast Guard, phone conversation, 10-4-12). The northern pier (#9 Figure 9) was repaired in 2011 following Hurricane Irene.

Oregon Inlet

Oregon Inlet separates Bodie Island and the northern end of Pea Island (Figure 10) and is the only permanent tidal inlet between Rudee Inlet in Virginia Beach, Virginia, about 137 km (85 mi) to the north of Oregon Inlet, and Hatteras Inlet about 72 km (45 mi) to the south. The Herbert Bonner Bridge was built across the inlet in 1962–1963 (Riggs and Ames 2009) and is scheduled to be replaced soon. Oregon Inlet is a high-energy environment and is the primary route to the ocean for hundreds of commercial and recreational fishing vessels. From 1999 to 2001 an average of 311 commercial fishing boats used the inlet 3,900 times per year (USGAO 2012).



Figure 10. The Herbert Bonner Bridge across Oregon Inlet and the northern end of Pea Island. The terminal groin is visible in the middle of the image. View is to the northwest (image by Kate Dallas).

The inlet was opened by a hurricane in 1846 and by 1989 had migrated almost 4 km (2.5 mi) to the south (Riggs et al. 2009a). The dynamic nature of the inlet has required regular dredging and the U.S. Army Corps of Engineers (USACE) has maintained the navigation channel at Oregon Inlet since 1960 (Riggs et al. 2009a). From 1960 to 2001 the USACE spent approximately \$108 million (in 1997 dollars) on dredging costs at Oregon Inlet (USGAO 2002).

Historic data (1960–2001) from the Terminal Groin Study by the North Carolina Coastal Resources Commission (NCCRC 2010a) and recent data (2002–2012) from the USACE Wilmington District (Dee Dee Fauser, DVD, 1-28-13) shows that nearly 9.2 million m³ (12 million yd³) of sediment has been removed from Oregon Inlet by dredging between 1960 and 2012 (see Appendix E for details). This total includes only dredging activities that removed sediment from within the inlet system. Sidecast dredging (where dredged material is deposited about 305 m [1,000 ft] off the side of the dredge), dredging that occurred in channels within Pamlico Sound, and dredging where sediment was placed in the inlet's scour hole (occurred 2010–2012) are not included, since these projects did not remove material that might otherwise have bypassed the inlet naturally. Prior to 1990, sediment dredged from Oregon Inlet was placed

offshore; beginning in 1990, the dredged sediment was placed directly on the northern beaches and nearshore of Pea Island (see next section).

In 1970 Congress authorized the construction of two rock jetties at Oregon Inlet. Congress, however, has never appropriated funds for construction (USGAO 2002). Since the jetties were first authorized, there have been major disagreements among federal, state, and local government agencies and non-governmental organizations about potential environmental impacts and whether or not the project is economically justified (USGAO 2002). Currently there is no specific proposal or formulated project for Oregon Inlet.

In order to stabilize the inlet and maintain the attachment between the north end of Pea Island and the bridge, a 905-meter (2,970 ft) long terminal groin (Figure 10) and 420-meter (1,350 ft) long rock revetment were built from October 1989 to October 1991 at a cost of \$13.4 million (Riggs and Ames 2009, NCCRC 2010a) (#24 & 25 Figure 6). While the terminal groin has largely stabilized the northern end of Pea Island, the southern end of Bodie Island continues to encroach into the inlet and sand has accumulated in the inlet along the northern side of the groin (Figure 10) (NCCRC 2010a).

Hatteras Island

Pea Island

Prior to groin construction, the northern end of Pea Island experienced long-term erosion due to a reduction in alongshore sediment transport, partly due to spit building at southern Bodie Island and the dredging of Oregon Inlet (NCCRC 2010a). From 1960–1989 over 4.3 million m³ (5.7 million yd³) of sediment was dredged from the inlet and placed offshore (NCCRC 2012a).

Accelerated dredging beginning in the 1980s (Figure 11) caused an increase in the rate of erosion on northern Pea Island from an average of -3 m/yr (-9.8 ft/yr) prior to 1980 to -5.2 m/yr (-17.1 ft/yr) during the 1980–1989 period (Riggs et al. 2009a). Since 1990, sediment dredged from the inlet has been deposited along northern Pea Island beaches and in water depths between 2.4–4.6 m (8–15 ft) along the beach beginning about 1,220 m (4,000 ft) south of the groin (Dee Dee Fauser, USACE, email, 2-26-13).

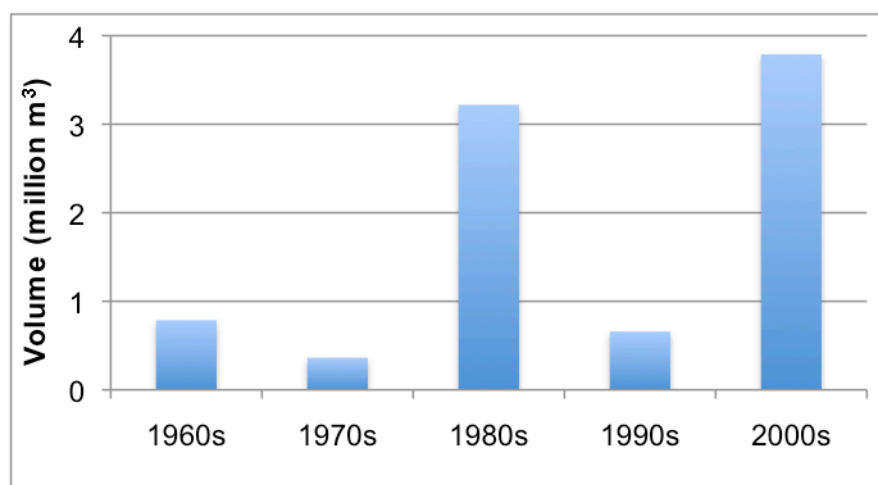


Figure 11. Graph of sediment dredged from Oregon Inlet between 1960 and 2009 (includes only dredging projects where sediment was removed from within the inlet system; additional volumes have

been dredged from the inlet and sidecasted off of the dredge, but are not included here) (data from NCCRC 2010a and Dee Dee Fauser [USACE]).

The total volume placed directly on northern Pea Island beaches or in the nearshore differs between sources and Riggs et al. (2009a) claims that the value is poorly known. NCCRC (2010a) provides detailed beach nourishment data that shows over 8.2 million m³ (10.7 million yd³) of sediment was placed along northern Pea Island beaches and nearshore between 1990 and 2009 during 25 episodes (see Appendix F). Riggs and Ames (2009) document that a total of 9.2 million m³ (12 million yd³) was placed in the same region from 1983 to 2009. Since the primary purpose of these projects was dredging of Oregon Inlet (and not beach nourishment), these projects are classified as dredging within this inventory and are not included in beach nourishment totals. Following groin construction and nourishment activities, the shoreline south of the groin (for roughly 1 km [0.6 mi]) has filled with sand and stabilized. However, the next 10 km (6.2 mi) of shoreline continue to erode (Riggs et al. 2009a).

The NCDOT has constructed and maintained multiple barrier dune-ridges along Pea Island and placed extensive sand bag installations in an attempt to protect Highway 12. In 1996 about 4.8 km (3 mi) of Highway 12 had to be relocated inland at a cost of \$4.3 million (Riggs and Ames 2009). Riggs and Ames (2009) report that from 1983–2009 over \$92 million dollars was spent on maintenance of the Oregon Inlet Bridge and Highway 12 on Pea Island (this includes highway relocations, terminal groin installation, highway maintenance, dredging, and nearshore disposal).

On August 27, 2011 Hurricane Irene cut two breaches on Pea Island approximately 11 km (7 mi) south of Oregon Inlet, severing the highway. A temporary bridge across one of the breaches opened on October 10, 2011 and was still in use during our field visit in April 2012 (Figure 12). Dennis McGuiness, a retired NPS maintenance chief, reports that an inlet existed in this general location until the late 1930s (phone conversation, 10-25-12). The current plan being pursued by the NCDOT is to reconstruct the bridge and make it permanent.

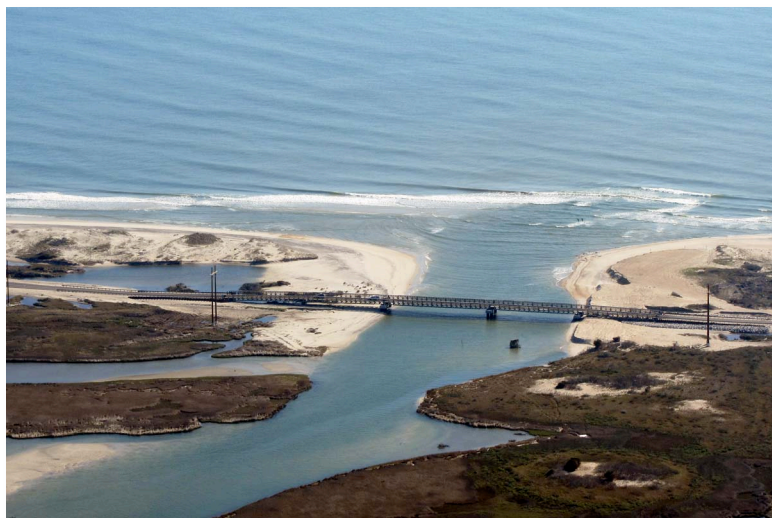


Figure 12. Inlet on northern Pea Island that formed during Hurricane Irene in 2011 (image by Kate Dallas).

Rodanthe & Avon

The 260-meter (853 ft) long Hatteras Island Fishing Pier is located in the community of Rodanthe (Figure 13 and #26 Figure 14). The pier was built in 1960, demolished and rebuilt after Hurricane Floyd in 1999, and repaired after Hurricane Isabel in 2003 (Rodanthe Pier staff, phone conversation, 10-4-12). Roughly 1,800 m (5,900 ft) of beach to the north of the pier was nourished in 1965 with sand dredged from Pamlico Sound (NPS 1965).



Figure 13. The Hatteras Island Fishing Pier in Rodanthe (#26 Figure 14, image by Kate Dallas).

The original 274-meter (900 ft) long timber Avon Pier was built in 1962 (#27 Figure 14). The pier has been repaired over time, including end repairs in 2004 after Hurricane Isabel (Avon Pier staff, phone conversation, 10-4-12). Storms have destroyed the end of the pier such that the current pier is approximately 210-meters (690 ft) long.

Roughly 5,000 m (16,400 ft) of dunes north of Avon were nourished circa 1962 with sand dredged from Pamlico Sound (NPS 1962a). Approximately 411,330 m³ (538,000 yd³) were placed on the dunes east of Highway 12 and an additional 13,000 m³ (17,000 yd³) were used to fill existing creeks on the west side of the highway (NPS 1962a). Following Tropical Storm Dennis in 1999, approximately 4,330 m (14,110 ft) of dunes were reconstructed (construction methods unknown) just north of Buxton (WCU 2012).

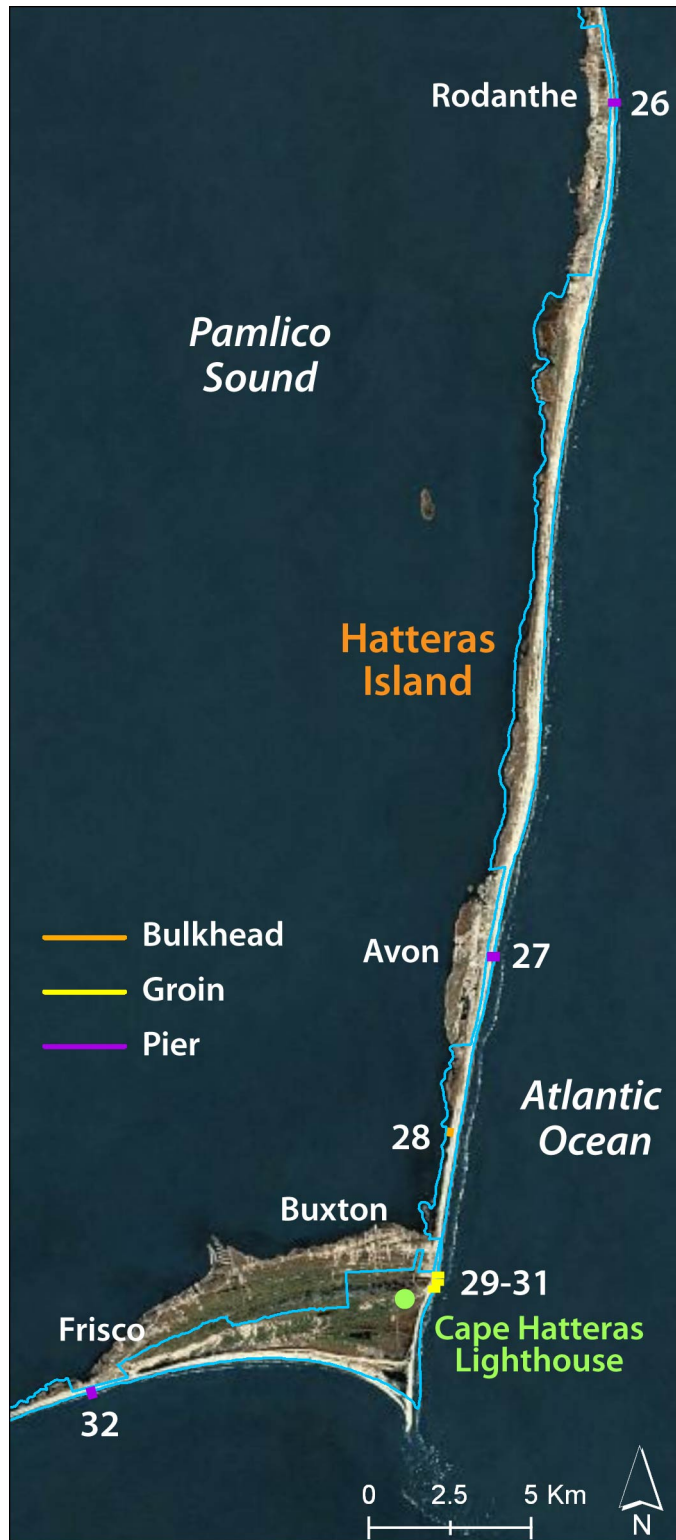


Figure 14. Southern Hatteras Island structure map (image from ESRI Bing Maps basemap layer 2012).

Buxton, Cape Hatteras Lighthouse, and Frisco

North of Buxton, on the sound side of the island, is a timber bulkhead at the Haulover Day Use Area (#28 Figure 14). The bulkhead was built in the 1980s and rebuilt following storms in the 1990s and in 2010 (Dennis McGuinness, retired NPS, phone conversation, 10-25-12).

The Ash Wednesday storm on March 7–8, 1962 opened a 215-meter (700 ft) wide inlet with a depth of 2.4 m (8 ft) that severed the island roughly 3.2 km (2 mi) north of Buxton. A subsequent storm in December 1962 widened the inlet to approximately 460 m (1,500 ft) with a maximum depth of 3.4 m (11 ft) (Wamsley and Kraus 2005). Local interests dumped broken culverts, automobiles, and other material in January–February of 1963 to mitigate erosion of the south bank (Wamsley and Kraus 2005). The USACE closed the inlet by February 1963 using sediment dredged from the flood tidal delta and the sound, placing 451,470 m³ (590,500 yd³) of sediment at a cost of \$4 million (Wamsley and Kraus 2005, Binkley 2007).

When the Cape Hatteras Lighthouse was built in 1870 it stood approximately 460 m (1,500 ft) from the shore, but by 1988 the ocean had advanced to within 50 m (160 ft) (NRC 1988). Between 1930 and 1984 beach nourishment projects, groin construction, sandbags, and plantings of offshore artificial seaweed were implemented in an attempt to stabilize the beach (Table 2). After years of studying various options to protect the lighthouse, the NPS moved it 884 m (2,900 ft) inland over 23 days in 1999 (Figure 15) (NPS no date).

Table 2. Timeline of shoreline protection measures in the Buxton/Cape Hatteras Lighthouse area (data from Dolan 1972, Dolan et al. 1974, NRC 1988, USACE 1994, Vincent 2003, Wamsley and Kraus 2005, Binkley 2007, Dolan no date).

Year	Project	Description
1930	Groins	300 m (1,000 ft) of steel sheet-pile groins were installed by the Lighthouse Service.
1930s	Dune construction	The Civilian Conservation Corps built artificial sand dunes along the entire length of Hatteras Island.
1933	Groins	Additional steel sheet-pile groins installed.
1962	Beach nourishment	The USACE placed 451,470 m ³ (590,500 yd ³) of sand north of Buxton to close an inlet after the Ash Wednesday Storm.
1964	Beach nourishment	The NPS placed 57,360 m ³ (75,024 yd ³) of sand onto the Buxton beach.
1966–1973	Beach nourishment	Nine episodes of beach nourishment placed a total of 1,955,120 m ³ (2,557,201 yd ³) of sediment near the Cape Hatteras Lighthouse.
1967	Sand bags	Large nylon sand-filled bags were placed in front of the lighthouse.
1969	Groins	The U.S. Navy built 3 groins at a cost of \$1,250,000 to protect a Navy facility.
1974	Groin repair	Repairs were made to the 1969 groins.
1980	Groin repair & rip-rap	The southern groin was extended 490 m (150 ft) landward and rubble riprap was placed at the foot of the extension.
1981	Seagrass	Artificial seagrass was installed offshore.
1982	Groin repair	The southern groin was extended an additional 490 m (150 ft).
1982	Seagrass	Additional artificial seagrass was installed offshore.
1982	Sand bags	700 sandbags were placed around the base of the lighthouse.
1983	Groin repair	A scour-mat apron was installed at the landward end of the southern groin.
1984	Seagrass	A third, even larger installation of artificial seagrass occurred.
1994	Groin repair	The southern groin was repaired.



Figure 15. View from the top of the Cape Hatteras Lighthouse. The bare strip of land in the middle of the image is the path the lighthouse took during its move inland in 1999. View is to the northeast (image by Kate Dallas).

The Cape Hatteras Lighthouse area was nourished 10 times from 1964 to 1973 with a total of 2,012,480 m³ (2,632,225 yd³) placed at a cost of over \$5 million (WCU 2012). In 1969, the Navy built 3 groins to protect a Navy facility, which later became a Coast Guard station, north of the lighthouse. The groins have been successful at trapping sediment, but have accelerated erosion rates farther south (see Impacts section). Maintenance of the groins ended when the lighthouse was moved inland in 1999 and the groins have gradually deteriorated. Currently, the primary impact on the shoreline is from the remnant of the southern groin (Figure 16).



Figure 16. Steel sheet-pile groin (that was built in 1969 to protect a Navy facility) at the former location of the Cape Hatteras Lighthouse (#31 Figure 14). View is to the northeast (image by Kate Dallas).

The wooden Cape Hatteras Pier, known locally as the Frisco Pier, was originally built in 1962 (#32 Figure 14) (Bowers 2012). Numerous hurricanes have caused extensive damages and the pier was closed in 2009 due to safety hazards. During our site visit to the park in April 2012 the pier was in very poor condition (Figure 17).



Figure 17. The Frisco Pier has been extensively damaged by storms and was closed in 2009 (#32 Figure 14) (image by Kate Dallas).

Hatteras Village

Between Frisco and Hatteras Village (Figure 2) Hatteras Island is extremely narrow (roughly 150 m [490 ft]). NPS plan drawings (1972) show the dunes in this area were nourished in 1972. A 600-meter (1,604 ft) wide inlet with three distinct channels developed in this location during Hurricane Isabel in September 2003 (Figure 18). The USACE and NDCOT closed the inlet and rebuilt the highway in October–November 2003 using 650,000 to 764,560 m³ (850,000 to 1,000,000 yd³) of sediment dredged from the navigation channel between Hatteras and Ocracoke Island (Pendleton et al. 2004) at an estimated cost of \$6.5 million, excluding road and utilities reconstruction (Smith et al. 2006). A second, smaller breach opened south of Hatteras Village and was filled in October 2003.



Figure 18. Hatteras Island breach near Hatteras Village after Hurricane Isabel in 2003. View is to the northwest (from USGS 2009).

The NPS began providing ferry service from Hatteras Village to Ocracoke Island in 1957 (Binkley 2007). Today, ferry service provided by the State of North Carolina operates from the Hatteras Ferry Landing Marina (Figure 19). A concrete and timber bulkhead extends along the eastern and southern margins of the marina (#34 Figures 20 and 21). Historic images from Google Earth show that the marina and bulkhead along the eastern side of the basin were added in the mid-1990s. Three short concrete piers (#35–37 Figure 21) are used by the Hatteras ferry, but no information could be found on their history.



Figure 19. The Hatteras Ferry Landing Marina and Hatteras Island U.S. Coast Guard Station. View is to the north (image by Kate Dallas).



Figure 20. Southern end of Hatteras Island and northern end of Ocracoke Island structure map. Blue line shows park boundary. Areas in yellow and pink boxes are enlarged in Figure 21 (image from ESRI Bing Maps basemap layer 2012).

On the northwest corner of the basin is the Hatteras Inlet Coast Guard Station, built in 1962 (Figure 21). The station has a steel sheet-pile bulkhead, concrete piers, and a rock revetment (#38–42 Figure 21). It is unknown exactly when these structures were built, but it likely coincided with the construction of the Coast Guard station in the early 1960s (Tod Midgett, U.S. Coast Guard, phone conversation, 10-5-12).

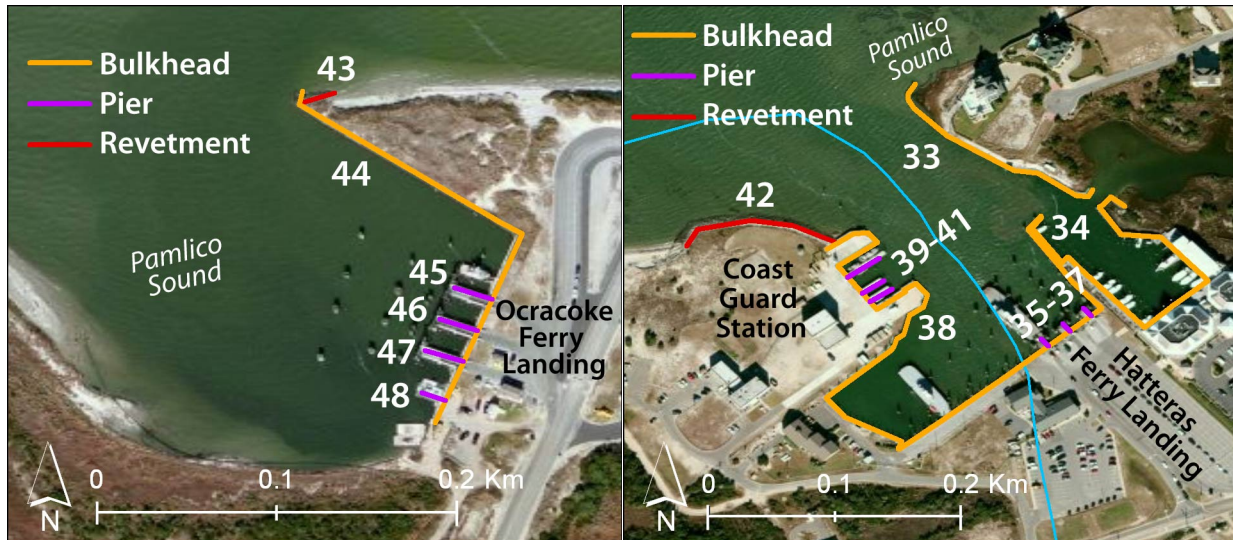


Figure 21. Ocracoke Ferry Landing (left) and Hatteras Ferry Landing Marina and Coast Guard Station (right) structure maps. Blue line shows park boundary (image from ESRI Bing Maps basemap layer 2012).

The Hatteras Inlet and the section of the Rollison Channel adjacent to the park (from the Hatteras Ferry Landing Marina to Hatteras Inlet) (Figure 20) are maintained by the USACE. The total volume of sediment dredged from these locations is unknown, but data from 2007–2012 shows that 243,228 m³ (318,130 yd³) was dredged from Hatteras Inlet and 149,005 m³ (194,891 yd³) was dredged from this section of the Rollison Channel over the 5-year period (Dee Dee Fauser, USACE, DVD, 1-28-13).

The channel from Hatteras Inlet to the northern ferry landing on Ocracoke Island is maintained by the NCDOT Ferry Division and is dredged every 2 to 3 years, with approximately 38,230–53,520 m³ (50,000–70,000 yd³) of sediment removed and placed at a spoil site on northern Ocracoke Island (Lancelot Winslow, NCDOT, email, 11-18-12). However, during the most recent dredging in November 2010–March 2011, 76,720 m³ (100,343 yd³) was dredged due to the presence of a large sandy shoal in the channel that had to be dredged for navigation purposes (Lancelot Winslow, NCDOT, email, 11-18-12). Shoaling after Hurricanes Irene and Sandy, and a few 2012/2013 winter storms, has necessitated additional dredging in the channel.

Valverde et al. (1999) documented that six beach nourishment projects occurred on Hatteras Island between 1974 and 1992, which placed a total of 340,381 m³ (445,201 yd³) at a cost of \$1,416,860 (see Appendix C). No additional information is provided, however, so the location of the projects is unknown.

Ocracoke Island

Ocracoke Island is 25 km² (6,177 ac) and has an average height of less than 1.5 m (5 ft) above sea level, leaving it vulnerable to storms and overwash. The artificial dunes, built in the 1950s, must be regularly maintained to protect Highway 12. For example, the dunes were rebuilt after Hurricanes Helena, Donna, and Isabel in 1958, 1960, and 2003, respectively (Binkley 2007, WCU 2012).

Ocracoke's beaches have also been nourished periodically to protect the dunes and highway, with at least 394,558 m³ (516,062 yd³) placed between 1986 and 1995. Additional nourishments are likely to have occurred, however, no further information could be found, so the exact locations of these nourishment projects is unknown (see Appendix C)

The Ocracoke Ferry Landing on the northern end of Ocracoke Island includes a 245-meter (786 ft) long steel bulkhead and four short concrete ferry piers (#44–48 Figure 21 & Figure 22). A small section of rock also exists at the northern end of the bulkhead facing Pamlico Sound (#43 Figure 21 & Figure 22). No background information could be found for these structures, but Google Earth imagery shows that they were built prior to 1993.

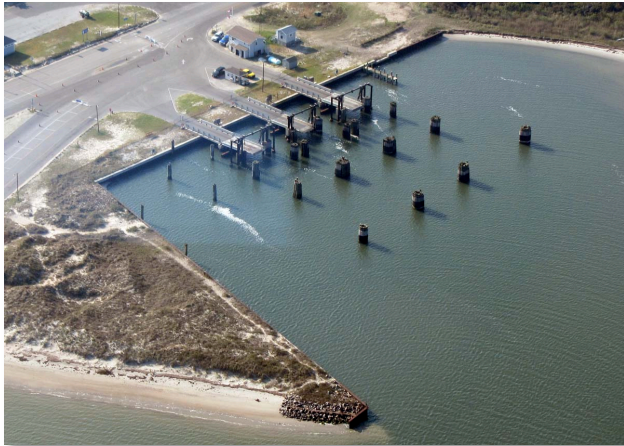


Figure 22. The ferry landing on northern Ocracoke Island (#43–48 Figure 21). View is to the southeast (image by Kate Dallas).

The Village of Ocracoke is located around a small, sheltered harbor called Silver Lake (Figure 23) on the southern end of the island and is not part of CAHA. Coastal engineering projects within Silver Lake are therefore not included in the inventory. The navigation channel from Silver Lake out to Ocracoke Inlet, however, is adjacent to park property and is dredged by the USACE, but the total volume of sediment dredged is unknown. Records from the USACE document that 11,650 m³ (15,240 yd³) of sediment was dredged from Ocracoke Inlet in 2011 (Dee Dee Fauser, USACE, DVD, 1-28-13).



Figure 23. Ocracoke Harbor, known locally as Silver Lake. View is to the east (image by Kate Dallas).

Impacts

Cape Hatteras National Seashore is located along a dynamic barrier island system. The natural processes of cross-shore and alongshore sediment transport, coupled with storm induced overwash and inlet formation, continually evolve the physical landscape. The dynamics of this complex system often conflict with the needs of commercial, residential and regulatory stakeholders seeking Outer Banks island stability. Over the last 80 years the interest in island stability has led to the implementation of a variety of coastal protection measures that have resulted in a suite of impacts to the natural environment.

Artificial Dune Construction

As noted in the inventory, artificial dunes that were initially constructed between 1937 and 1956 extend from the Virginia State Line to the southern end of Ocracoke Island. The stabilized dunes approach 10 m (33 ft) in height (averaging about 6 m [19.7 ft]) and 100 m (328 ft) in width in some areas and effectively cut off the sediment flux between the open ocean coast and the backshore (Birkemeier et al. 1984, Dolan and Lins 1985, Burroughs and Tebbens 2008). The dunes are regularly maintained following storms for limited purposes, such as for the protection of Highway 12.

Figure 24 conceptually illustrates the extent to which dune stabilization has altered beach, dune, and marsh geomorphology and led to changes in backshore ecosystems. Prior to dune construction the low-lying, sparsely vegetated barrier islands were dominated by regular flooding and overwash (Godfrey and Godfrey 1973, Dolan and Lins 1985). This natural barrier island system allowed for ongoing renewal of the estuarine shoreline (Riggs et al. 2009a). After dune stabilization, the islands (including the soundside marshes) became thickly vegetated as shrubs and other vegetation colonized locations where historically they would have been absent due to flooding and burial by overwash (Birkemeier et al. 1984, Dolan and Lins 1985). This contrasts with natural barrier systems where native early-succession vegetation communities are established quickly following flooding events (Dolan et al. 1973).

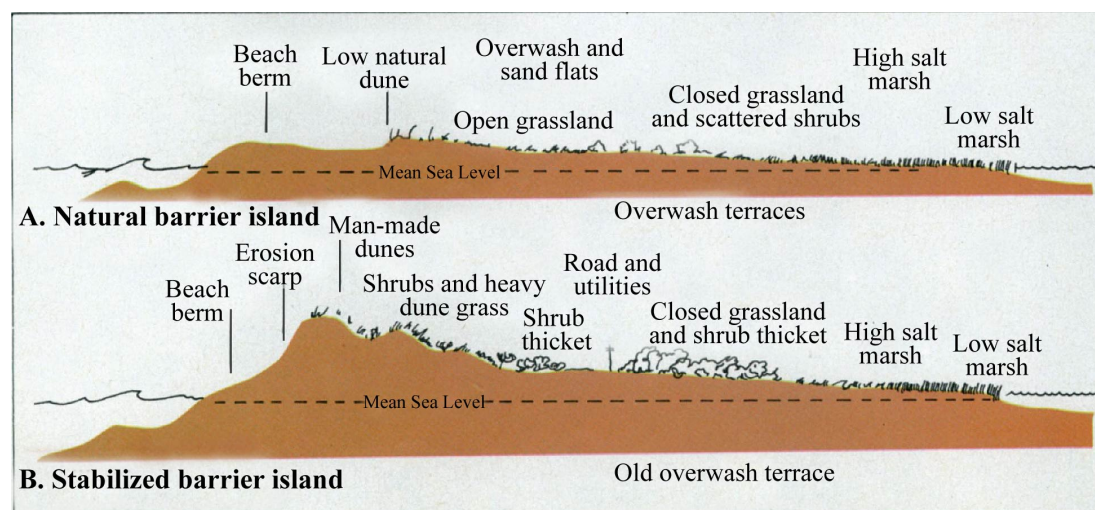


Figure 24. Typical cross sections of a (A) natural barrier island and (B) stabilized barrier island show how dune stabilization may effect island morphology. For example, natural islands have wider beaches and extensive sand flats and grasslands (modified from Dolan et al. 1973).

Along the estuarine shoreline of the natural Core Banks barrier island system (located to the south of CAHA) overwash and inlet generation processes have continued to produce estuarine shoreline accretion, in contrast to the shoreline behind stabilized dunes, where the estuarine shoreline has eroded (Dolan and Lins 1985). Stabilized dunes have also reduced overwash processes, thereby decreasing the natural nesting habitats available for piping plovers, terns, oyster catchers, black skimmers and others seabirds (Riggs and Ames 2009).

Dune stabilization projects have also impacted the ocean beaches. Prior to stabilization, the beach width at CAHA approached 125 m (410 ft), similar to beach widths at the unstabilized Core Banks (150 m [492 ft]) (Dolan et al. 1973, Birkemeier et al. 1984). Along the Avon-Buxton portion of CAHA, the island has eroded 760 m (2,500 ft) since 1852 (76% island width reduction) and Highway 12 has been relocated four times since 1955 (Figure 25) (Riggs et al. 2009b).

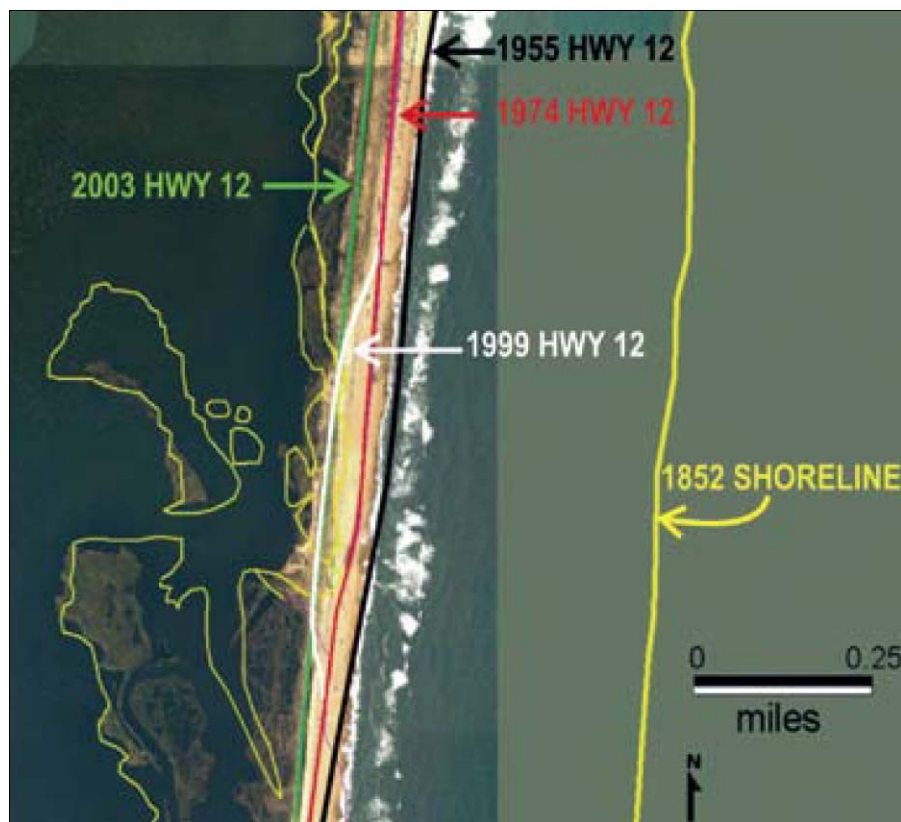


Figure 25. 1852 historic shoreline and subsequent Highway 12 locations in 1955, 1974, 1999 and 2003 in the Avon-Buxton area overlain on a 2003 aerial imagery (from Riggs et al. 2009b).

Beaches in CAHA have narrowed by as much as 85% and in Birkemeier et al. (1984) were reported to be routinely less than 30 m (98 ft) wide. The narrowed beaches concentrate wave energy dissipation in an increasingly restricted area, resulting in steeper beach profiles and increased erosion (Dolan et al. 1973). The steepening of the beach face is linked to the constructed dune ridges, a natural sand deficiency, and net shoreline erosion related to sea-level rise (Riggs et al. 2009a). Subsequently, this increasingly high-energy environment is thought to limit turtle and shorebird nesting sites (Riggs and Ames 2009). Comparison of natural Portsmouth Island (south of CAHA, Figure 2) with the manipulated Ocracoke Island illustrates a striking dissimilarity in beach and dune width between stabilized and natural barrier islands (Figure 26).



Figure 26. Comparison of Ocracoke Island (left) and Portsmouth Island (right). The artificial dunes that parallel the highway on Ocracoke Island (left) have fixed the shoreline location, while the beach has continued to narrow over time. In contrast, Portsmouth Island (right) has naturally migrated inland and maintained a relatively wide beach and well-developed dune system (images by Kate Dallas).

Smith et al. (2008) evaluated long-term (1852–1998) barrier island width statistics along Pea Island and found a strong correlation between changes in island width and the natural depositional processes of overwash and flood tide delta formation. The northern end of Pea Island, which was historically the site of two natural inlets and is not stabilized by dunes, experienced a net increase in width (3 m/yr [9.9 ft/yr]). In contrast, the southern end of Pea Island narrowed by -4 m/yr (-13.1 ft/yr). Historically, this area had limited inlet activity, high ocean-side erosion rates, little estuarine shoreline accretion, and dune stabilization since the 1930s (Smith et al. 2008). These findings reinforce the conclusion that barrier island width is maintained through the redistribution of sediment from flood tide deltas and overwash fans. Since construction of dune ridges in the 1930s, there has been a significant reduction in sediment transported to the island's soundside via these processes.

Additional impacts related to dune stabilization include degradation to wetland systems, which can affect water quality and local fisheries. On the other hand, dune stabilization has resulted in relative stability of the island, allowing increased access to the region (via Highway 12, constructed in 1952) and encouraging today's largely tourism-based economy (Riggs et al. 2009b). Future impacts of the extensive dune construction likely include continued island narrowing and habitat degradation.

Oregon Inlet

Following its formation after a hurricane in 1846, Oregon Inlet migrated southward at a rate of 23 m/yr (75 ft/yr) and westward at 5 m/yr (16 ft/yr) (Inman and Dolan 1989) (Figure 27). Oregon Inlet has been altered by a system of coastal modifications in order to maintain a navigation channel. Modifications include dredging of nearly 9.2 million m³ (12 million yd³) of sediment from the inlet system between 1960 and 2012, and construction of a 905-meter (2,970 ft) long terminal groin and 420-meter (1,350 ft) long revetment on the southern inlet shoreline (Pea Island) between 1989 and 1991 (Figure 28) (NCCRC 2010a).

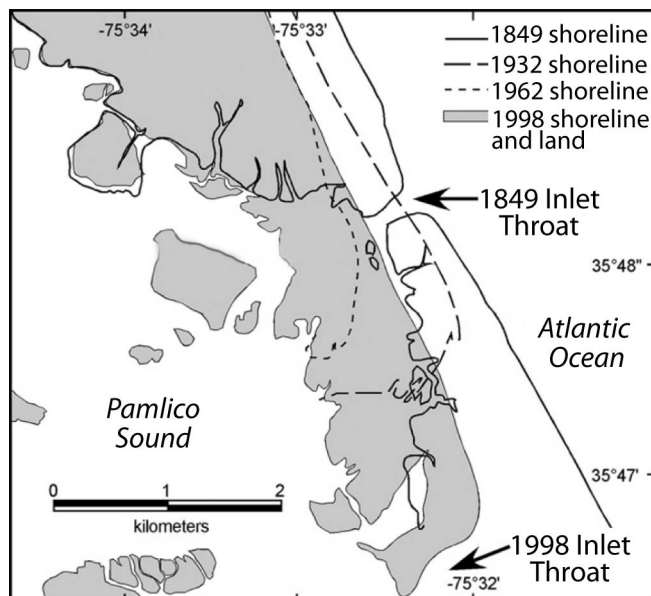


Figure 27. Map showing historic shorelines from 1849–1998. Note the 1962 shoreline was measured after the Ash Wednesday nor'easter that contributed significant erosion (from Mallinson et al. 2011).

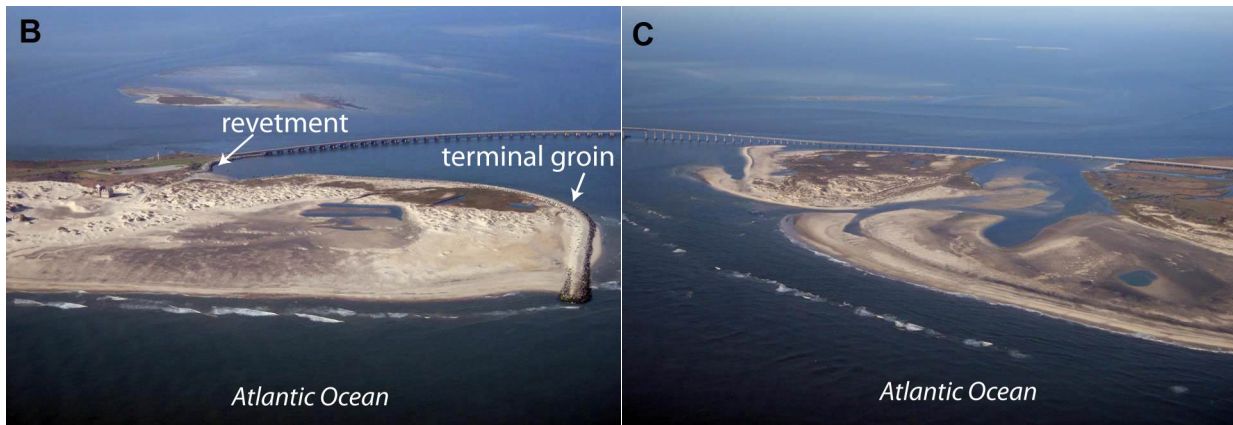
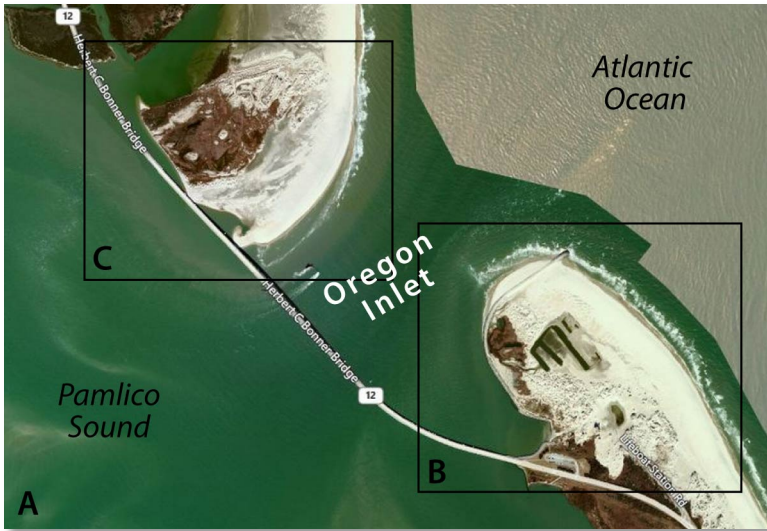


Figure 28. Oregon Inlet (A) overview map (from Bing Maps 2012), (B) southern side (Pea Island) and (C) northern side (Bodie Island). View is toward the east (bottom images by Michael Berry).

If the terminal groin had not been constructed, Oregon Inlet would have continued to migrate southward (Figure 29) (NCCRC 2010a). The construction of the groin, combined with the southward growth of Bodie Island, has caused Oregon Inlet to narrow and deepen (Mallinson et al. 2008). The narrowing of the channel has contributed to localized scour around the bridge pilings and continually shifting shoals that require dredging in order to maintain the navigable waterway (Mallinson et al. 2008).

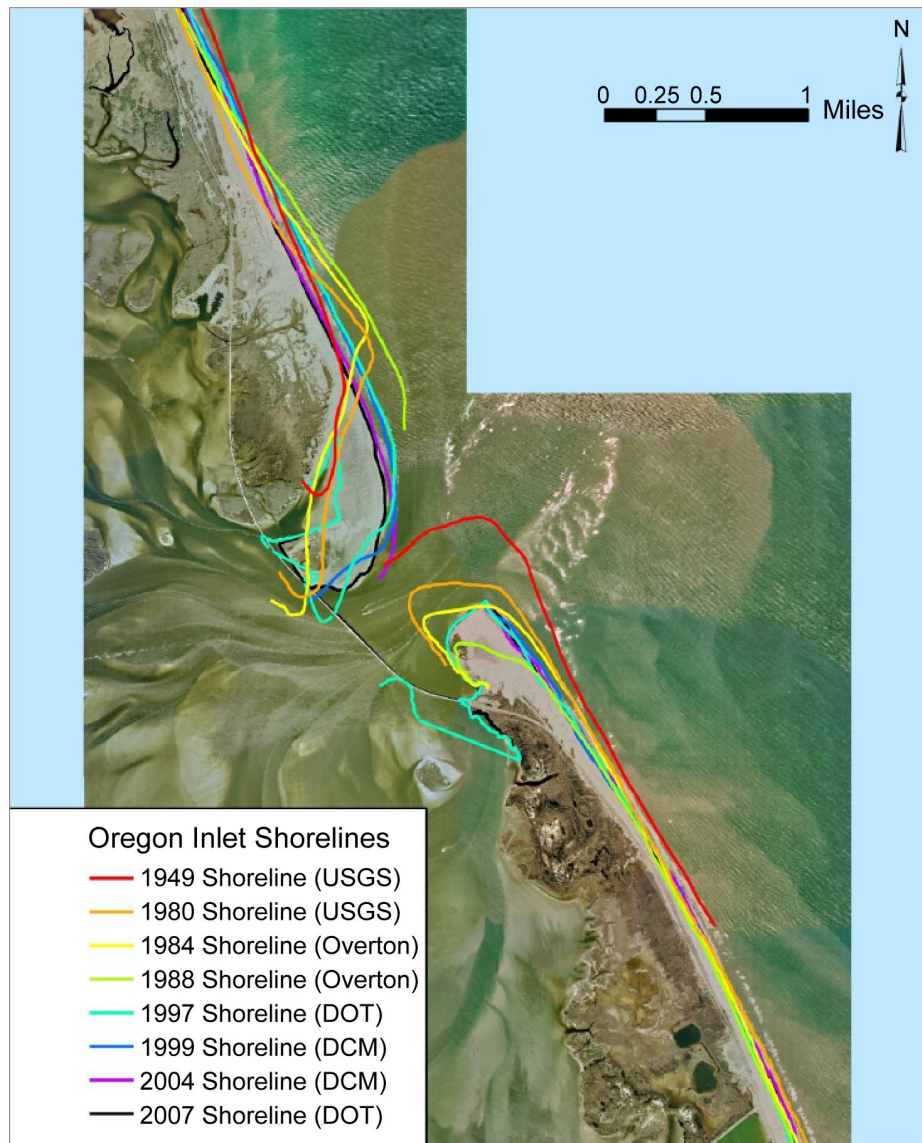


Figure 29. Oregon Inlet historic shorelines from 1949–2007 (from NCCRC 2010).

Following groin construction, the region downdrift of the groin (up to 10 km [6.2 mi]) experienced shoreline erosion rates of up to -4 m/yr (-13.1 ft/yr), which is double the pre-groin erosion rates, in spite of frequent placement of dredged sediment, installation of sand bags and artificial dune construction (Riggs and Ames 2009, Riggs et al. 2009a, NCCRC 2010a). While erosion rates decreased along the northern 5 km (3.1 mi) where dredged sediment was placed on the beach they increased substantially along the downdrift shoreline (Riggs et al. 2009a). Riggs and Ames (2009) report that dredged sediment placement within this area has slowed an underlying erosional trend, and has proven to be a costly measure for maintaining Highway 12. The NCCRC report (2010a) states that the specific impacts of groin construction on Pea Island shoreline retreat rates are highly variable and linked to dredging quantity and placement location, northern spit formation, and natural variability in environmental forcing characteristics (e.g., wave height and direction).

In addition to impacting sediment transport and coastal change, the inlet modification measures have also impacted both aquatic and terrestrial habitat. Beach nourishment along Pea Island has been reported to negatively impact the benthic infauna habitat along the beach and surf zone due to changes in beach mineralogy and grain size (Dolan et al. 2004). Consequently, this negatively impacts swash zone feeding habitats of shorebirds and fish within the surf zone (Riggs and Ames 2009).

The region immediately to the south of the groin (Figure 28b) has also become a problematic nesting site for endangered species (such as the piping plover and loggerhead sea turtle) due to higher flooding frequency within the low-lying dune and marsh area (Riggs and Ames 2009, NCCRC 2010a). Impacts at Oregon Inlet are likely to continue into the future as the dynamic nature of the inlet is in conflict with static human infrastructure (Mallinson et al. 2008).

Cape Hatteras Lighthouse Area

Groins (#29–31 Figure 30), sandbags, offshore plantings, and beach nourishment have all been employed to help stabilize the beach fronting the historic Cape Hatteras Lighthouse. As with much of the CAHA coastline, the shoreline in the vicinity of the lighthouse has historically eroded as the barrier island system naturally adjusts to sea-level rise (Dolan and Lins 1985). From 1872 to 1988 the Cape Hatteras Lighthouse shoreline retreated nearly 440 m (1,440 ft), averaging -3.8 m/yr (-12.5 ft/yr) (Figure 31) (NRC 1988). South of the groin field there was a local maximum in the erosion rate of -8 m/yr (-26.2 ft/yr) (Inman and Dolan 1989).



Figure 30. Cape Hatteras Lighthouse and groins. View is to the northwest (image by Scott Geib).

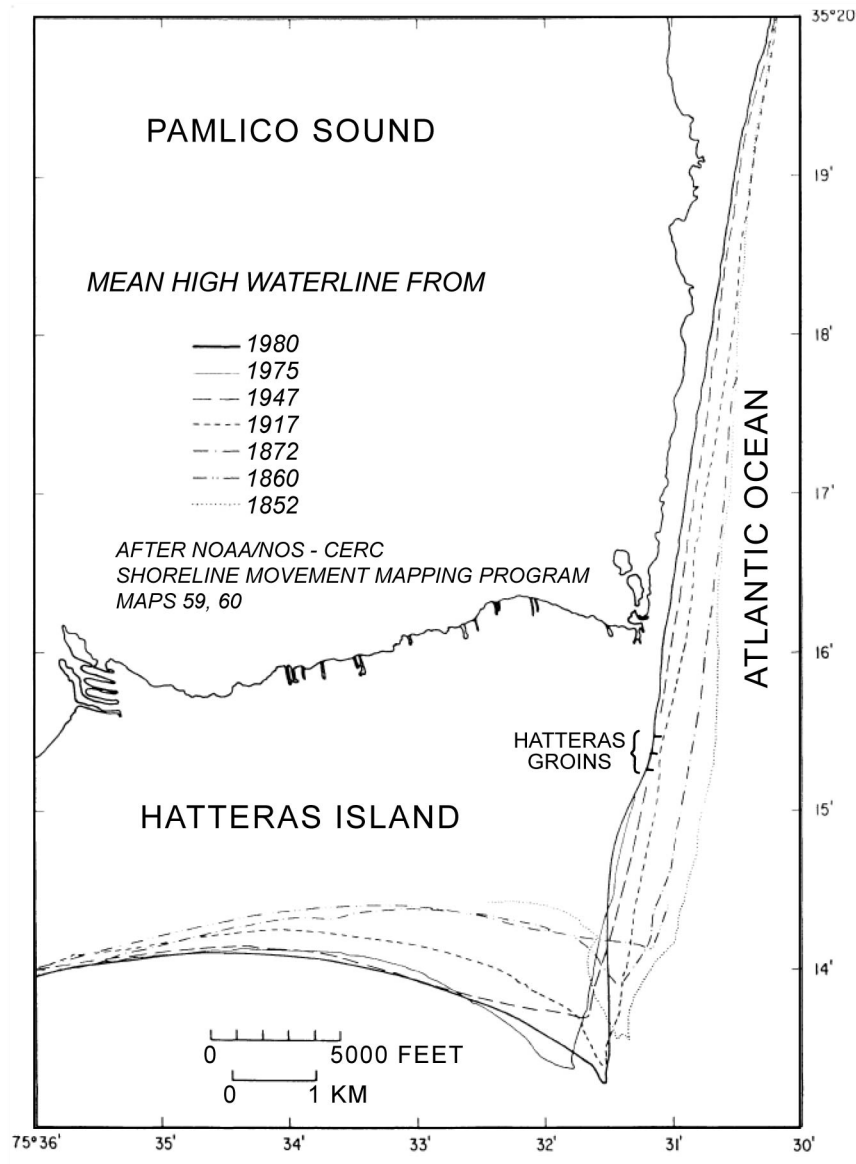


Figure 31. Historic shorelines from 1852 to 1980 around the Cape Hatteras Lighthouse. Note the inflection point immediately south of the Hatteras groins (adapted from Inman and Dolan 1989).

Prior to the lighthouse's relocation inland, the structure was about 50 m (164 ft) from the water's edge (Figure 32) with periodic storm surge and swell reaching the structure (NRC 1988). The groins, built in 1969 by the U.S. Navy to protect a former Navy facility, have impounded sediment on their northern sides, resulting in erosion on their southern flanks (Figure 30) due to the net southerly alongshore sediment transport direction. Given the groin impoundment, consistent long-term erosion rates, and a shoreline inflection point, it is likely that some degree of shoreline stabilization has been gained from the installation of groins, sandbags, and beach nourishment projects in the area since the 1930s. Since the groins are no longer maintained, it is likely that the groins will eventually collapse and the inflection point will subside. Areas to the north of the groin field that have benefitted from a wide beach due to groin impoundment will likely experience erosion following groin collapse.



Figure 32. Photograph shows the proximity of the lighthouse to the ocean prior to relocation (circa 1990). Note the impoundment of sediment along the north (right) side of the groin. View is to the west (NPS photo).

Discussion and Recommendations for Further Study and Management

Coastal engineering projects within and adjacent to Cape Hatteras National Seashore alter the natural flow of sediment, modify park geomorphology, and play a substantial role in barrier island evolution. The present day landscape is dominated by the presence of an artificial dune system originally constructed to promote island stability and protect infrastructure.

Consequently, the artificial dune system has led to a decrease in beach and island width because it limits the natural processes of overwash, inlet formation, and flood tidal delta formation (Dolan et al. 1973) that are the mechanisms by which natural island systems build elevation and width, and transgress westward in response to sea level rise (Riggs et al. 2009a).

With most of the park only a few hundred meters in width and generally low-lying, CAHA is considered to be at high risk to the effects of future sea level rise (Pendleton et al. 2004). Impacts due to sea level rise are thought to be accelerated rates of erosion, economic losses due to storm-induced flooding, and the potential catastrophic collapse of portions of the barrier islands resulting in significant losses of coastal and estuarine habitats (Riggs and Ames 2003). Current relative sea level rise rates in the northern Outer Banks are estimated at 4.2 to 4.5 mm/yr (0.16 to 0.18 in/yr) (Zervas 2004, ECU 2008); sea level is likely to rise an additional 0.4 to 1.4 m (15 to 55 in) above present by 2100, but not necessarily in a linear fashion (NCCRC 2010).

CAHA has been struggling to maintain infrastructure since its inception. Devastating nor'easters, tropical storms, and hurricanes often destroy various elements of infrastructure and subsequent repairs are performed at great cost to the park, state agencies and residents (Riggs et al. 2009a). The park must extend great effort and resources in trying to preserve and protect habitats in the face of natural events and human influences on island evolution and sediment transport. Coastal planners must balance maintaining natural barrier island dynamics with economic development and infrastructure demands (Riggs et al. 2009a).

Future work should continue to focus on the impacts of the present policies of island stabilization and to evaluate alternative means of island access. These impacts and alternatives should be integrated into the park's next General Management Plan and associated public outreach efforts. The NPS should continue working with the U.S. Fish and Wildlife Service and Federal Highway Administration regarding Highway 12 restoration plans within the Pea Island National Wildlife Refuge that integrate natural coastal processes (e.g., bulldozing overwashed sand towards the bay rather than back onto the beach to mimic overwash/island-building, considering alternate configurations of Highway 12, and developing longer-term solutions such as bridges and ferries). All such efforts would benefit from public outreach campaigns to improve stakeholder understanding of coastal processes and feasible, compatible solutions.

Additional research could also focus on CAHA's increasing vulnerability to sea level rise and storms associated with projected climate change and development of soft and non-traditional engineering alternatives to protect key cultural resources from the inevitable coastal change and flood hazards present within this dynamic barrier island system.

Literature Cited

- Bing Maps. 2012. Bird's Eye imagery of Oregon Inlet from 2012 accessed online. Imagery by Nokia. Available at <http://www.bing.com/maps/default.aspx?q=oregon+inlet+nc+&mkt=en&FORM=HDRSC4> (accessed 19 October 2012).
- Binkley, C. 2007. The Creation and Establishment of Cape Hatteras National Seashore. The Great Depression through Mission 66. National Park Service, Atlanta, Georgia. Available at <http://ia701501.us.archive.org/2/items/creationestablis00bink/creationestablis00bink.pdf>
- Birkemeier, W., R. Dolan, and N. Fisher. 1984. The Evolution of a Barrier Island: 1930–1980. *Journal of the American Shore & Beach Preservation Association* 52(2): 2–12.
- Bowers, A. C. 2012. Future of the Frisco Pier is still uncertain. Island Free Press online. <http://islandfreepress.org/2012Archives/06.04.2012-FutureOfTheFriscoPierIsStillUncertain.html> (accessed 4 October 2012).
- Burroughs, S. M. and S. F. Tebbens. 2008. Dune retreat and shoreline change on the Outer Banks of North Carolina. *Journal of Coastal Research* 24(2B): 104–112.
- Church, J. A. and N. J. White. 2006. A 20th century acceleration in global sea-level rise. *Geophysical Research Letters* 33.
- Coastal Science & Engineering (CSE) 2011. 2011 Nags Head Beach Nourishment Project Nags Head North Carolina. Unpublished report, Columbia, South Carolina.
- Coburn, A. S., A. D. Griffith, and R. S. Young. 2010. Inventory of Coastal Engineering Projects in Coastal National Parks. Natural Resource Technical Report NPS/NRPC/GRD/NRTR—2010/373. National Park Service, Fort Collins, Colorado.
- Dolan, R. 1972. Beach Erosion and Beach Nourishment. Cape Hatteras North Carolina. Dune Stabilization Study. NRR No. 4. National Park Service, Washington, D.C.
- Dolan, R. No date. Beach Nourishment Near Cape Hatteras, North Carolina. Unpublished Report.
- Dolan, R., S. Dofflemeyer, C. Donoghue, and J. Jones-Smith. 2004. Analysis of Changes in the Beach Sediment and Beach-Face Organisms Associated with Sand Bypassing from the Oregon Inlet to Pea Island, North Carolina, 1990–2002. Coastal Research Associates Report. Available at [http://www.fws.gov/nc-es/port/Analysis of Changes.pdf](http://www.fws.gov/nc-es/port/Analysis%20of%20Changes.pdf)
- Dolan, R., P. J. Godfrey, and W. E. Odum. 1973. Man's impact on the barrier islands of North Carolina. *American Scientist* (61):152–162
- Dolan, R., B. Hayden, R. Riddel, and J. Ponton. 1974. 1973 Buxton Beach Nourishment Project: An Annotated Photographic Atlas. Coastal Research Associates Unpublished Report.

- Dolan, R. and H. Lins. 1985. The Outer Banks of North Carolina. United States Geological Professional Paper 1177-B. Washington, D.C. Available at <http://pubs.usgs.gov/pp/1177b/report.pdf>
- Environmental Systems Research Institute (ESRI). 2012. ESRI ArcGIS Bing Maps basemap data layer. Aerial imagery of Cape Hatteras National Seashore from 2010.
- Godfrey, P. J. and M. M. Godfrey. 1973. Comparison of Ecological and Geomorphic Interactions Between Altered and Unaltered Barrier Island Systems in NC. Pages 239-258 *in* Coastal Geomorphology, D.R. Coates, editor. State University of New York, Binghamton, New York.
- Gregory, M. B. and K. A. Smith. 2011. Assessment of Estuarine Water and Sediment Quality at Cape Lookout and Cape Hatteras National Seashores. National Park Service NRDR 2011/179. Available at <http://science.nature.nps.gov/im/units/SECN/reports.cfm>
- Inman, D. L. and R. Dolan. 1989. The Outer Banks of North Carolina: Budget of Sediment and Inlet Dynamics Along a Migrating Barrier System. *Journal of Coastal Research* 5(2): 193–237.
- Mallinson, D. J., S. R. Riggs, S. J. Culver, D. V. Ames, J. P. Walsh, and C. W. Smith. 2008. Past, Present and Future Inlets of the Outer Banks Barrier Islands, North Carolina. East Carolina University Printing Press, Greenville, North Carolina. Available at http://www.ecu.edu/icsp/ICSP/Reports_files/PastPresentAndFutureInletsDec2008.pdf
- Mallinson, D. J., C.W. Smith, S. Mahan, S. J. Culver and K. McDowell. 2011. Barrier Island Response to late Holocene climate events, North Carolina, USA. *Quaternary Research* (76)1:46–57.
- National Oceanographic and Atmospheric Administration (NOAA). 2012. Tides and Currents web site. <http://tidesandcurrents.noaa.gov/> (accessed 17 September 2012).
- National Park Service (NPS). No date. Cape Hatteras Lighthouse Flyer. National Park Service.
- National Park Service (NPS). 1962a. Hydraulic Fill – Little Kinnakeet to Avon plan drawing. Plan number 603_3217A on file at Cape Hatteras National Seashore, Manteo, North Carolina.
- National Park Service (NPS). 1962b. Hydraulic and Land Fill – Ocracoke Island. Plan number 603_3211B on file at Cape Hatteras National Seashore, Manteo, North Carolina.
- National Park Service (NPS). 1962c. Dune Fill – Headquarters Area. Plan number 603_3218 on file at Cape Hatteras National Seashore, Manteo, North Carolina.
- National Park Service (NPS). 1963. Seventh Year of Dune Building at Cape Hatteras National Seashore Annual Report Fiscal Year 1963. National Park Service Unpublished Report. File number 603_D171 on file at Cape Hatteras National Seashore, Manteo, North Carolina.

- National Park Service (NPS). 1964. Dune Reconstruction Rodanthe, Salvo-Kinnakeet & Cape Point. Plan number 603_3238 on file at Cape Hatteras National Seashore, Manteo, North Carolina.
- National Park Service (NPS). 1965. Hydraulic Fill Hatteras Island. Plan number 603_3242A on file at Cape Hatteras National Seashore, Manteo, North Carolina.
- National Park Service (NPS). 1966. Bulkhead Renovation Oregon Inlet Marina. Plan number 603_3321A on file at Cape Hatteras National Seashore, Manteo, North Carolina.
- National Park Service (NPS). 1972. Dune Construction Sandy Bay. Plan number 603_60085 on file at Cape Hatteras National Seashore, Manteo, North Carolina.
- National Park Service (NPS). 1979. Replace Wooden Bulkhead Oregon Inlet Marina. Plan number 603_80011A1 on file at Cape Hatteras National Seashore, Manteo, North Carolina.
- National Park Service (NPS). 2006. Management Policies. National Park Service, Washington, D.C.
- National Research Council (NRC) 1988. Saving Cape Hatteras Lighthouse from the Sea. Options and Policy Implications. National Academy Press, Washington, D.C. Available online at: http://books.nap.edu/catalog.php?record_id=9502
- North Carolina Coastal Resources Commission (NCCRC). 2010a. Terminal Groin Study. Final report. Available at http://dcm2.enr.state.nc.us/CRC/tgs/terminal_groin_study.html
- North Carolina Coastal Resources Commission (NCCRC). 2010b. North Carolina Sea-Level Rise Assessment Report. Available at [http://dcm2.enr.state.nc.us/slr/NC Sea-Level Rise Assessment Report 2010 - CRC Science Panel.pdf](http://dcm2.enr.state.nc.us/slr/NC_Sea-Level_Rise_Assessment_Report_2010_-_CRC_Science_Panel.pdf)
- North Carolina Department of Environment and Natural Resources (NCDENR). 2013. Albemarle-Pamlico National Estuary Partnership website. <http://portal.ncdenr.org/web/apnep/basinsandrivers> (accessed 11 January 2013).
- Pendleton, E. A., E. R. Thieler, and S. J. Williams. 2004. Coastal Vulnerability Assessment of Cape Hatteras National Seashore (CAHA) to Sea-Level Rise. United States Geological Survey Open File Report 2004-1064. Available at <http://pubs.usgs.gov/of/2004/1064/images/pdf/caha.pdf>
- Riggs, S. R., W. J. Cleary, and S. W. Snyder. 1995. Influence of inherited geologic framework on barrier shoreface morphology and dynamics. *Marine Geology* 126(1-4): 213-234.
- Riggs, S. R. and D. V. Ames. 2003. Drowning the North Carolina Coast: Sea-Level Rise and Estuarine Dynamics. North Carolina Sea Grant Program, Raleigh, North Carolina. Pub. No. UNC-SG-03-04. Available at [http://core.ecu.edu/geology/riggs/DROWNING The NC Coast.pdf](http://core.ecu.edu/geology/riggs/DROWNING_The_NC_Coast.pdf)

- Riggs, S. R. and D. V. Ames. 2009. Impact of the Oregon Inlet Terminal Groin on Downstream Beaches of Pea Island, NC Outer Banks. Unpublished Paper. Available at [http://core.ecu.edu/geology/riggs/IMPACTS OREGON INLET TERMINAL GROIN 11-30-09 \(2\).pdf](http://core.ecu.edu/geology/riggs/IMPACTS OREGON INLET TERMINAL GROIN 11-30-09 (2).pdf)
- Riggs, S. R., D. V. Ames, S. J. Culver, D. J. Mallinson, D. R. Corbett, and J. P. Walsh. 2009a. Eyes of a human hurricane: Pea Island, Oregon Inlet, and Bodie Island, northern Outer Banks, North Carolina. Geological Society of America Special Paper 460-04: 43–72.
- Riggs, S. R., S. J. Culver, D. V. Ames, D. J. Mallinson, D. R. Corbett and J.P. Walsh. 2009b. North Carolina's Coasts in Crisis: A Vision for the Future. White Paper published by East Carolina University. Available at <http://core.ecu.edu/geology/riggs/Coasts in Crisis Booklet for web.pdf>
- Schupp, C. A. and T. Thornberry-Ehrlich. In press. Cape Hatteras National Seashore Geologic Resources Inventory Report. National Park Service, Denver, Colorado.
- Smith, J. J., R. Dolan, and H. Lins. 2006. Hurricane History of the North Carolina Outer Banks (USA), 1586 to 2004. *Shore and Beach* 74(3): 19–23.
- United States Army Corps of Engineers (USACE). 1994. Cape Hatteras Lighthouse, North Carolina South Groin Rehabilitation General Site Plan. Plan number 603_80052 on file at Cape Hatteras National Seashore, Manteo, North Carolina.
- United States Coast Guard (USCG) 2012. Sector North Carolina Station Oregon Inlet website. <http://www.uscg.mil/d5/sectnorthcarolina/StaOregonInlet.asp> (accessed 4 October 2012).
- United States General Accounting Office (USGAO) 2002. Oregon Inlet Jetty Project Environmental Concerns Still Need to Be Resolved. United States General Accounting Office, Washington, D.C. GAO-02-803. Available at <http://www.gao.gov/assets/240/235765.pdf>
- United States Geological Society (USGS). 2009. Coastal Change During Hurricane Isabel 2003. U.S. Geological Society Fact Sheet 2009-3025. Available at <http://pubs.usgs.gov/fs/2009/3025/pdf/fs2009-3025.pdf> (accessed 4 October 2012).
- United States Geological Society (USGS). 2011. Aerial Photos of Outer Banks Show Coastal Damage from Hurricane Irene website. <http://www.usgs.gov/newsroom/article.asp?ID=2921#.UG5Qhvk-uHc> (accessed 4 October 2012).
- Valverde, H. R., A. C. Trembanis, and O. H. Pilkey. Summary of Beach Nourishment Episodes on the U.S. East Coast Barrier Islands. *Journal of Coastal Research* 15 (4): 1100–1118.
- Village Realty, Inc. 2012. Outer Banks Fishing Piers website. <http://www.villagerealtyobx.com/OuterBanks/OuterBanksFishingPiers/JennettesPier/> (accessed 4 October 2012).

- Vincent, S. H. 2003. Cape Hatteras Light Station, Cape Hatteras National Seashore Cultural Landscape Report. National Park Service, Atlanta, Georgia.
- Wamsley, T. V. and N. C. Kraus. 2005. Coastal Barrier Island Breaching, Part 2: Mechanical Breaching and Breach Closure. U.S. Army Corps of Engineers Technical Note. Available at <http://chl.erdc.usace.army.mil/library/publications/chetn/pdf/chetn-iv-65.pdf>
- Western Carolina University (WCU). 2012. Program for the Study of Developed Shorelines Beach Nourishment website. <http://www.wcu.edu/1038.asp> (accessed 10 October 2012).
- Zervas, C. 2004. North Carolina bathymetry/topography sea level rise project: determination of sea level trends. NOAA Technical Report NOS CO-OPS 041. Available at <http://tidesandcurrents.noaa.gov/publications/techrpt41.pdf>

Appendix A: Glossary

Beach Nourishment: The introduction of sediment along a shoreline to increase or protect the size of a beach (includes dune and berm construction and nearshore disposal of sediment for the purpose of shoreline stabilization).

Breakwater: Shore-parallel structures that reduce the amount of wave energy reaching a harbor or stretch of shoreline located behind the structure. Breakwaters are similar to natural bars, reefs or nearshore islands and are designed to dissipate wave energy. The reduction in wave energy results in gradients in littoral drift, causing sediment deposition in the sheltered area behind the breakwater. Some longshore sediment transport may continue along the coast behind the breakwater. Structures can be detached, attached or utilized as a headland control feature depending on design and functionality characteristics.

Bulkhead: Vertical structures or partitions, usually running parallel to the shoreline, for the purpose of retaining upland soils while providing protection from wave action and erosion. Bulkheads are either cantilevered or anchored sheet piles or gravity structures such as rock-filled timber cribs and gabions, concrete blocks or armorstone units.

Dike: Earthen structures (dams) that keep elevated water levels from flooding interior lowlands. The protected area is often below sea level. In open coast areas, dikes that separate low-lying areas from open water are often constructed with a revetment or similar armor layer on the open waterside to protect the dike from wave action and erosion.

Dredging: The mechanical removal of sediment, often used to increase or maintain the depth of a navigable waterway.

Groin: Structures that extend perpendicular or at nearly right angles from the shore and are relatively short when compared to navigation jetties at tidal inlets. Often constructed in groups called groin fields, their primary purpose is to trap and retain sand. Groins can be constructed from a wide range of materials including armorstone, pre-cast concrete units or blocks, rock-filled timber cribs and gabions, steel sheet pile, timber sheet pile, or grout filled bags and tubes.

Headland Control: The concept of systematically placing structures (typically breakwaters) to create artificial headlands in an effort to promote equilibrium beach formation. Bays are sculptured between these headlands, such that diffraction and refraction cause waves to develop perpendicular to the coast. This is intended to result in a stable shoreline even if sediment is still passing through a system of headlands. This concept is often employed as a regional approach to shore protection.

Jetty: Structures that extend perpendicular or at nearly right angles from the shore commonly used to limit the volume of sediment deposited in inlet channels and prevent inlet migration.

Levee: Flood protection structure that holds back water during flood stage, typically built along a river to protect against flooding.

Pier: A platform extending from a shore over water and supported by piles or pillars, used to secure, protect, and provide access to ships or boats.

Revetment: A cover or facing of material placed directly on an existing slope, embankment or dike to protect the area from waves and strong currents. Like seawalls, revetments are designed to armor and protect the land behind them. Revetments are commonly constructed using armorstone (high wave energy environments) or riprap stone (lower wave energy environments) in combination with smaller stone and geotextile fabrics. Other construction materials include gabions, poured concrete (usually in stepped fashion), pre-cast concrete blocks, and grout filled bags. Structures can be partially detached from the shore (spur) depending on design considerations.

Seawall: Vertical structures used to protect backshore areas from heavy wave action, and in lower wave energy environments, to separate land from water. They can be constructed using a range of materials including poured concrete, steel sheet pile, concrete blocks, gabions, sandbags, or timber cribs.

Sill: Combination of elements from offshore breakwaters and rock revetments, typically built relatively close to shore, continuous and low-lying. Sills are generally built in lower wave energy regimes with the intent of reducing the wave climate and establishing marsh ecosystems or perched beaches.

Appendix B: Coastal Structure Data

ID	Location	Structure	Year Built	Year Maintained	Length (m)	¹ Source
1	Nags Head	Pier	1939	1947, 1963, 1996, 2011	285	1
2	Nags Head	Pier	1947	1963	190	2
3	Nags Head	Groin	1960s	2003	52	3
4	Bodie Lighthouse	Pier	early 1960s		30	4
5	Oregon Inlet Coast Guard Station	Bulkhead	circa 1990		163	5
6	Oregon Inlet Coast Guard Station	Pier	circa 1990		18	5
7	Oregon Inlet Coast Guard Station	Pier	circa 1990		19	5
8	Oregon Inlet Coast Guard Station	Pier	circa 1990		16	5
9	Oregon Inlet Coast Guard Station	Pier	circa 1990		25	5
10	Oregon Inlet Fishing Center	Bulkhead	pre 1993		12	6
11	Oregon Inlet Fishing Center	Pier	1930s		11	7
12	Oregon Inlet Fishing Center	Pier	pre 1993	2012	31	7
13	Oregon Inlet Fishing Center	Pier	pre 1993	2012	15	7
14	Oregon Inlet Fishing Center	Pier	pre 1993	2012	15	7
15	Oregon Inlet Fishing Center	Pier	pre 1993	2012	15	7
16	Oregon Inlet Fishing Center	Pier	pre 1993	2012	15	7
17	Oregon Inlet Fishing Center	Pier	pre 1993	2012	15	7
18	Oregon Inlet Fishing Center	Pier	pre 1993	2012	15	7
19	Oregon Inlet Fishing Center	Revetment	1990s		144	7
20	Oregon Inlet Fishing Center	Bulkhead	pre 1957		534	8
21	Oregon Inlet Fishing Center	Pier	pre 1957		12	8
22	Oregon Inlet Fishing Center	Pier	pre 1957		12	8
23	Oregon Inlet Fishing Center	Pier	pre 1993		11	6
24	Oregon Inlet	Groin	1989–1991		905	9
25	Oregon Inlet	Revetment	1989–1991		418	9
26	Rodanthe	Pier	1960	1999, 2003	259	2
27	Avon	Pier	1962	2004	239	2
28	Haulover Day Use Area	Bulkhead	1980s	early 1990s, 2010	50	7
29	Cape Hatteras Lighthouse	Groin	1969	1974	138	8
30	Cape Hatteras Lighthouse	Groin	1969	1974	124	8
31	Cape Hatteras Lighthouse	Groin	1969	1974, 1980	158	8
32	Frisco	Pier	1962		187	8
33	Hatteras Ferry Landing	Bulkhead	mid 1990s		164	6
34	Hatteras Ferry Landing	Bulkhead	pre 1993		701	6
35	Hatteras Ferry Landing	Pier	pre 1993		8	6
36	Hatteras Ferry Landing	Pier	pre 1993		8	6

ID	Location	Structure	Year Built	Year Maintained	Length (m)	¹ Source
37	Hatteras Ferry Landing	Pier	pre 1993		8	6
38	Hatteras Inlet Coast Guard Station	Bulkhead	1960s		204	5
39	Hatteras Inlet Coast Guard Station	Pier	1960s		18	5
40	Hatteras Inlet Coast Guard Station	Pier	1960s		17	5
41	Hatteras Inlet Coast Guard Station	Pier	1960s		25	5
42	Hatteras Inlet Coast Guard Station	Revetment	1960s		110	5
43	Ocracoke Hatteras Ferry Landing	Revetment	mid 1990s		16	6
44	Ocracoke Hatteras Ferry Landing	Bulkhead	pre 1993		245	6
45	Ocracoke Hatteras Ferry Landing	Pier	pre 1993		18	6
46	Ocracoke Hatteras Ferry Landing	Pier	pre 1993		18	6
47	Ocracoke Hatteras Ferry Landing	Pier	pre 1993		19	6
48	Ocracoke Hatteras Ferry Landing	Pier	pre 1993		12	6

¹Source: 1: Sign at pier, 2: pier staff, 3: John Abel (NCDOT), 4: Dan Barker (Gun Club), 5: USCG staff, 6: Google Earth, 7: Dennis McGuiness (retired NPS), 8: Binkley 2007, 9: Riggs and Ames 2009.

Appendix C: Beach Nourishment & Dune Construction Data

This table represents only those beach nourishment and dune construction/renourishment projects where documentation was found. The beaches and dunes have been nourished on many more occasions over time, primarily after storms. See Appendix E for detailed dune renourishment data. All costs are project-year costs.

Location	¹ Type	First Year	Renourishment Year	Volume (m ³)	Cost (USD)	² Lead Con. Agcy	In CAHA	³ Length (m)	⁴ Source
Bodie Island	Dune	1937	1962, 2004, 2005			NPS, CCC, WPA	Yes	6,730	1, 2, 3
Hatteras Island	Dune	1937	1962, 1964, 1972, 1999, 2003			NPS, CCC, WPA	Yes	66,980	2, 3, 4, 5, 6
Ocracoke Island	Dune	1956	1962, 2003			NPS	Yes	21,480	2, 3, 7
Buxton hotspot	Beach	1962–1963		451,470	\$4,000,000	USACE	Yes	620	2, 8
Cape Hatteras Lighthouse	Beach	1964	10 episodes 1964–1973	2,012,480	\$5,416,860		Yes	1,760	2, 3
Rodanthe	Beach	1965				NPS	Yes	1,830	9
Hatteras Island	Beach	1974		135,293	\$164,818	USACE		410	10
Hatteras Island	Beach	1977		97,029	\$248,521	USACE		300	10
Hatteras Island	Beach	1984		29,972	\$155,625	USACE		90	10
Hatteras Island	Beach	1986		90,114	\$303,195	USACE		280	10
Hatteras Island	Beach	1988		74,646	\$359,861	USACE		230	10
Hatteras Island	Beach	1992		18,147	\$184,840	USACE		60	10
Ocracoke Island	Beach	1986		167,755	\$471,410	USACE		510	10
Ocracoke Island	Beach	1988		90,773	\$420,821	USACE		280	10
Ocracoke Island	Beach	1989		113,229	\$557,830	USACE		350	10
Ocracoke Island	Beach	1992		100,000	\$653,748	USACE		310	10
Ocracoke Island	Beach	1995		44,305	\$145,135	USACE			10
Nags Head	Beach	2001	2002	152,911			No	3,040	3
Btwn Frisco and Hatteras	Beach	2003		707,213	\$4,000,000	USACE, NCDOT	Yes	3,120	3, 11
Nags Head	Beach	2011		3,528,517	\$30,184,000	USACE	No	16,020	12
TOTAL				7,813,854	\$47,266,664				

¹Dune = Dune Construction, Beach = Beach Nourishment

²Lead Construction Agency

³Length is very approximate

⁴Source: 1: NPS 1962c, 2: Binkley 2007, 3: WCU 2012, 4: NPS 1962a, 5: NPS 1964, 6: NPS 1972, 8: Wamsley and Kraus 2005, 9: NPS 1965, 10: Valverde et al. 1999, 11: Pendleton et al. 2004, 12: CSE 2011.

Appendix D: Dune Renourishment (repair) Data

This table represents only those dune repair projects where documentation was found. The dunes have been nourished and rebuilt on many more occasions over time, primarily after storms.

Location	Renourishment		In CAHA	¹ Length (m)	Source
	Year	Volume (m ³)			
South of Nags Head	1962		Yes	1,150	NPS 1962c
North of Avon	1962	424,330	Yes	4,960	NPS 1962a
NE Ocracoke	1962	175,848	Yes	1,080	NPS 1962b
Rodanthe, Salvo, Cape Point	1964		Yes	11,680	NPS 1964
Hatteras to Frisco	1972		Yes	4,040	NPS 1972
South of Avon	1999		Yes	4,330	WCU 2012
North of Rodanthe	2003		Yes	3,750	WCU 2012
NE Ocracoke	2003		Yes	7,600	WCU 2012
Nags Head	2004		No	2,370	WCU 2012
Nags Head	2005		No	6,210	WCU 2012

¹Length is very approximate.

Appendix E: Dredging Data for Oregon Inlet

Sidecast dredging (where dredged material is deposited about 305 m [1,000 ft] off the side of the dredge), dredging that occurred in channels within Pamlico Sound, and dredging where sediment was placed in the inlet's scour hole (occurred 2010–2012) are not included since these projects did not remove material that might otherwise have bypassed the inlet naturally (1960–2001 data from NCCRC 2010a, 2002–2012 data from Dee Dee Fauser, USACE, DVD, 1-28-13).

Year	Volume (m ³)	Disposal Location	Year	Volume (m ³)	Disposal Location
1960	48,160	Offshore	2002	94,614	Beach/Nearshore
1961	15,301	Offshore	2002	267,594	Beach/Nearshore
1962	83,463	Offshore	2002	222,199	Beach/Nearshore
1963	58,770	Offshore	2003	38,524	Beach/Nearshore
1964	9,786	Offshore	2003	560,504	Beach/Nearshore
1965	143,845	Offshore	2003	16,979	Beach/Nearshore
1967	164,557	Offshore	2003	236,444	Beach/Nearshore
1968	161,650	Offshore	2004	113,055	Beach/Nearshore
1969	100,949	Offshore	2004	411,940	Beach/Nearshore
1970	30,988	Offshore	2004	14,018	Nearshore
1971	101,035	Offshore	2005	26,533	Beach/Nearshore
1972	231,053	Offshore	2005	34,405	Beach/Nearshore
1984	206,787	Offshore	2005	12,011	Nearshore
1984	18,669	Offshore	2005	12,726	Nearshore
1984	367,551	Offshore	2005	16,533	Nearshore
1985	348,882	Offshore	2006	787	Nearshore
1985	216,757	Offshore	2006	13,059	Nearshore
1985	398,671	Offshore	2006	19,622	Nearshore
1986	167,684	Offshore	2007	5,467	Nearshore
1986	197,829	Offshore	2007	47,571	Nearshore
1986	203,716	Offshore	2008	29,818	Nearshore
1987	279,755	Offshore	2008	34,348	Nearshore
1987	407,648	Offshore	2008	9,523	Nearshore
1987	31,653	Offshore	2009	605,397	Beach/Nearshore
1988	209,615	Offshore	2009	197,170	Beach/Nearshore
1988	163,455	Offshore	2009	7,057	Nearshore
1997	207,732	Nearshore	2009	17,241	Nearshore
1998	198,924	Nearshore	2009	10,390	Nearshore
1999	251,477	Nearshore	2010	322,262	Beach/Nearshore
2000	320,582	Beach	2010	21,186	Nearshore
2001	392,756	Beach	2010	31,859	Nearshore
TOTAL				9,190,535	

Appendix F: Dredged Sediment Placement Data for Pea Island

Most of the sand placed on the northern Pea Island shoreline or in the nearshore region was dredged from the Oregon Inlet navigation channel and associated bar (data from Riggs and Ames 2009 and NCCRC 2010a).

Year	Volume (m ³)	¹ Location
1990	194,927	Beach
1991	359,341	Beach
1991	140,907	Beach (station 60 to 100)
1991	216,063	Beach (station 45 to 55 & 85 to 100)
1992	120,494	Beach
1992	824,190	Beach (station 80 to 134)
1993	331,232	Beach (station 80 to 105)
1995	155,351	Beach
1995	49,873	Beach (station 79 to 80)
1995	128,751	Nearshore
1996	382,443	Beach
1996	207,197	Nearshore
1997	207,732	Nearshore
1998	198,924	Nearshore
1999	251,477	Nearshore
2000	320,582	Beach
2000	186,892	Nearshore
2001	392,756	Beach (station 40 to 43 & 52 to 100)
2002	560,306	Beach (station 80 to 151) & Nearshore
2003	787,142	Beach (station 66 to 188)
2003	82,290	Nearshore
2004	471,308	Beach (station 45–70, 90–115) & Nearshore
2005	131,622	Nearshore
2008	605,397	Beach (station 45–110)
2009	904,578	Beach (station 45–150)
TOTAL	8,211,775	

¹Station numbers are from NCCRC (2010a). Unfortunately, no map of the station numbers could be found.

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.

NPS 603/120139, March 2013

National Park Service
U.S. Department of the Interior



Natural Resource Stewardship and Science

1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

www.nature.nps.gov