National Park Service
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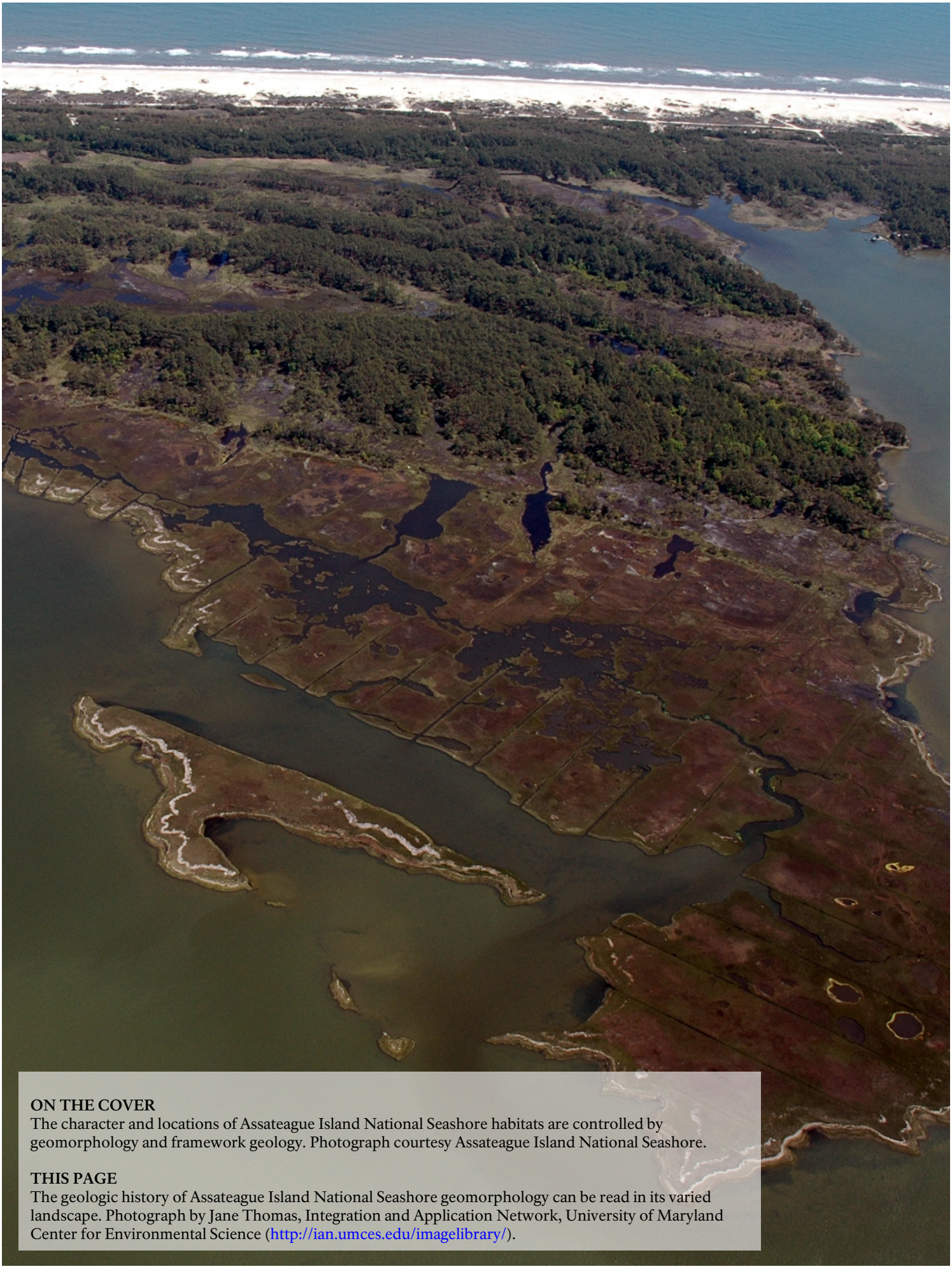
Natural Resource Stewardship and Science

Assateague Island National Seashore

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2013/708



ON THE COVER
The character and locations of Assateague Island National Seashore habitats are controlled by geomorphology and framework geology. Photograph courtesy Assateague Island National Seashore.

THIS PAGE
The geologic history of Assateague Island National Seashore geomorphology can be read in its varied landscape. Photograph by Jane Thomas, Integration and Application Network, University of Maryland Center for Environmental Science (http://ian.umces.edu/imagelibrary/).

Assateague Island National Seashore

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National Park Service
Geologic Resources Division
PO Box 25287
Denver, CO 80225

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

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Contents

Lists of Figures and Tables iv

Executive Summary v

Acknowledgements viii
Credits viii

Introduction 1
Geologic Resources Inventory Program 1
Park Setting 1
Geologic Setting 2

Geologic Issues 11
Storm Impacts 11
Coastal Vulnerability and Sea-Level Rise 12
Inlet Impacts on Sediment Transport Processes 18
Benthic Habitats 22
Landscape and Shoreline Evolution 24
Recreation and Watershed Land Use 26
Disturbed Lands 27
Archeological Resources 30
Paleontological Resources 31
Seismicity 31

Geologic Features and Processes 33
Wave and Current Activity 33
Wind Activity 34
Tidal Activity 34
Sediment Transport Processes 35
Barrier Island System Units 37

Geologic History 45
Mesozoic Era (248 to 65.5 Million Years Ago): Freeing Mountain Sediments to Nourish Beaches 45
Cenozoic Era (the Past 65.5 Million Years): Isostatic Adjustment 45

Geologic Map Data 49
Geologic Maps 49
Source Maps 49
Geologic GIS Data 49
Geologic Map Graphic 50
Map Unit Properties Table 50
Use Constraints 50

Glossary 51

Literature Cited 55

Additional References 67

Appendix A: Scoping Meeting Participants 68

Appendix B: Geologic Resource Laws, Regulations, and Policies 69

GRI Digital Products CD ..... attached

Geologic Map Graphic ..... in pocket

Map Unit Properties Table ..... in pocket

List of Figures

Figure 1. Map of Assateague Island.....1
Figure 2. Schematic cross section of Coastal Plain sediments.....2
Figure 3. Geologic time scale.....3
Figure 4. Neogene and Quaternary geologic time scale.....4
Figure 5. General stratigraphic column for Assateague Island National Seashore.....4
Figure 6. Typical Holocene transgressive barrier island sequence.....5
Figure 7. Graphic illustrating barrier island migration.....5
Figure 8. Schematic graphic of inlets and associated features.....5
Figure 9. Schematic graphics of barrier island habitats.....6
Figure 10. Map of Assateague Island geomorphic areas.....7
Figure 11. Map of inlet formation and closure.....8
Figure 12. Marine shelf bathymetry east of Assateague Island.....8
Figure 13. Bathymetry of Coastal Bays.....9
Figure 14. Sediment distribution map for the Coastal Bays.....10
Figure 15. Photographs of storm impacts......11
Figure 16. Graphic of sea-level rise projections.....15
Figure 17. Map of sea-level rise scenarios and impacts.....16
Figure 18. Coastal vulnerability map.....17
Figure 19. Photograph of Ocean City Inlet.....18
Figure 20. Maps of Assateague Island shoreline migration.....19
Figure 21. Photographs of overwash and subsequent marsh growth.....19
Figure 22. Map of North End Restoration Project activities.....20
Figure 23. Photographs of hopper dredge operations......20
Figure 24. Schematic graphic of local and regional groundwater flow along Assateague Island......21
Figure 25. Photograph of former inlet.....24
Figure 26. Aerial imagery of the southern end of Assateague Island.....25
Figure 27. Map and photograph of mosquito ditches.....28
Figure 28. Photograph of shipwreck.....31
Figure 29. Graph of monthly wave heights measured offshore of Ocean City Inlet Maryland.....33
Figure 30. Schematic graphic of longshore current and sediment transport.....33
Figure 31. Rose diagrams of seasonal wind speed and direction.....34
Figure 32. Map of Toms Cove location over time.....36
Figure 33. Schematic graphic of aeolian sand transportation process......37
Figure 34. Photograph of artificial berm.....37
Figure 35. Photograph of modified land and parking lots.....38
Figure 36. Photograph of shrubland and forest......39
Figure 37. Photograph of heavy minerals on beach......40
Figure 38. Photograph of remnant dune.....41
Figure 39. Photograph of marsh.....42
Figure 40. Photograph of a pond.....44
Figure 41. Paleogeographic maps of North America......46

List of Tables

Table 1. An extremal statistics analysis of water levels and wave heights offshore.....12
Table 2. Summary of projected changes in regional climatic conditions.....13
Table 3. Geology data layers in the Assateague Island National Seashore GIS data......50

Executive Summary

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service Inventory and Monitoring Program. The Geologic Resources Division held a Geologic Resources Inventory (GRI) scoping meeting for Assateague Island National Seashore in Maryland and Virginia on 26-28 July 2005 to discuss geologic resources, the status of geologic mapping, and resource management issues and needs. This report synthesizes those discussions and is a companion document to the previously completed GRI digital geologic map data.

Assateague Island National Seashore is a barrier island that formed about 5,000 years ago along what is now the Atlantic coast of Maryland and Virginia. The island is constantly shaped and reshaped by dynamic coastal processes, including storm-driven overwash, dune formation, and sediment transport driven by waves and wind. These geologic processes, in combination with the island's underlying geology, control a suite of habitats, including bayside mudflats, beach and intertidal zones, dunes and grassland, inland wetlands, salt marsh, and shrub and forest. The island is one of the first areas to exhibit the impacts of climate-related changes, including sea-level rise, storm frequency and intensity, and changes in precipitation.

Assateague Island is protected and managed in its entirety by three government agencies. Assateague Island National Seashore, managed by the National Park Service (NPS), was created in 1965 and includes the majority of the Maryland portion of the island along with the waters that surround the island. The Maryland Department of Natural Resources manages a 3-km-long area as Assateague State Park, and the Virginia section of the island is managed by the U.S. Fish and Wildlife Service as Chincoteague National Wildlife Refuge.

Morton et al. (2007) is the source map for the digital geologic data for Assateague Island National Seashore. The units mapped by Morton et al. (2007) emphasize the origins of the surficial features and are all of Holocene age. Krantz (2010) produced a hydrogeomorphic map of the national seashore that is also included in the digital geologic data

This Geologic Resources Inventory (GRI) report was written for resource managers to assist in resource management and science-based decision making, but it may also be useful for interpretation. The report was prepared using available geologic information. The Geologic Resources Division did not conduct any new fieldwork in association with this report. The report discusses geologic issues facing resource managers at the national seashore, distinctive geologic features and processes within the national seashore, and the geologic history leading to the national seashore's present-day landscape. An overview graphic illustrates the geologic data. The Map Unit Properties Table summarizes the main features, characteristics, and potential management issues for all unconsolidated deposits on the digital geologic map for Assateague Island National Seashore. This report also contains a glossary and a geologic time scale.

Geologic issues of particular significance for resource management at Assateague Island National Seashore were identified during a 2005 GRI scoping meeting. They include the following:

- Storm Impacts. Major storm events shape and reshape the island's geomorphology through waves, island overwash, and, sometimes, breaches. Storms can cause significant beach erosion and overwash that can penetrate the island's interior. Several efforts have been made to identify the combination of storm parameters required to cause specific impacts, such as overwash and erosion, at the national seashore. The magnitude of impact has been related to combinations of peak water level, peak storm-surge height, and storm duration. Climate change projections suggest that hurricanes and northeasters will be more intense in the future, and northeasters will be more frequent. In combination with sea-level rise and diminished sediment supply, increased storm frequency could cause beach and dune erosion, extensive overwash, and inlet formation.
- Coastal Vulnerability and Sea-Level Rise. The rate of sea-level rise is increasing and will impact the national seashore in several ways: shoreline erosion, saltwater intrusion into groundwater aquifers, inundation of wetlands and estuaries, threats to cultural and historic resources as well as infrastructure, increased coastal flooding, changes to coastal geomorphologic processes, and the heights of storm surges, waves, and tides. The North End is already experiencing high shoreline erosion rates and submergence during moderate storms, and has been breached and segmented by large storms in the past. This area may already be at a geomorphic threshold that, with any increase in the rate of sea-level rise, will exhibit large changes in morphology, ultimately leading to the degradation of the island. The NPS-led Climate Change Scenario Planning process has identified likely drivers of landscape change and described multiple plausible future states under these conditions to inform park planning and management.
- Inlet Impacts on Sediment Transport Processes. The stabilization of Ocean City Inlet along the northern

boundary of Assateague Island has changed the nearshore bathymetry and disrupted sediment transport to the national seashore, leading to increased shoreline erosion, decreased island elevation, and island migration. After an island breach in 1962 and extensive overwash events in 1992 and 1998, the U.S. Army Corps of Engineers predicted that without mitigation, the northern end of the island would destabilize and have the potential for another major breach. The North End Restoration Project began in 2002 to mitigate impacts of the loss of natural sand transport processes. This project included a one-time beach renourishment, construction of a temporary foredune and, beginning in 2004, the use of dredge vessels to move sand into the nearshore area of the North End twice each year.

- Hydrology. The geomorphology of the island, combined with natural processes including precipitation, evapotranspiration, and storm overwash, largely control the groundwater hydrology. In turn, the distribution of fresh and brackish groundwater in the unconfined, surficial aquifer, and the geometry of the fresh groundwater lens under the island, control the distribution of vegetation communities and habitat. Contrary to theoretical assumptions of a single, deep, connected fresh groundwater lens that runs beneath the island, data have shown that a fresh lens occurs in segments and is much shallower than predicted.
- Benthic Habitats. Marine surveys in 2012 revealed a remarkable diversity of seafloor habitats. These resources are threatened by ongoing commercial shellfish dredging within Assateague Island National Seashore waters, which creates biological wastelands on the seafloor; and by offshore energy development proposals that include nearshore infrastructure and offshore construction that could alter sediment transport processes. The estuary within and adjacent to Assateague Island provides spawning and nursery areas for many commercial and recreational fish, hard clams, and blue crabs due to the food and habitat structure provided by seagrass and sandy bottoms. Bathymetry and sediment characteristics control the locations of many estuarine resources, including submerged aquatic vegetation, benthic invertebrate communities, and clam distribution and abundance. Because the estuary has a relatively high tendency to retain nutrients and contaminants, they are highly susceptible to pollution. Threats to the estuary's ecological viability include eutrophication due to excess nutrients from agriculture and residential developments; contamination of sediments by toxic non-point pollutants; and destruction of aquatic and wetland habitats by land conversion and boating activity.
- Landscape and Shoreline Evolution. Assateague Island's geomorphologic evolution over several millennia has been driven by sea level, storms, and sediment supply, and controlled by the underlying geologic framework. Overwash plays an important role in the response of barrier islands to storm events and sea-level rise by transporting sand from the beach to island interiors, replenishing back-barrier marshes, creating overwash fans, and driving island migration. Multiple inlets have been documented along Assateague Island. These inlets formed during storms, reworked the seafloor and underlying sediments, deposited new sediments on the marsh platform and in the Coastal Bays, and were subsequently filled back in as a result of natural processes.
- Recreation and Watershed Land Use. Land use along the mainland side of the estuary impacts the sediments and water quality of the Coastal Bays, primarily by increasing nutrient loads and secondarily by increasing in development-related pollution and sediment runoff. Recreation within the national seashore is predominantly low impact. However, over-sand vehicle (OSV) use along a portion of the beach and intertidal zone has geomorphologic and biological impacts. It may disrupt the landward exchange of sediment between the beach and dune, preventing post-storm dune recovery; damage embryo dunes and vegetation within the backshore; and inhibit seaward development of dunes. OSV driving also limits the survival, abundance, and diversity of shorebirds and invertebrates.
- Disturbed Lands. Approximately 30.7 ha (75.9 ac; 0.22%) of Assateague Island is covered by impervious surfaces such as roads, parking lots, and rooftops, mainly within the developed zones of Assateague Island National Seashore and Assateague State Park. The ecosystem function in 100% of the island's 960 ha (2375 ac) of salt marsh has been altered by more than 140 km (87 mi) of ditches created during a 1930s-era effort to control mosquitoes. To restore wetland hydrology, the national seashore is currently filling these ditches using limited quantities of sand mined from the OSV-zoned beach. An artificial dune is maintained within the national seashore's developed zone and Assateague State Park to protect infrastructure (roads and visitor facilities), but impedes sand transport and overwash processes. A low foredune constructed on the North End to prevent island breaching has impeded overwash processes and degraded habitat. Recent modifications should mitigate these impacts. Recreational boat propellers sometimes damage seagrass beds. Feral horses cause dune erosion, marsh compaction, and changes in plant community structure.
- Archeological Resources. Many historic accounts describe shipwrecks within or near the national seashore, and some wreckage has been found and inventoried. Waves and sediment movement can not only break apart and bury existing shipwrecks, but also move the wreckage alongshore. Ships that wrecked in the historic inlets or the estuary have since been buried within the body of the island, and are sometimes exposed after large storms temporarily move sediment off of the beaches. Meanwhile, the migrating shoreline has become further removed from wrecks in the nearshore. As the shoreface within the national seashore continues to erode, artifacts from shipwrecks sometimes wash ashore. Additionally, artifacts from

prehistoric cultures are periodically deposited on the Ocean City (Maryland) beaches.

- Paleontological Resources. Pleistocene-aged fossils are known to occur at the national seashore. They are usually fragmentary and are not found in situ, but rather are washed ashore or eroded from the shoreface or body of the island.
- Seismicity. A tsunami may be triggered by large-scale submarine slope failure along the continental shelf off of southern Virginia and North Carolina. This risk may be increased due to warming bottom waters and the subsequent melting of gas hydrates in the seafloor. Tsunami impacts would also be possible along the Maryland and Virginia coastline if a thrust earthquake occurred along the eastern Iberian–African plate boundary or west of Spain.

Geologic features of particular significance for resource management at Assateague Island National Seashore include the following:

- Wave and Current Activity. The ocean coastline is wave dominated, with a mean deep-water significant wave height of 1.2 m (3.9 ft). Hurricanes and extra-tropical (northeaster) storms can produce local wave heights in excess of 8 m (26 ft). Waves drive the longshore current, which in turn moves sediment predominantly southward.
- Wind Activity. Predominant wind direction changes seasonally. Winter winds from the northwest often exceed 10 m/s (22 mi/hr). Along the western and northern margins of the Coastal Bays estuary, wind conditions have a greater effect on water levels and current velocities than do tides. Sustained high winds can build waves in the estuary, increasing turbidity and marsh erosion. Wind also transports significant quantities of sediment between the beach and dunes, into the island's interior, and into the Coastal Bays.
- Tidal Activity. The national seashore's ocean coastline is classified as microtidal and has a semi-diurnal tide with a mean range of 1.02 m (3.36 ft) and an extreme range (spring tide) of 1.22 m (4.00 ft). In the Maryland Coastal Bays, tidal cycles exert significant control on circulation patterns and tidal ranges. Tidal influence diminishes rapidly with increasing distance from the inlet, and wind becomes the stronger influence.
- Sediment Transport Processes. The ocean shoreline derives sand from erosion of the shoreface and Pleistocene headlands at Rehoboth Beach and Bethany Beach, Delaware. Net longshore sediment transport is southward due to strong winter northeaster storms; in the summer, waves from the southeast drive sand transport less vigorously northward. The net annual longshore transport is estimated to be between 115,000 and 214,000 m^3/year (150,400 and 279,900 yd^3/year) toward the south. Depth of closure, defined as the depth beyond which sediment transport of engineering significance does not occur, is estimated to be –6.2 m (–20.3 ft) and is typically found about 275 to 400 m (900 to 1300 ft) from the high tide line. Toms Cove Spit, an accretionary spit complex, is at the terminus of the regional sediment transport system and has grown by 6 km (3.7 mi) since the mid-1800s; it continues to build southwestward at the rate of approximately 50 m (164 ft) per year. Sediment transported into the Coastal Bays comes from several sources: suspended sediments transported by streams, seawater that becomes turbid during storms, erosion of the mainland shoreline, overwash across the island, and windblown sand from the island. Aeolian processes are important to beach/dune interactions, including building and maintaining dunes, and for carrying sediment to the island interior and into the estuary.
- Barrier Island System Units. A summary of 19 geomorphic map units can be found in the Map Unit Properties Table, and detailed descriptions of each unit, including their features and processes, are available in the "Geologic Features and Processes" chapter.

Acknowledgements

The GRI is administered by the Geologic Resources Division of the Natural Resource Stewardship and Science Directorate.

The Geologic Resources Division relies on partnerships with institutions such as Colorado State University, the U.S. Geological Survey, state geological surveys, local museums, and universities to develop GRI products.

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Introduction

This chapter briefly describes the National Park Service Geologic Resources Inventory Program, as well as the regional geologic setting and history of Assateague Island National Seashore.

Geologic Resources Inventory Program

The Geologic Resources Inventory (GRI) is one of 12 baseline natural resource inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division of the NPS Natural Resource Stewardship and Science Directorate administers the GRI.

The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (section 204), the 2006 NPS Management Policies, and in the Natural Resources Inventory and Monitoring Guideline (NPS-75). Refer to the "Additional References" chapter for links to these and other resource management documents.

The objectives of the GRI are to provide geologic map data and pertinent geologic information to support resource management and science-based decision making in more than 270 natural resource parks throughout the National Park System. To realize these objectives, the GRI team undertakes three tasks for each natural resource park: (1) conduct a scoping meeting and provide a scoping summary, (2) provide digital geologic map data in a geographic information system (GIS) format, and (3) provide a GRI report. These products are designed and written for nongeoscientists. Scoping meetings bring together park staff and geologic experts to review available geologic maps, develop a geologic mapping plan, and discuss geologic issues, features, and processes that should be included in the GRI report. Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan into digital geologic map data in accordance with their data model. Refer to the "Geologic Map Data" chapter for additional map information. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the geologic report. This geologic report assists park managers in the use of the map, and provides an overview of the national seashore geology, including geologic resource management issues, geologic features and process, and the geologic history leading to the national seashore's present-day landscape.

For additional information regarding the GRI, including contact information, please refer to the Geologic Resources Inventory website (http://www.nature.nps.gov/geology/inventory/). The current status and projected completion dates for GRI products are available on the GRI status website (http://www.nature.nps.gov/geology/GRI_DB/Scoping/Quick_Status.aspx).

Park Setting

Assateague Island is part of the Delmarva (**Del**aware-**Mar**yland-**Virgin**ia) Peninsula, which lies along the Atlantic Coast of North America (fig. 1). This barrier island stretches along 59.5 km (37 mi) of the coastline through Worcester County, Maryland, and Accomack County, Virginia. It separates the Atlantic Ocean from the Sinepuxent and Chincoteague bays, part of the lagoonal estuary system known as the Coastal Bays. It is bounded by Ocean City Inlet to the north and Chincoteague Inlet to the south.

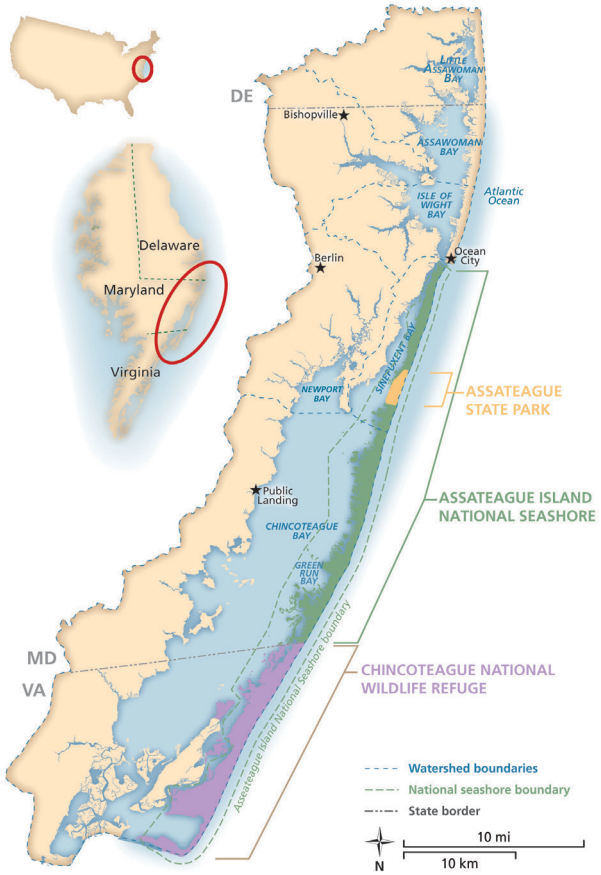


Figure 1. Map of Assateague Island. Assateague Island is a barrier island along the Atlantic coast of Maryland and Virginia. It is managed by three different agencies; the National Park Service manages Assateague Island National Seashore. Figure 2.5 from Carruthers et al. (2011).

Assateague Island is protected and managed in its entirety by three government agencies. The NPS has managed Assateague Island National Seashore since 21 September 1965, when Congress authorized it "…for the purpose of protecting and developing Assateague Island in the States of Maryland and Virginia for public outdoor recreation use and enjoyment" (Public law 89-195). The

legislation was amended on 21 October 1976 to include "measures for the full protection and management of the natural resources and natural ecosystems of the Seashore" (Public law 94-578). The NPS owns most (3340 ha [8253 ac]) of the land along the Maryland portion and some (10 ha [24 ac]) of the land along the Virginia portion of Assateague Island. The NPS also manages the island's surrounding waters in Virginia and Maryland (13,034 ha [32,194 ac]): marine waters up to 0.8 km (0.5 mi) beyond the mean high water line on the Atlantic (eastern) side, and estuarine waters extending a variable distance (0.18 to 1.5 km [0.11 to 0.93 mi]) on the bay (western) side. The barrier island also includes lands protected by two other agencies. The U.S. Fish and Wildlife Service protects and manages migratory birds and other wildlife and provides for wildlife-oriented public use within the Virginia portion of Assateague Island known as Chincoteague National Wildlife Refuge. The Maryland Park Service manages the resources to provide extensive visitor services within a 3-km-(1.8-mi-) long section of the island known as Assateague State Park (fig. 1). The island is relatively undeveloped, with small areas dedicated to visitor-services infrastructure, such as short roads, campgrounds, and contact stations. Two bridges connect the island to the mainland peninsula, one in Maryland and one in Virginia.

Assateague Island supports a suite of habitats dependent on underlying geology and geologic processes, including bayside mudflats (215 ha [532 ac]), beach and intertidal zones (962 ha [2377 ac]), dunes and grassland (909 ha [2247 ac]), inland wetlands (225 ha [555 ac]), salt marsh (2120 ha [5239 ac]), and shrub and forest (2930 ha [7240 ac]) settings (Carruthers et al. 2011). Land use in the watersheds surrounding the estuary, known as the Coastal Bays, has a more rural character than the surrounding Mid-Atlantic coast. It includes agriculture (33.3%), forest (38.4%), wetlands (16.3%), and beaches and bare ground (1.8%), but it faces increasing development, including commercial and urban (3.6%) and residential (6.8%) land use (Carruthers et al. 2011). Assateague Island is dynamic, shaped by underlying geology and geologic processes over time scales ranging from thousands of years (glacial melting) to days (storms).

Geologic Setting

Assateague Island is within the Atlantic Coastal Plain, a physiographic province characterized by a low and flat landscape underlain by unconsolidated or partially consolidated sediments such as gravel, sand, silt, and clay. If viewed in cross section, the Coastal Plain sediments would be wedge shaped, thinnest in the west and thickening eastward to almost 2.4 km (1.5 mi) thick at the Atlantic coastline (Krantz et al. 2009) (fig. 2). Although the Atlantic coast evolved over a 250-million-year period (figs. 3 and 4), Assateague Island formed only about 5000 years ago, and the sediments and landforms that are exposed on the national seashore, and detailed in the geologic map, are all of Holocene age (figs. 4 and 5).

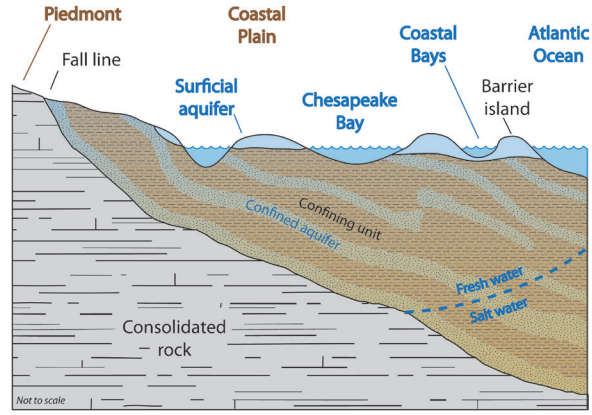


Figure 2. Schematic cross section of Coastal Plain sediments. In cross section, Coastal Plain sediments are wedge shaped, thickening eastward to the Atlantic coastline. The primarily unconsolidated Coastal Plain sediments overlie consolidated, much older and much harder metamorphosed rocks of the Piedmont province. Graphic by Rebecca Port (NPS Geologic Resources Division) redrafted from Krantz et al. (2009).

These sediments and landforms tell the story of barrier island response to rising sea level. As the barrier island migrates landward, beach and dune sands are pushed westward onto the marsh and into the estuary. This results in interbedded layers of sands, muds, and peats (fig. 6) that are then exposed on the ocean side of the island as the rollover continues (fig. 7). Inlets have opened and closed along the length of the island, reworking sediments and leaving deposits of coarse sand, gravel, and sandy flood and ebb tidal deltas (fig. 8).

The resulting landforms and underlying geologic framework, with its control on groundwater flow and availability, shape the character and locations of the island's many habitat types (fig. 9), which are further influenced by ongoing physical processes such as storms and waves, and anthropogenic modifications including inlet stabilization and dune construction.

The width of the island ranges from 260 to 2000 m (0.16 to 1.25 mi), and elevations are generally around 2 m (6.5 ft), although dunes may be up to 10 m (33 ft) high. The island has three distinct components: the low, narrow, and erosional northern end; the wider, more stable middle; and the accretionary southern end (fig. 10).

The northern 10 km (6.2 mi) of Assateague Island (the North End) is a dynamic storm-structured environment that is low and narrow relative to the rest of the island; cross-island widths are 260 to 625 m (850 to 2050 ft). The North End has a beach and low (2 m [6.5 ft] North American Vertical Datum of 1988 [NAVD88][1]) berm on the ocean side of the island, a sparsely vegetated back-barrier flat (2.2 to 2.45 m [7.2 to 8 ft]), discontinuous low dunes (3 to 4 m [9.8 to 13 ft]), and narrow fringing salt marsh and overwash fans bounded by the Coastal Bays estuary (Schupp et al. 2013). It also has been influenced by anthropogenic modifications, including a jetty, an

[1]Mean high water is equivalent to 0.34 m (1.1 ft) NAVD88.

Eon	Era	Period	Epoch	mya	Life Forms	North American Events
Phanerozoic	Cenozoic (CZ)	Quaternary (Q)	Holocene (H)	0.01	Age of Mammals: Modern humans	
			Pleistocene (PE)	2.6	Extinction of large mammals and birds	Ice ages
						Cascade volcanoes (W)
		Tertiary (T): Neogene (N)	Pliocene (PL)	5.3	Large carnivores	Linking of North and South America
			Miocene (MI)	23.0	Whales and apes	Sierra Nevada Mountains (W)
						Basin-and-Range extension (W)
		Tertiary (T): Paleogene (PG)	Oligocene (OL)	33.9		
			Eocene (E)	56.0	Early primates	Laramide Orogeny ends (W)
			Paleocene (EP)	**66.0**	Mass extinction	
	Mesozoic (MZ)	Cretaceous (K)		145.0	Age of Dinosaurs: Placental mammals	Laramide Orogeny (W)
						Western Interior Seaway (W)
					Early flowering plants	Sevier Orogeny (W)
		Jurassic (J)		201.3		Nevadan Orogeny (W)
						Elko Orogeny (W)
						Breakup of Pangaea begins
		Triassic (TR)			Mass extinction First mammals Flying reptiles	
				252.2	Mass extinction	Sonoma Orogeny (W)
	Paleozoic (PZ)	Permian (P)		298.9	Age of Amphibians: Coal-forming forests diminish	Supercontinent Pangaea intact
						Ouachita Orogeny (S)
		Pennsylvanian (PN)		323.2	Coal-forming swamps Sharks abundant First reptiles	Alleghany (Appalachian) Orogeny (E)
						Ancestral Rocky Mountains (W)
		Mississippian (M)		358.9		Antler Orogeny (W)
					Mass extinction	
		Devonian (D)		419.2	Fishes: First amphibians First forests (evergreens)	Acadian Orogeny (E-NE)
		Silurian (S)		443.4	First land plants Mass extinction	Taconic Orogeny (E-NE)
		Ordovician (O)		485.4	Marine Invertebrates: First primitive fish Trilobite maximum Rise of corals	
		Cambrian (C)		**541.0**	Early shelled organisms	Extensive oceans cover most of proto-North America (Laurentia)
						Avalonian Orogeny (NE)
Proterozoic	Precambrian (PC, X, Y, Z)				First multicelled organisms	Supercontinent rifted apart
					Jellyfish fossil (~670 mya)	Formation of early supercontinent
						Grenville Orogeny (E)
						First iron deposits
				2500		Abundant carbonate rocks
Archean					Early bacteria and algae	Oldest known Earth rocks (~3.96 billion years ago)
				4000		
Hadean					Origin of life	Oldest moon rocks (4–4.6 billion years ago)
				4600	Formation of the Earth	Formation of Earth's crust

Figure 3. Geologic time scale. The divisions of the geologic time scale are organized stratigraphically, with the oldest at the bottom and youngest at the top. GRI map abbreviations for each geologic time division are in parentheses. Major North American life history and tectonic events are included Compass directions in parentheses indicate the regional locations of events. Bold horizontal lines indicate major boundaries between eras; boundary ages are millions of years ago (mya). Figure 4 provides additional detail about Atlantic Coast events during the Quaternary and Neogene periods (indicated by green bar). Graphic design by Trista Thornberry-Ehrlich (Colorado State University) and Rebecca Port (NPS Geologic Resources Division), with ages from the International Commission on Stratigraphy (http://www.stratigraphy.org/ICSchart/ChronostratChart2012.pdf).

Era	Period	Epoch	Age	mya	Atlantic Coast Events
Cenozoic	Quaternary	Holocene		0.01	Barrier islands moved to their present position when the rate of sea level rise slowed and the low-lying basins flooded to create the Coastal Bays
		Pleistocene	Tarantian (Upper)	0.13	Continental glaciers began melting again, causing sea level to rise and push sediments westward from the (present-day) continental shelf (about 18,000 years ago)
			Ionian (Middle)	0.78	Last Glacial Maximum of the Wisconsinan glaciation (about 22,000-20,000 years ago); sea level dropped to 125 m below present; rivers incised the basins that would later become the Coastal Bays estuary
			Calabrian	1.8	
			Gelasian	2.6	
	Tertiary – Neogene	Pliocene	Piacenzian		
			Zanclean	5.3	Delmarva Peninsula began forming from glacial sediments being carried down rivers
		Miocene	Messinian		
			Tortonian		
			Serravallian		
			Langhian		
			Burdigalian		
			Aquitanian	23.0	

Figure 4. Neogene and Quaternary geologic time scale. This time scale details Atlantic coast events during the past 23 million years (mya) as indicated by the green bar on figure 3. Graphic design by Trista Thornberry-Ehrlich (Colorado State University) and Rebecca Port (NPS Geologic Resources Division), with ages from the International Commission on Stratigraphy (http://www.stratigraphy.org/ICSchart/ChronostratChart2012.pdf).

Era	Period	Epoch	Age*	Unit	Description	Approx. depth**
Cenozoic	Quaternary	Holocene	0.01–present	Barrier sand (Qbs); Tidal marsh (Qtm)	Barrier sand: light-colored, well-sorted, fine- to very coarse-grained feldspathic quartz sand with gravel and shell fragments; extensive cross bedding due to wave action; up to 6 m (20 ft) thick. Tidal marsh deposit: clay/silt with high organic matter; unconsolidated and soupy; less than 5 m thick; exposed along western (bay) side of island.	Surface to –4.5 m
					Lagoonal sandy mud/silt	–4.5 to –8 m
					Base of basal peat layer marks the base of Holocene deposits; sometimes exposed along bay side or (after large storms) interior, and chunks sometimes erode from shoreface and are carried onto beach.	–8 to –10 m
		Pleistocene	1.2–0.8	Sinepuxent Formation (Qs)	Marginal marine deposit. Coastal sequence of dark-colored, poorly sorted, silty, fine to medium sand with thin beds of peaty sand and black clay. Abundant heavy minerals (amphibole and pyroxene materials). All major clay mineral groups present (kaolinite, montmorillonite, illite, chlorite). Sand consists of quartz, feldspar, and abundance of mica (muscovite, biotite, and chlorite) that makes Qs lithologically distinct from older underlying units.	–10 to –23 m
	Tertiary – Neogene	Pliocene	24–1.8	Beaverdam Formation (Tb)	Medium sand with scattered beds of coarse sand, gravelly sand, and silty clay, interbedded with clay-silt laminae. Unweathered Beaverdam Sand sediments may be pale blue-green or white; weathered sediments are orange or reddish brown.	–23 to –30 m
		Pliocene–Miocene		Yorktown-Eastover formations (undivided) (Tye)	Lenticular silts, clays, and fine sand	Below –30 m
					Grey, medium- to fine- grained shelly sand	
		Paleocene				

Age is in millions of years before present and indicates the time spanned by the associated epoch or period. Rock/sediment units associated with those epochs or periods may not encompass the entire age range. ** depth is meters, relative to Mean Sea Level.

Figure 5. General stratigraphic column for Assateague Island National Seashore. The Sinepuxent, Beaverdam, and Yorktown-Eastover Formations are mapped in the subsurface of the national seashore (map unit symbols in parentheses). Colors are standard colors approved by the U.S. Geological Survey to indicate different time periods on geologic maps; they also correspond to the colors on the Map Unit Properties Table. See the Map Unit Properties Table for more detail. Column compiled using the following sources: Biggs (1970), Owens and Denny (1979), Kraft et al. (1987), Wells (1994), Dillow et al. (2002), Wells et al. (2002), Bratton et al. (2004, 2009), Hobbs et al. (in press), and David Krantz, professor of geology, University of Toledo, personal communication, 18 June 2009.

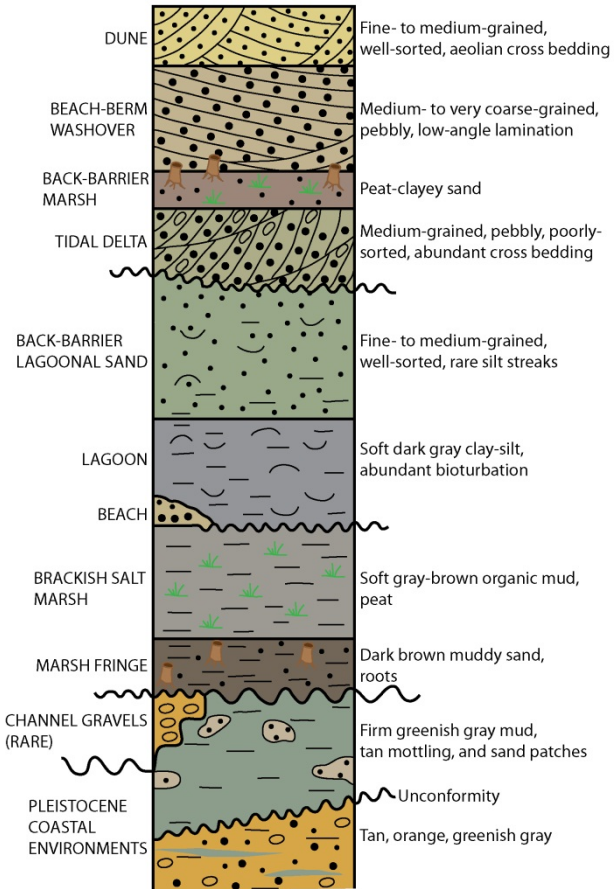


Figure 6. Typical Holocene transgressive barrier island sequence. As the barrier island migrates landward, beach and dune sands are pushed westward onto the marsh and into the estuary. This process results in interbedded layers of sands, muds, and peats. Graphic redrafted by Trista Thornberry-Ehrlich (Colorado State University) after figure 23 in Kraft (1971).

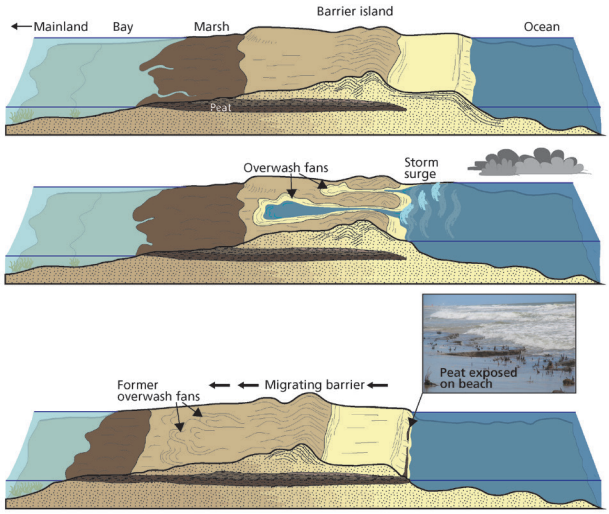


Figure 7. Graphic illustrating barrier island migration. Overwash carries sand onto and across the island, moving sand from the ocean shoreface to the bay. Over time, the island migrates landward, building on top of the old marsh. Peat from the old marsh that lies beneath the beach sands is exposed as the island migrates westward. Graphic by Trista Thornberry-Ehrlich (Colorado State University). Assateague Island National Seashore photograph.

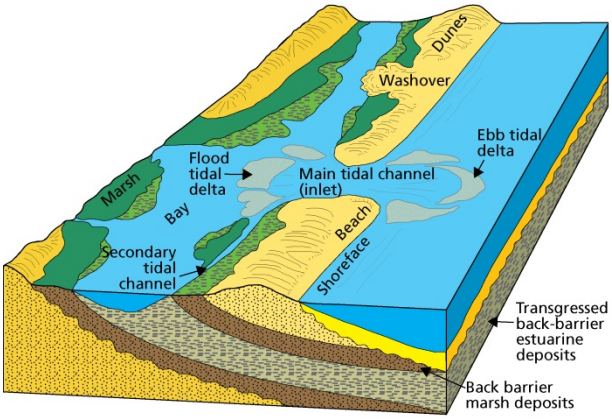
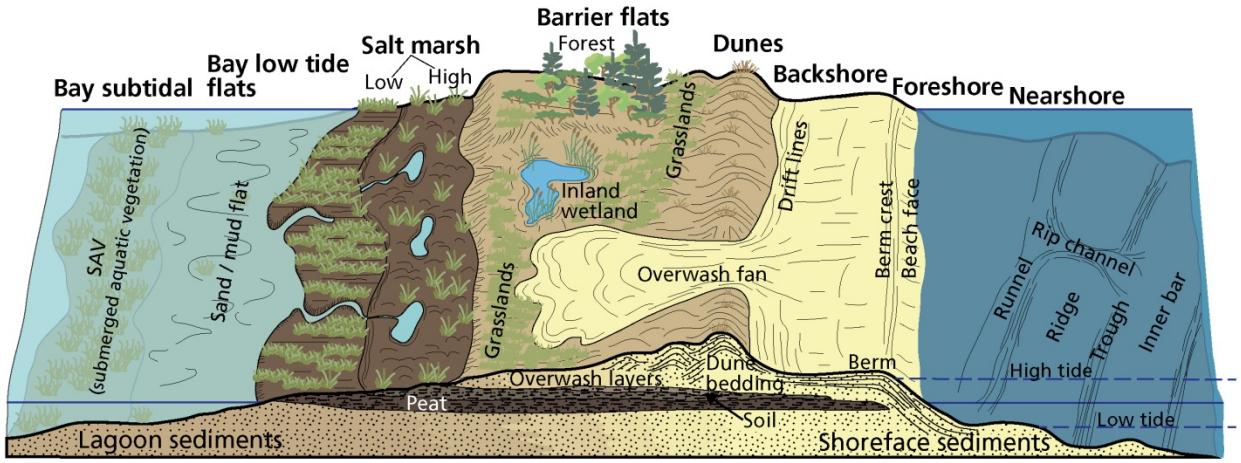


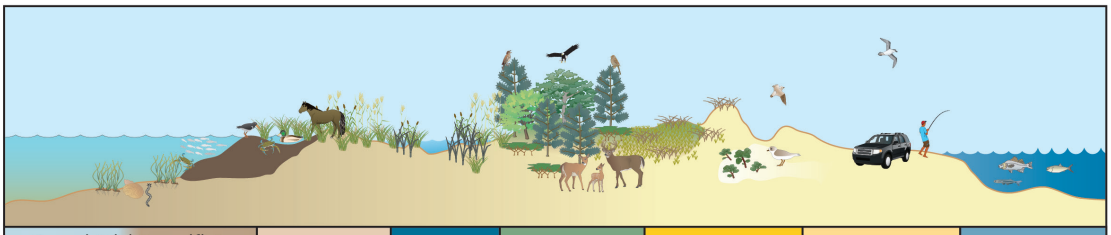
Figure 8. Schematic graphic of inlets and associated features. Inlets connect the ocean to the estuary, reworking sediments and leaving deposits of coarse sand, gravel, and sandy flood and ebb tidal deltas. Graphic by Trista Thornberry-Ehrlich (Colorado State University) redrafted after figure from Reinson (1992), available online from Society for Sedimentary Geology at http://www.sepmstrata.org/page.aspx?pageid=299 (accessed 28 January 2013).

artificial berm, and spoil dunes (reclaimed land) (see Map Unit Properties Table and Geologic Map Graphic). Its low and narrow character makes it particularly vulnerable to storm-driven waves and overwash. This geomorphic variability is, in turn, strongly correlated with vegetation community composition and supports diverse and regionally significant natural resources and processes (Roman and Nordstrom 1988). The globally rare sand overwash flats and sparsely vegetated upper beaches are both prime early-succession beach habitats that are used by multiple state and federally-listed rare, threatened, and endangered species (Schupp et al. 2013).

The middle section of Assateague Island is the widest section of the island (700-2000 m [0.40 to 1.20 mi]), with a wide barrier core and multiple accretion mounds. It contains the oldest sections of the island, including established maritime forests. The middle section has experienced inlet formation and closure at multiple locations (fig. 11), sometimes repeatedly; this history can be read in the landscape of accretion mounds, accretion mound swales, and inactive overwash zones. For example, the remnant flood-tidal delta and beach ridges at Green Run mark the location of a former inlet that was likely stable for long periods of time (Krantz et al. 2009). As a result of this and other inlets, the ancestral Chincoteague Bay would have been different in character from the modern bay. The dynamics were probably similar to those of the marshy coastal lagoons behind the Virginia barrier islands, with greater influence of seawater and exchange with the coastal ocean, more fine suspended sediment entering the Coastal Bays from the ocean, substantially larger tidal range, more vigorous tidal currents, and considerably shorter residence time (Krantz et al. 2009).

The southern end of Assateague Island is known as Toms Cove Hook. This beach ridge complex is an accretionary spit that has grown by 6 km (3.7 mi) since the mid-1800s and continues to build southward. Just north of this beach ridge complex is a very low and narrow isthmus





	Bay subtidal & mudflats		Salt marsh	Inland wetlands	Forest & shrubland	Dunes & grassland	Beach & intertidal	Atlantic subtidal
	Bay subtidal	Bay mudflats						
Area (ha)	6,628.0	215.1	2,120.0	224.6	2,930.0	909.4	962.1	6,402.0
% Total Land	--	--	29.7	3.1	41.0	12.7	13.5	--
							Total area of Assateague Island (ha)	20,391.2

Figure 9. Schematic graphics of barrier island habitats. The character and locations of island habitats are controlled by the island's underlying geologic framework, groundwater flow and availability, ongoing physical processes such as storms and waves, and anthropogenic modifications including inlet stabilization and dune construction. Upper: Typical barrier island zonation. Graphic redrafted by Trista Thornberry-Ehrlich (Colorado State University) after a figure from "Environmental Geology", http://people.hofstra.edu/j_b_bennington/33notes/coastal_landforms.html (accessed 28 January 2013). Lower: Conceptual diagram of Assateague Island habitats and total areas. Figure 2 from Carruthers et al. (2012).

that continues to function as an active overwash zone and occasionally experiences temporary breaching during strong storms. The marshes and artificial impoundments on this southern end also provide important habitat for birds and other wildlife.

On the eastern side of Assateague Island, the nearshore marine shelf is surfaced with medium to fine sand. Shore-oblique ridges are spaced 2 to 4 km (1.2 to 2.5 mi) apart and extend kilometers to tens of kilometers (Swift et al. 2003) in a southwest–northeast orientation with a maximum relief of 5 to 10 m (16 to 33 ft) (Hobbs et al. in press) (fig. 12). These ridges are common along the mid-Atlantic coast in regions that feature barrier island transgression, mixed-energy wave-dominated shorelines, and lateral inlet migration to the south or southwest (McBride and Moslow 1991). The Assateague Island area has the largest number and highest density of shore-oblique ridges. They may have developed from ebb-tidal delta sediments reshaped by inlet migration and shoreface retreat (McBride and Moslow 1991). These ridges abruptly disappear at the southern end of Assateague Island, at the northern extent of Chincoteague Bight. Recent seismic surveys of Chincoteague Bight discovered several large, deep paleochannels, possibly of an ancestral Potomac River, which explain the presence of what appears to be a broad shelf valley extending toward Washington Canyon. The paleochannels may also be the reason for the offset of Wallops and Assateague islands (Wikel 2008).

Along the western side of Assateague Island, the Coastal Bays are lagoonal estuaries with a mean depth of 1 to 1.2 m (3.3 to 3.9 ft) (fig. 13). Depths greater than 3 m (10 ft) and up to 9.8 m (32 ft) occur in some locations as a result of dredging. For example, the Federal Navigation Channel, which is maintained at a depth of 3 m (10 ft), extends from Ocean City Inlet north into Isle of Wight Bay and south into Sinepuxent Bay, where it connects with channels that are maintained at 1.8 m (6 ft). Numerous dredge holes are also present in Assawoman Bay and along the eastern side of Isle of Wight Bay. The sediment from Isle of Wight Bay was taken to fill in low-lying areas on Fenwick Island for development or to replenish the Ocean City beach after the March 1962 storm (Wells and Conkwright1999).

Near the tidal inlets, sediment is almost entirely a medium to fine sand with some gravel (fig. 14). Away from the inlets, fine-grained sediments and organic-rich muds settle after being transported by streams or eroded from the shoreline and marsh. Overwash sheets on the back-barrier flat are predominantly sand, but are often interbedded with marsh peats and lagoonal silts deposited between storm events (Krantz et al. 2009).

These predominantly sandy soils facilitate groundwater flow, the major pathway of freshwater to the bays (Wazniak et al. 2004). An estimated 75% of the sand comes from storm overwash, inlet transport, and wind-blown (aeolian) transport across Assateague Island, with the remainder (25%) coming from shoreline erosion (Wells et al. 2003).

Figure 10. Map of Assateague Island geomorphic areas. Island areas include the low, narrow, and erosional northern end; the wider, more stable middle; and the accretionary southern end. Graphic by Rebecca Port (NPS Geologic Resources Division)

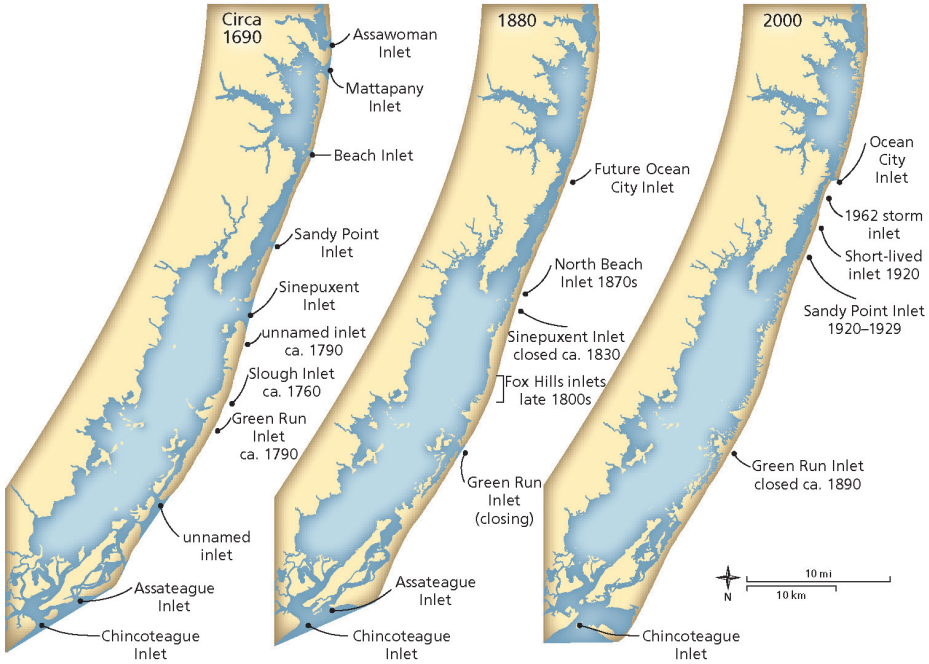


Figure 11. Map of inlet formation and closure. Assateague Island has experienced inlet formation and closure at multiple locations, sometimes repeatedly. Figure 2.12 from Carruthers et al. (2011).

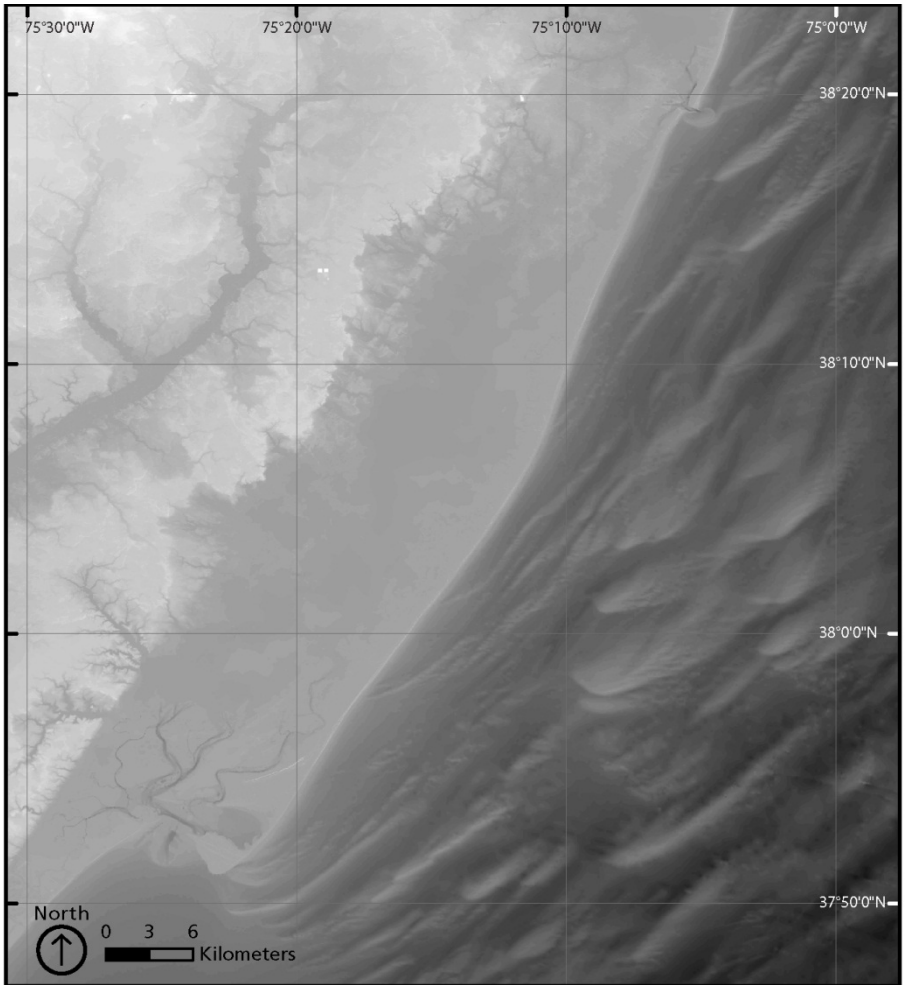


Figure 12. Marine shelf bathymetry east of Assateague Island. The nearshore marine shelf bathymetry includes shore-oblique ridges that are spaced 2 to 4 km (1.2 to 2.5 mi) apart and extend kilometers to tens of kilometers in a southwest–northeast orientation with a maximum relief of 5 to 10 m (16 to 33 ft). Graphic by Rebecca Port (NPS Geologic Resources Division) using data from Grothe et al. (2010).

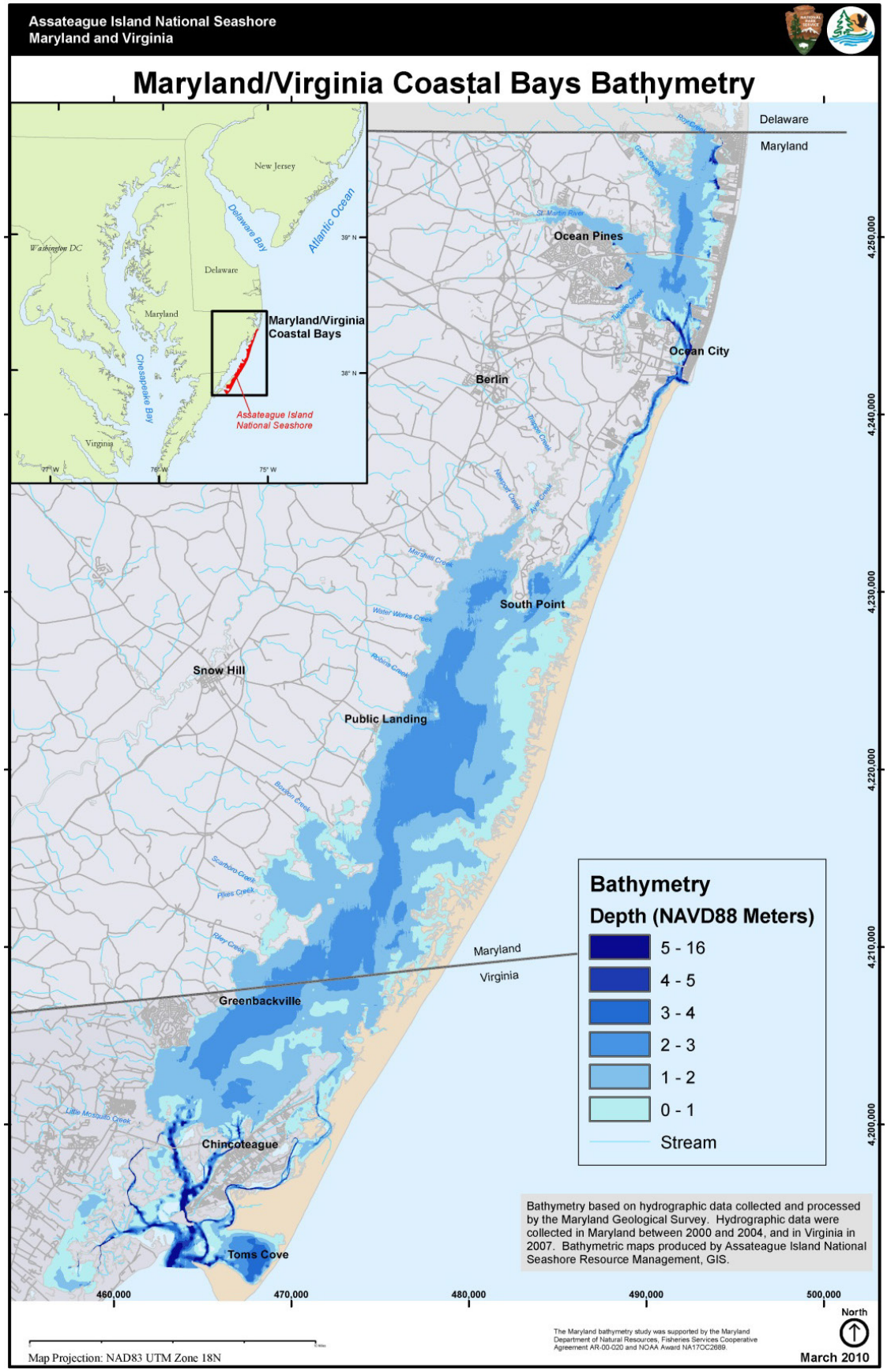


Figure 13. Bathymetry of Coastal Bays. Data by National Park Service and Maryland Geological Survey. Figure by Assateague Island National Seashore (2008).

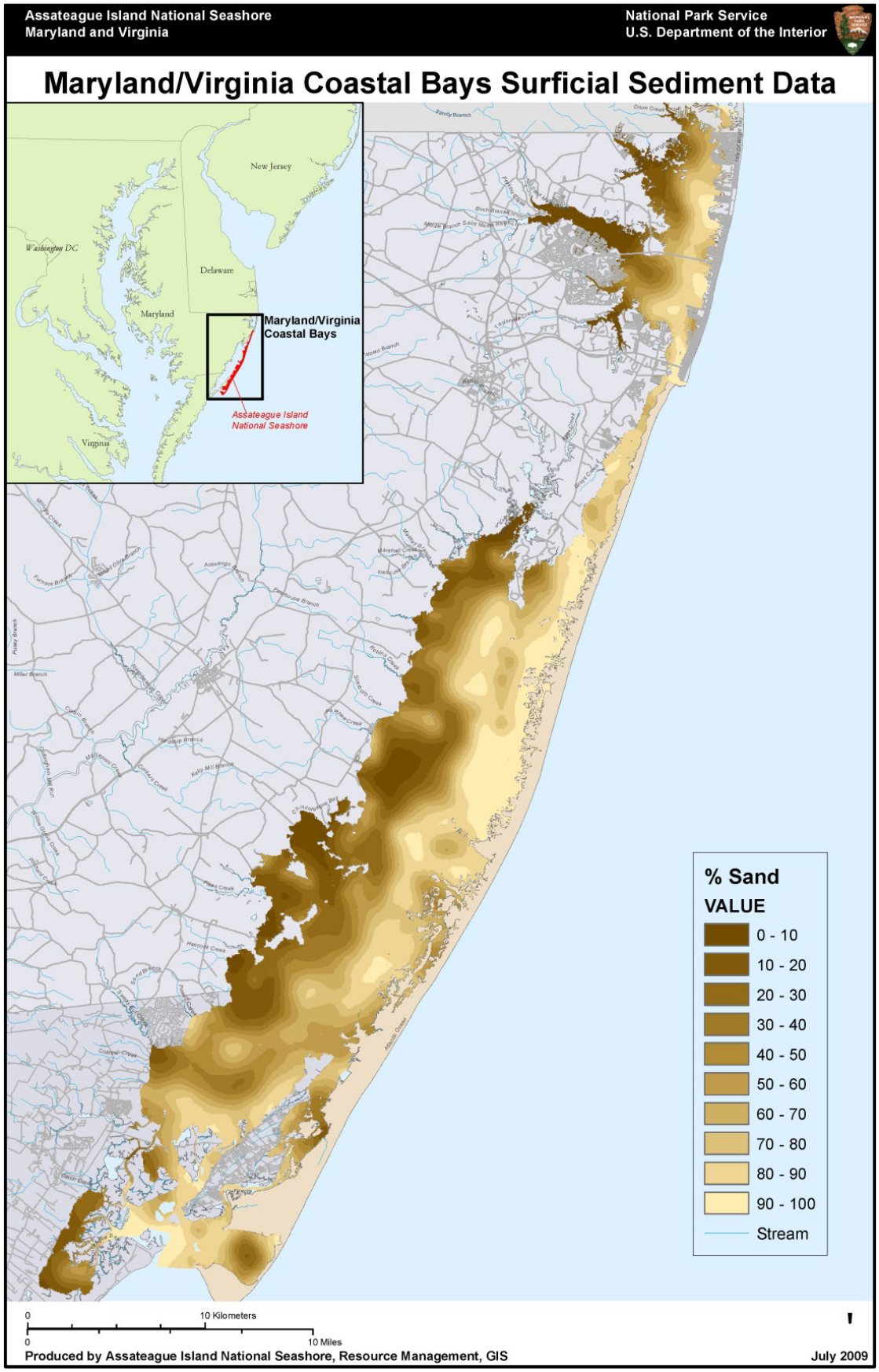


Figure 14. Sediment distribution map for the Coastal Bays. Higher proportions of sand are found at current and former inlet sites. Data by National Park Service and Maryland Geological Survey. Figure by Assateague Island National Seashore (2008).

Geologic Issues

Geologic issues described in this chapter may impact park resources or visitor safety and could require attention from resource managers. Contact the Geologic Resources Division for technical and policy assistance.

Geologic issues facing Assateague Island National Seashore include natural processes, anthropogenic influences, and natural processes exacerbated by anthropogenic influences. The 2005 scoping meeting (summarized by Thornberry-Ehrlich 2005) identified 11 major geologic issues that shape the national seashore's resources and require additional study:

- Storm Impacts
- Coastal Vulnerability and Sea-Level Rise
- Inlet Impacts on Sediment Transport Processes
- Hydrology
- Benthic Habitats
- Landscape and Shoreline Evolution
- Recreation and Watershed Land Use
- Disturbed Lands
- Archeological Resources
- Paleontological Resources
- Seismicity

Storm Impacts

Major storm events shape and reshape the island's geomorphology through waves; overwash, a process that moves water and sand onto and sometimes across the island; and breaches, which are new openings through the island that allow water to move back and forth between the ocean and estuary over multiple tidal cycles. These storms fall into two main categories: 1) extra-tropical storms in the fall (October–November) or winter (February–March) and 2) hurricanes during summer and fall (July–November) (Krantz et al. 2009). Extra-tropical storms, which form outside the tropics, are referred to as "northeasters" or "nor'easters" due to the most damaging wind direction during these storms, as they move north along the coast. One strong northeaster, the 1962 Ash Wednesday Storm, breached the North End, destroying private infrastructure on the island and fueling public support for protection and conservation of Assateague Island. Hurricanes, the second type of major storm, tend to be of shorter duration than northeasters and rarely make landfall along the mid-Atlantic barrier islands. However, they can still impact the island with large waves and storm surges. For example, the hurricane of 1933 opened Ocean City Inlet (Dolan et al. 1980).

Storms can cause significant beach erosion and overwash (fig. 15) that has penetrated the island's interior at elevations up to 2.2 m (NAVD88) during the 2005-2011 data collection period (Carruthers et al. 2011). The frequency and intensity of overwash are in large part controlled by six factors: 1) beach topography (Leatherman 1976); 2) berm width and beach volume (Matias et al. 2009); 3) significant wave height (which is, in turn, driven by wind); 4) water level and storm surge (Fisher et al. 1974; Leatherman 1976; Morton and Sallenger 2003; Krantz et al. 2009); 5) storm duration (Morton and Sallenger 2003; Munger and Kraus 2010); and 6) nearshore bathymetry (Morton and Sallenger 2003).

Figure 15. Photographs of storm impacts. Storms can cause beach erosion, dune scarping (top), and overwash (bottom). Assateague Island National Seashore photographs.

Several efforts have been made to quantify the combination of storm parameters that produce specific impacts, such as overwash and erosion, at Assateague Island National Seashore. One study indicated that overwash along the North End is likely during weather events that include both a peak water level greater than 0.7 m (2.3 ft) and a peak storm surge height greater than 0.7 m (2.3 ft) (Schupp et al. 2013). Munger and Kraus (2010) studied storm impacts on the North End and

Table 1. An extremal statistics analysis of water levels and wave heights offshore Assateague Island National Seashore during the period 1930–1999 (USACE 2008) provides context for three major storms that impacted the island.

Storm Date	Storm Surge	Surge Return Period (years)	Significant Wave Height (m)	Wave Return Period (years)	Impact
September 1933	2.24 m (7.3 ft)	36	6.2 m (20.3 ft)	22	Created Ocean City Inlet
March 1962	1.81 m (5.9 ft)	10	6.3 m (20.6 ft)	25	Breached North End
January 1998	1.64 m (5.4 ft)	5	5.3 m (17.4 ft)	6	Overwashed 2.4 km (1.5 mi) of North End
1930–1999	2.27 m (7.4 ft)	39	6.3 m (20.6 ft)	25	Highest recorded surge and wave heights for the 69-year period

concluded that for tropical storms, erosion was highly correlated with "integrated wave height," which is the significant wave height integrated over the duration of the storm. For extra-tropical storms, erosion was highly correlated with the "integrated hydrograph," which combines water level height and storm duration (Munger and Kraus 2010).

An analysis of water levels and wave heights offshore of the national seashore during the period 1930–1999 by the U.S. Army Corps of Engineers (USACE 2008) identified the highest storm surge as 2.27 m (7.4 ft) (September 1945 and September 1965), and the largest maximum wave height as 6.3 m (20.6 ft) (September 1933, March 1962, and September 1967). This maximum wave height, but not the storm surge height, was reached during the 1933 hurricane that created Ocean City Inlet (table 1). Two other significant storms, the1962 Ash Wednesday storm that breached the North End and the January 1998 storm that overwashed 2.4 km (1.5 mi) of the North End, had lower wave heights and storm surges (table 1) (USACE 2008).

Although climate change projections regarding the intensity and frequency of hurricanes and northeasters along the Eastern Shore are uncertain, both types of storms will likely be more intense and northeasters will likely be more frequent (The Nature Conservancy [TNC] 2010). In combination with sea-level rise and diminished sediment supply, an increase in the frequency of class 4 (severe northeasters) and class 5 (extreme northeasters) storms (as defined by Dolan and Davis 1992) could cause severe to extreme beach recession and erosion, severe dune erosion or destruction, widespread dune breaching, extensive overwash, and inlet formation (TNC 2010).

Coastal Vulnerability and Sea-Level Rise

Natural resources are vulnerable to many expected impacts of climate variability and climate change (table 2). Sea-level rise is of particular concern due to potential impacts on the shoreline, marsh stability, and fresh groundwater resources of Assateague Island.

Historic Sea-Level Rise

Sea level has varied by nearly 150 m (490 ft) over the past 2.5 million years. Approximately 22,000 to 20,000 years ago, during the last glacial maximum, sea level was 125 m (410 ft) below its present elevation, and then rose rapidly between 15,000 and 10,000 years ago (Krantz et al. 2009). Rates of sea-level rise influence the formation of particular types of landforms. Global deltas began to form approximately 8500 years ago (Stanley and Warne 1994) when rates of sea-level rise slowed to less than 10 mm/year (0.4 in/year), rising only 18 m (60 ft) over the next 2000 years (Fairbanks 1989). Barrier islands and Atlantic wetlands formed approximately 5,000 years ago when rates of sea-level rise fell below 5 to 7 mm/year (0.2 to 0.3 in/year) (Fairbanks 1989; Shennan and Horton 2002; Horton et al. 2009). Various data sources indicate that relative sea level along the Delaware coast rose about 3 mm/year (0.1 in/year) during the Early Holocene until it reached –11 m (–36 ft) approximately 5000 years ago (Horton et al. 2009). Basal salt marsh dates from the southern Delmarva Peninsula are commonly between 3000 and 4000 years old. They occur at depths of 3 to 4 m (10 to 13 ft) below present sea level, suggesting a relative sea-level rise rate of 1.5 to 2.0 mm/year (0.06 to 0.08 in/year) over the past 5000 years (Kraft 1976).

The rate of relative sea-level rise in the mid-Atlantic region of the United States is the sum of eustatic (global) and local rates of sea-level rise. Global sea level has risen approximately 0.18 m (0.6 ft) in the past century, a rate of 1.8 mm/year (0.07 in/year) (Douglas 1997). Locally, land has been subsiding at a rate of 1.2 to 1.8 mm/year (0.05 to 0.07 in/year), and this rate is expected to continue (Boesch 2008). Land subsidence occurs through a process known as glacial isostatic adjustment (Engelhart et al. 2011), which results from the relative lowering of land surfaces that had "bulged" upward along the periphery of massive ice age glaciers after those glaciers retreated. Additional changes can be attributed to tectonic subsidence (Pendleton et al. 2004), compaction (Kraft 1971), and coastal downwarping related to groundwater withdrawal (Oertel and Kraft 1994).

A recent study (Sallenger et al. 2012) found that rates of sea-level rise are increasing 3 to 4 times faster along parts

Table 2. Summary of projected changes in regional climatic conditions. Assateague Island National Seashore's natural resources are vulnerable to many expected impacts of climate variability and climate change. This table summarizes projected changes in regional climatic conditions expected by the year 2040. The information was developed from Christensen et al. (2007), IPCC (2007), and Meehl et al. (2007) based on the A1B emissions scenario (IPCC 2007), which is now believed to underestimate emissions and, in turn, likely rates of sea-level rise. Table based on ASIS (2012b).

Climate Variable	General Change Expected	Rate of Change Expected & Reference Period	Size of Expected Change Compared to Recent Changes	Synoptic Signs	Confidence
Sea Level	Increase	80 – 220 mm (3.5 – 9 in) by 2040*	Large	When coincident with lunar phase, northeasters and hurricanes will enhance floods. Increased flushing into Coastal Bays.	Moderate degree of confidence, though it may take some alignment of storms, tides, and winds to have a large-scale effect. *IPCC projection is now considered very conservative
Temperature	Non-uniform increase	1.0 – 1.9°C (1.8 – 3.5°F) increase by 2040	Moderate to Large	Trend to milder winters with lengthening periods of above-freezing temperatures.	Virtually certain that temperature will increase. Predictions for rate and magnitude of change vary, but forecasts consistently call for an ecologically significant rise in temperature.
Precipitation	Probable decrease in total annual precipitation	1 – 6% increase during colder months by 2040; 3 – 7% decrease during warmer months	Small to Moderate. Most changes within the bounds of the observed record.	Wetter springs and autumns are a signal of more active mid-latitude cyclones.	Low confidence. The model trend is toward drier warm seasons, but this runs contrary to the decadal shift toward more precipitation.
Drought	Modest increase in drought frequency in the warm season	Rainfall deficits during the growing season may approach 10 –25%.	Small to Moderate	Greatest impacts in summer. Likely to lower flows into estuaries, which will increase pollutant concentrations.	Moderate level of confidence. Will be largely influenced by regional and sectional droughts, which are driven by thermal anomalies on the continent and adjacent oceans.
Snow Cover	Increase in snow-free days, and decreased snow accumulation	Up to > 50% reduction in average annual snowfall by 2040	Moderate	Shift in winter storm tracks away from coastal development	High level of confidence; matches current trend. "Odd" extreme snowfalls are likely.
Length of Growing Season	Increase	Likely to be two or more weeks longer by 2040	Moderate to Large	More large-scale, stagnant, high-pressure systems during the spring and fall.	High degree of confidence. Synoptic patterns will also allow occasional late/early freezes.

Climate Variable	General Change Expected	Rate of Change Expected & Reference Period	Size of Expected Change Compared to Recent Changes	Synoptic Signs	Confidence
Extreme Events: Temperature	Warm events increase. Cold events decrease.	Record minimums less likely in winter. Record maximums more likely in winter.	Moderate	Increased frequency of thaws in winter, as seen by emergence of subtropical high.	Moderate to high degree of confidence; continues existing trend. The greatest increase in summer heat will occur later in the period.
Extreme Events: Precipitation	Possible decreased frequency of heavy rain, countered by rise in intensity. Repetitive storms cause excessive precipitation.	Uncertain	Moderate	Potential for more intense spring and autumn floods due to active storm tracks.	Low confidence. Precipitation forecasts are the least skilled forecasting models.
Extreme Events: Cold Season Storms	Increased intensity	Uncertain	Moderate to Large	Increased frequency of transition season storms (northeasters).	Low to moderate confidence.
Extreme Events: Warm Season Storms	Increased intensity; possible decreased frequency.	Uncertain	Moderate	Increased strength of tropical storms. Possibility of two storm strikes in a short time period.	Low confidence.

of the U.S. Atlantic coast than globally. Since about 1990, global sea level has risen 0.6 to 1.0 mm/year (0.02 to 0.04 inches/yr). In comparison, sea-level rise in the 1,000-km (600 mile) stretch of coastal zone from Cape Hatteras, North Carolina, to north of Boston, Massachusetts has increased 2 to 3.7 mm/yr (0.08 to 0 .14 inches/yr) and is expected to continue rising if global temperatures continue to increase (Sallenger et al. 2012). This sea-level-rise hotspot is consistent with the slowing of Atlantic Ocean circulation, which in turn may be related to changes in water temperature, salinity, and density in the subpolar North Atlantic (Sallenger et al. 2012).

As a result of these global and local processes, the relative sea-level rise rate around Assateague Island is almost twice the rate of global sea-level rise. Data from tide gauges near Assateague Island indicate increases in the rate of relative sea-level rise to 3.39 ± 0.27 mm/year (0.13 ± 0.01 in/year) to the north of the national seashore (based on 93 years of data at Lewes, Delaware) and to 3.58 ± 0.36 mm/year (0.14 ± 0.01 in/year) to the south (based on 61 years of data, 1951-2012, at Kiptopeke, Virginia) (NOAA 2013).

Future Sea-Level Rise

The rate of eustatic sea-level rise is increasing (IPCC 2007). Some climate models predict that even without the contribution of glacial melting, an additional rise of up to 0.59 m (1.9 ft) will occur by 2100 (IPCC 2007), which is more than double the rate of rise for the 20th century. Many assessment studies (fig. 16) over the past several years project a 1 m (3.3 ft) global average sea-level rise by 2100 as a reasonable value to be used for planning purposes (Williams 2013) because that rate only requires that the linear relationship between temperature and sea level that was noted in the 20th century remains valid for the 21st century (Rahmstorf 2007). Some estimates include the possibility that sea level may rise as much as 2 m (6.6 ft) by 2100 along the Mid-Atlantic (Rahmstorf 2007). The Intergovernmental Panel on Climate Change (IPCC) will release the fifth assessment report in 2013 and 2014. Refer to the IPCC website for additional information (http://www.ipcc.ch/).

Models that also consider accelerated glacial melting and the relationship between sea level and temperature predict that sea level may rise by 0.9 to 1.2 m (2.9 to 3.9 ft) by the end of this century (Boesch 2008; Karl et al. 2009; World Bank 2012), with variable regional and

temporal influences on local rates of sea-level rise depending on geophysical and oceanographic factors (Williams 2013). With continued warming, some scientists postulate that accelerated melting in Greenland and West Antarctica could lead to sea-level rise of 4 m (13 ft) or more over the next several hundred years (Williams 2013). The maximum possible rise, if global warming continues such that all ice sheets melt, would be 70 m (230 ft). Such a scenario would likely require several centuries of high global temperatures (Williams 2013).

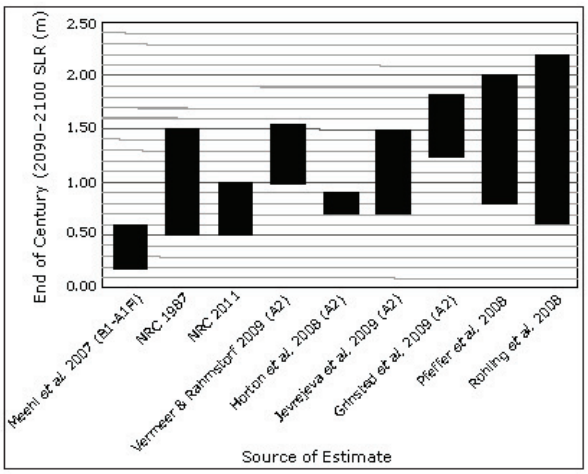


Figure 16. Graphic of sea-level rise projections. Over the next century, global sea level will rise, though the magnitude of projections vary. Notations "B1", "A2", and A1Fi" refer to IPCC emisisons scenarios described in Moser et al. (2012). Figure 6 from Williams (2013).

As a result of these global and regional processes, local sea level is predicted to increase an additional 0.19 m (0.62 ft) by 2030 (Najjar et al. 2000), up to 0.4 m (1.3 ft) by 2050 (Boesch 2008), and from 0.82 to 1 m (2.7 to 3.4 ft), but less than 1.2 m (4 ft) by 2100 under a high-emissions scenario that accounts for glacial melting (Boesch 2008). Some estimates include the possibility that sea level may rise as much as 2 m (6.5 ft) by 2100 along the Mid-Atlantic (Rahmstorf 2007).

Coastal Impacts of Sea-Level Rise

The geologic framework (underlying geology) and nearshore bars are thought to exert some control on the shoreline response to waves, storms, and relative sea-level rise (Honeycutt and Krantz 2003; Browder and McNinch 2006; Miselis and McNinch 2006; Schupp et al. 2006; Wikel 2008). Along southern Assateague Island, variability in shoreline change and the geologic framework appear to be strongly correlated on both interannual and long-term time scales. Steeper shoreface profiles that are characterized by relatively smaller cross-shore volumes have been correlated with erosional trends (Wikel 2008).

Potential coastal impacts of sea-level rise include the following:

- Shoreline erosion;
- Saltwater intrusion into groundwater aquifers;
- Inundation of wetlands and estuaries;
- Threats to cultural and historic resources, as well as infrastructure (Pendleton et al. 2004);
- Coastal flooding;
- Pond salinity changes;
- Heights of storm surges, waves, and tides (TNC 2010); and
- Changes to coastal geomorphologic processes (Najjar et al. 2000).

Quantitative predictions of how shorelines may change with future storms and sea-level rise are difficult to develop (Gutierrez et al. 2009). The most easily applied models generally incorporate relatively few processes and make assumptions that may not apply to on-the-ground conditions or future conditions (Thieler et al. 2000; Cooper and Pilkey 2004). More detailed models that are developed for specific locations require precise knowledge regarding the underlying geology or sediment budget in that location, which may be difficult to obtain (Gutierrez et al. 2009).

According to Moore et al. (2010), if sea level rises or sediment supply rates decrease, a barrier island will respond by 1) migrating landward to higher elevations, 2) disintegrating if sand volume and relief above sea level are not sufficient to prevent inundation during storms, or 3) drowning in place and transforming into a submerged marine sand body.

Gutierrez et al. (2009) described the expected changes for wave-dominated barrier islands in the mid-Atlantic region, including Assateague Island, under potential future rates of sea-level rise using percent-likelihoods expressed in terms such as “virtually certain” and “likely” (fig. 17). They postulated that if mid-Atlantic sea-level rise continues at the present-day rate (a total of 0.3 to 0.4 m [1 to 1.3 ft] by 2100), it is virtually certain that the majority of the wave-dominated barrier islands along the mid-Atlantic coast will continue to experience morphologic changes through erosion, overwash, and inlet formation as they have over the last several centuries (fig. 17). Gutierrez et al. (2009) noted that the North End is already experiencing high shoreline erosion rates and submergence during moderate storms, and has been breached and segmented by large storms in the past. They suggested that this area may already be at a geomorphic threshold and that, with any increase in the rate of sea-level rise, it is virtually certain that the island will exhibit large changes in morphology, ultimately leading to its degradation. However, the ongoing North End Restoration Project is currently reducing erosion and shoreline retreat.

Gutierrez and others (2009) also estimated that if the rate of sea-level rise increases 2 mm/year (0.08 in/year) over the 20th century rate, the North End is very likely to exhibit barrier segmentation and threshold behavior involving a high potential for significant and irreversible changes, such as reduction in size or increased presence

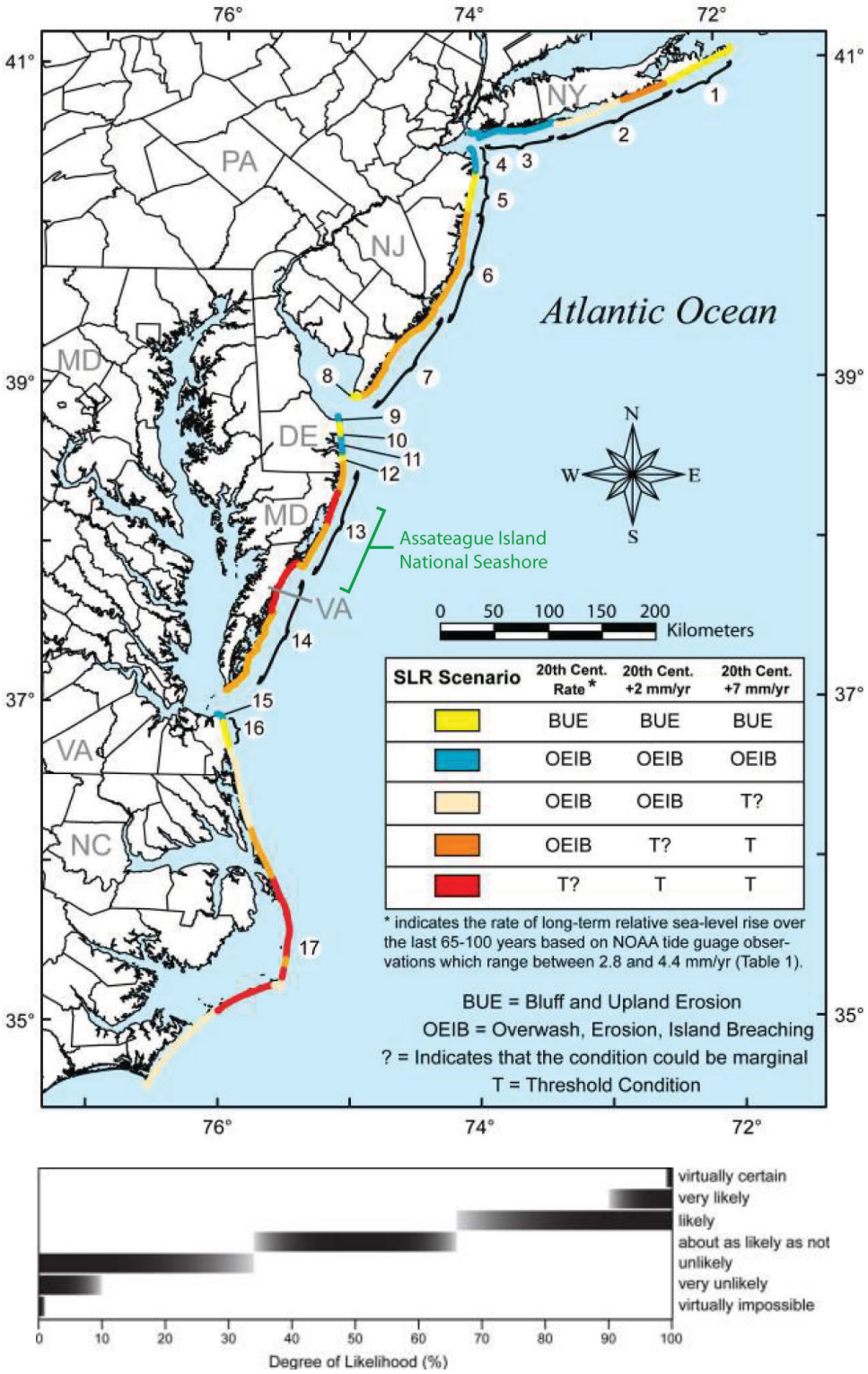


Figure 17. Map of sea-level rise scenarios and impacts. The Assateague Island region may already be at a geomorphic threshold; with any increase in the rate of sea-level rise, it is virtually certain that this barrier island will exhibit large changes in morphology, ultimately leading to the degradation of the island. Phrases such as "virtually certain" represent a percentage range of likelihood. Figures 3.2 (top) and P.1. (bottom) from Gutierrez et al. (2007).

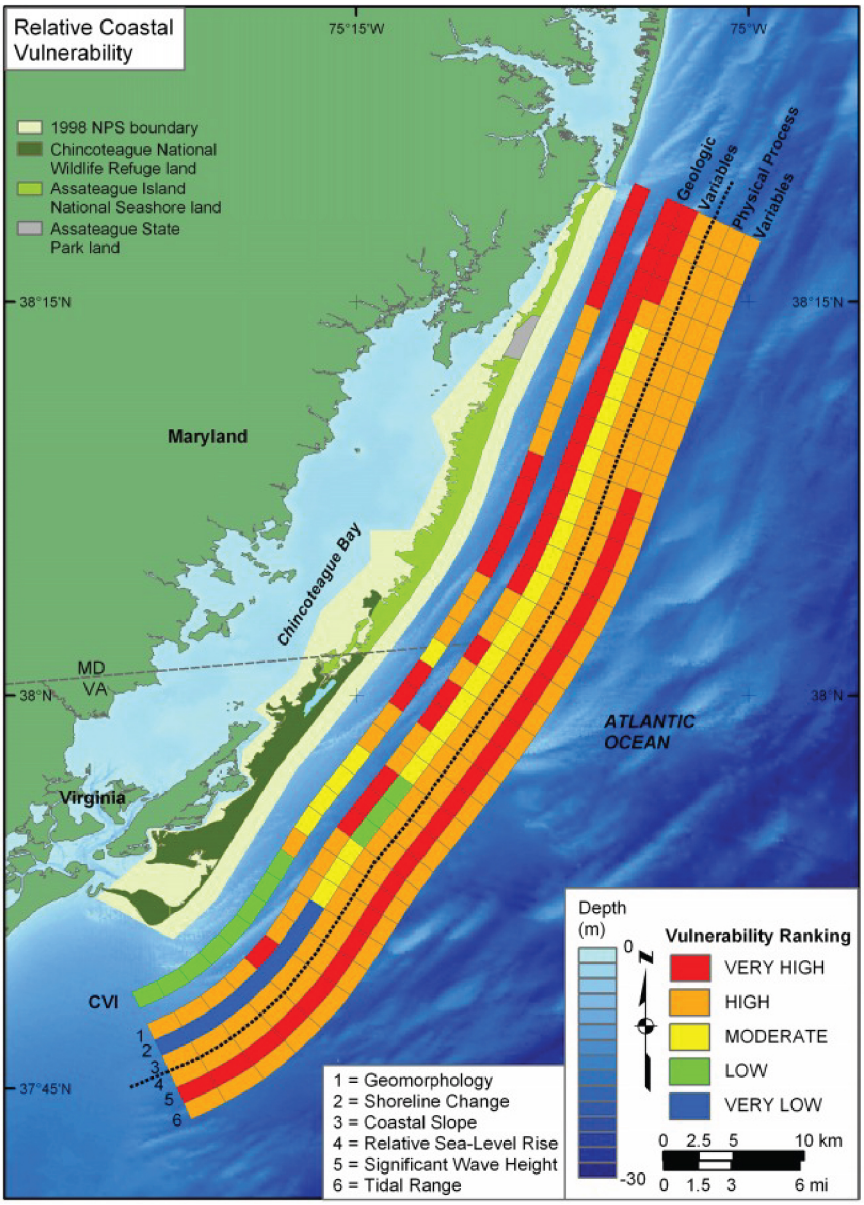


Figure 18. Coastal vulnerability map. The coastal vulnerability of Assateague Island was evaluated based on six factors. Areas with the highest occurrence of overwash and highest rates of shoreline change are likely to be most vulnerable to sea-level rise. Figure 5 from Pendleton et al. (2004).

of tidal inlets. Under this scenario, the ability of wetlands to maintain their elevation through accretion at higher rates of sea-level rise may be reduced (Reed et al. 2008), and it is about as likely as not that the loss of back-barrier marshes will lead to changes in hydrodynamic conditions between tidal inlets and back-barrier lagoons, thus affecting the evolution of barrier islands (e.g., FitzGerald et al. 2006, 2008).

With an increase of 7 mm/year (0.3 in/year) over the 20th century rate of sea-level rise, it is very likely that the potential for threshold behavior will increase along many of the mid-Atlantic barrier islands, and with a 2 m (6.6 ft) sea-level rise over the next few hundred years, it is virtually certain that the barrier islands will exhibit threshold behavior (segmentation or disintegration) (Gutierrez et al. 2009).

Pendleton and others (2004) evaluated the coastal vulnerability of Assateague Island to sea-level rise based on six variables: 1) geomorphology, which accounts for a shoreline's relative resistance to erosion; 2) shoreline change (erosion/accretion); 3) regional coastal slope, which indicates the relative susceptibility to flooding; and three physical process variables that contribute to the inundation hazards of a coastline: 4) relative sea level change, 5) mean significant wave height, and 6) mean tidal range (fig. 18). Of the six equally ranked variables, shoreline change had the largest range in values and therefore the strongest influence on overall vulnerability score for each section of the island. The study concluded that areas with the highest occurrence of overwash and highest rates of shoreline change are likely to be most vulnerable to sea-level rise. Of the 60 km (37 mi) of ocean and inlet shoreline mapped, 60% was classified as having

high or very high vulnerability and 18% as having low vulnerability (fig. 18).

The NPS-led Climate Change Scenario Planning process has identified likely drivers of landscape change (e.g., storms and sea-level rise) and described multiple plausible future states under these conditions. Exploration of these end-member scenarios, their likelihoods, and commonalities among them allows for better-informed and more flexible decision making. Applications of Scenario Planning include development of General Management Plan alternatives that consider climate changes over the next 25 years (e.g., acquisition of mainland areas for infrastructure replacement); confirmation of the value of current projects (e.g., marsh restoration, topographic monitoring); and identification of the island's most vulnerable resources (e.g., fresh groundwater).

These studies have offered a great deal of insight into the vulnerability of Assateague Island National Seashore to current and future storm impacts, but managers need additional information for planning and management purposes, such as decision-making about infrastructure placement and best use of funds. One urgent need is for short-term (20-year time frame) projections related to locations or likelihood of inundation, severe erosion, and shortages of fresh groundwater due to drought or saltwater intrusion. Longer-term (40-year) projections are also needed for longer-term management plans. To address this need, the U.S. Geological Survey (USGS) has begun development of a sea-level rise decision support tool based on parameters such as groundwater, shoreline behavior, topography, and critical habitat needs. This GIS-based tool will allow managers to explore predicted sea-level rise scenarios and their impacts in terms of spatial distribution of vulnerabilities at specific forecast horizons, and time series of vulnerabilities at specific locations of interest (Rob Thieler and Nathaniel Plant, research geologists, USGS, personal communication, 10 December 2009).

Inlet Impacts on Sediment Transport Processes

After a 1933 hurricane breached Assateague Island, a new inlet was created. It was subsequently stabilized with a pair of jetties in order to serve as a navigational channel, now known as Ocean City Inlet. This feature has changed the nearshore bathymetry off of Assateague Island, forming a flood tidal delta and a large ebb tidal delta that extends north and south of the inlet, curving to form a 300-m- (984-ft-) wide attachment bar that currently meets the shoreline 650 to 950 m (0.4 to 0.6 mi) south of the inlet (fig. 19). The growth of the ebb tidal delta since inlet formation, and its shoreline attachment by 1980, are well documented (Dean and Perlin 1977; Leatherman 1984; Underwood and Hiland 1995; Rosati and Ebersole 1996; Stauble 1997; Kraus 2000). This attachment bar is a significant bathymetric feature in the nearshore, rising 3.5 m (11.5 ft) above the surrounding seafloor; its south flank is steeper (1:46 slope) than its north flank (1:180 slope) (Schupp et al. 2007).
The inlet and jetties disrupt southward sediment transport. The cumulative volume of sediment that would have been delivered to the northernmost 12 km (7.5 mi) of Assateague Island between 1934 and 1996, had the inlet not been stabilized, is estimated to be 9.7 million m^3 (12.7 million yd^3) (USACE 1998). The associated volume loss in the active profile (from the beach berm offshore to the depth of closure) also

Figure 19. Photograph of Ocean City Inlet. The ebb tidal delta and the attachment bar that curves southward to meet Assateague Island (bottom) is clearly defined by the breaking waves around Ocean City Inlet. The post-inlet migration of Assateague Island is apparent in the offset from Fenwick Island / Ocean City (top). Photograph by Jane Thomas, Integration and Application Network, University of Maryland Center for Environmental Science (http://ian.umces.edu/imagelibrary/).

increased after the inlet was stabilized from an estimated 150,000 m^3/year (196,200 yd^3/year) to 370,000 m^3/year (484,000 yd^3/year) (Schupp et al. 2007). This sediment starvation has more than doubled shoreline erosion along the northern 13.2 km (8.2 mi) of Assateague Island, from a pre-inlet rate (1850–1933) of –1.5 m/year (–4.9 ft/year) to a post-inlet rate (1942–1997) of –3.70 m/year (–12.1 ft/year) (Schupp et al. 2007). These rates are much higher than the erosion rate along the rest of Assateague Island. During the 70 years following inlet stabilization, the North End has migrated almost 500 m (0.3 mi) westward through overwash and shoreline erosion, due in part to loss of sediment supply (Schupp et al. 2013), with a resultant narrowing of Sinepuxent Bay (fig. 20).

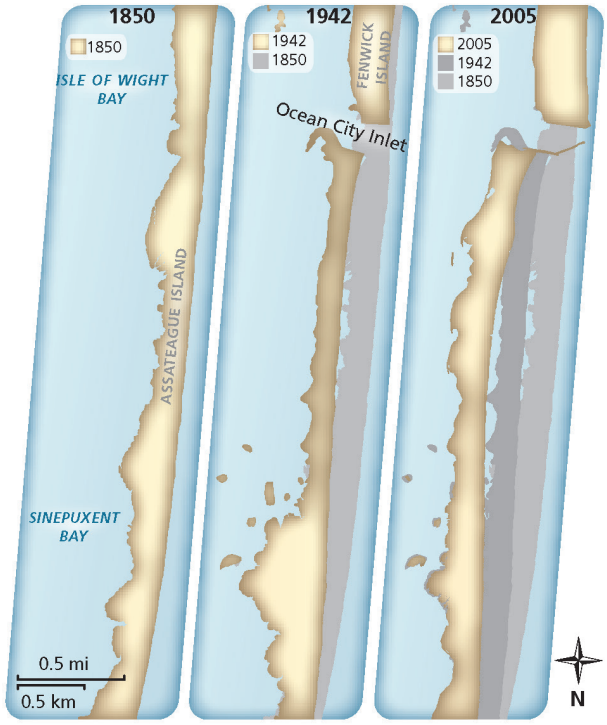


Figure 20. Maps of Assateague Island shoreline migration. Assateague Island migrated rapidly landward following stabilization of the Ocean City Inlet in 1934. Figure 2.15 from Carruthers et al. (2011).

North End Restoration Project

The increased vulnerability to overwash and breaching resulting from the stabilization of Ocean City Inlet allowed a strong northeaster in 1962 to breach the North End. Over the next few decades, the North End was increasingly vulnerable to overwash and erosion of dunes and shoreline. Following a series of strong storms during the period 1991–1998, the North End was overwashed up to 20 times per year, with well-defined overwash channels and mean elevation lower than 2.25 m (7.4 ft) (NAVD88) (USACE 1998). During two northeasters in early 1998, a 2.4-km- (1.5-mi-) long area experienced sustained overwash that resulted in the creation of a large overwash fan and exposure of peat along the shoreline and within the island's interior (USACE 1998) (fig. 21).

Figure 21. Photographs of overwash and subsequent marsh growth. A) During two northeasters in early 1998, the North End experienced sustained overwash that resulted in the creation of a large overwash fan and exposure of peat along the shoreline and within the island's interior. B) By 2006, and following the inauguration of the North End Restoration Project, the island had gained elevation and new marsh had grown on the new overwash fans. View is to the north. Photographs by Jane Thomas, Integration and Application Network, University of Maryland Center for Environmental Science (http://ian.umces.edu/imagelibrary/), annotations by Rebecca Port (NPS Geologic Resources Division).

The USACE predicted that without mitigation, the northern end of Assateague Island would destabilize and have the potential for a major breach (USACE 1998). Such a breach would have a significant impact on the values and purpose of Assateague Island National Seashore and serious implications for adjacent mainland communities, including infrastructure vulnerability, loss of estuarine habitats, and increased maintenance needs for Ocean City Inlet. To mitigate impacts of the loss of natural sand transport processes, local and national government agencies developed a comprehensive, two-phase restoration plan (fig. 22). In the first phase, a one-time beach nourishment in 2002 widened the beach by 30 m (100 ft) in the area between 2 and 12.5 km (1.2 and 7.5 mi) south of the inlet. The 1.4 million m^3 (1,832,000 yd^3) of sand was placed just seaward of the mean high water line to replace about 15% of the sand captured by the inlet since 1934 (USACE 1998).

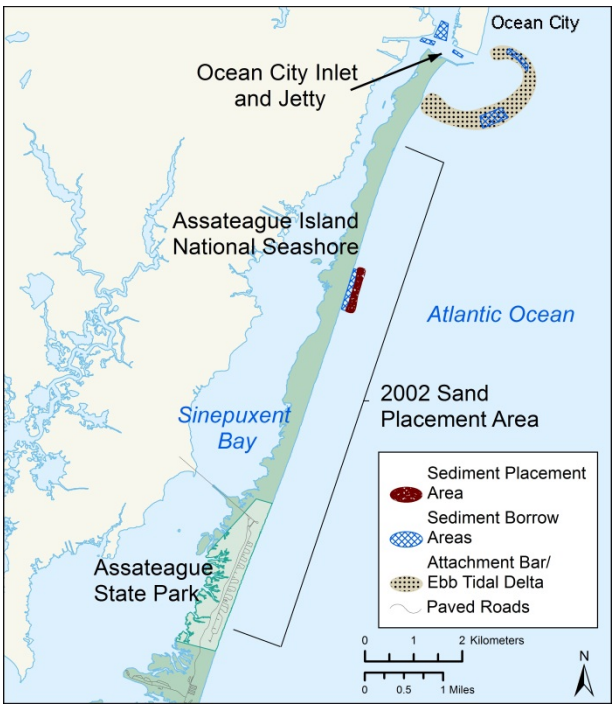


Figure 22. Map of North End Restoration Project activities. The two-phase North End Restoration Project is intended to mitigate impacts of the loss of natural sand transport processes. In 2002, sand was placed on the beach; in 2004, biannual long-term sand bypassing began. Redrafted by Courtney Schupp (Assateague Island National Seashore) after Figure 1 from Schupp et al. (2007).

The second phase began in 2004 and was planned to continue for 25 years. It addresses the source of the problem, sediment starvation, by restoring sediment transport to the North End. Twice each year, a dredge vessel moves sand into the nearshore area, placing a volume approximately equal to the natural pre-inlet longshore transport rate (144,000 m^3/year [188,000 yd^3/year]) (fig. 23). The intent of the project is not to create a fixed-width beach or to stop erosion, but rather to reduce the erosion rate to the pre-inlet conditions by restoring the sediment transport pathway (Schupp et al. 2007). Beginning in January 2004, and recurring every early spring and fall, a hopper dredge takes approximately 72,000 m^3 (94,200 yd^3) of sand from the

Figure 23. Photographs of hopper dredge operations. Beginning in January 2004, and recurring every early spring and fall, a hopper dredge takes approximately 72,000 m³ (94,200 yd³) of sand from the ebb and flood tidal deltas and deposits it just seaward of the surf zone on Assateague Island. National Park Service photographs.

ebb and flood tidal deltas and deposits it just seaward of the surf zone on Assateague Island (fig. 23), approximately 2.5 to 5 km (1.5 to 3.1 mi) south of the inlet (fig. 22). Sand is not deposited along the northernmost 2.5 km (1.5 mi) of the island because USACE hydrodynamic models indicate that sediment has a localized net northward transport direction in that region, apparently caused by wave refraction and wave breaking on the ebb tidal delta and attachment bar (Buttolph et al. 2006). Unlike a typical beachfill project in which the material is pumped high on the beach, the bypassed borrow material is deposited on the crest and just seaward of the nearshore bar, which has an approximate crest elevation of –1.45 to –1.75 m (–4.8 to –5.7 ft) (NAVD88). The dredge deposits the majority of sand in depths of –1.5 to –5 m (–4.9 to –16 ft) (NAVD88), which is approximately 80 to 250 m (260 to 820 ft) from shore (Schupp et al. 2007). Because the sediment is placed landward of the depth of closure, waves and longshore transport processes then move this material onshore, shaping this sand into a natural configuration in the surf zone and on the beach. The first 8 years of this effort have been successful, with the North End erosion rate slowing to match natural pre-inlet rates of shoreline change during most years (Carruthers et al. 2013).

Hydrology

Several recent studies (Hall 2005; Krantz 2010; Banks et al. 2012) have helped to characterize the groundwater hydrology of Assateague Island. The Krantz (2010) report and data are provided on the enclosed CD and available at http://go.nps.gov/gripubs. The geomorphology of the island, combined with natural processes including precipitation, evapotranspiration, and storm overwash, largely control the groundwater hydrology. In turn, the distribution of fresh and brackish groundwater in the unconfined surficial aquifer and the geometry of the fresh groundwater lens under the island control the distribution of vegetation communities and habitat (Krantz 2010).

Contrary to theoretical assumptions of a single, deep, connected fresh groundwater lens that runs beneath the island, data from Krantz (2010) indicate that a fresh lens occurs in segments and is much shallower than predicted (fig. 24). Higher, protected sections of the island core produce and sustain a moderately deep fresh groundwater lens, observed to be up to 8 m (26 ft) thick (Hall 2005). A low-permeability layer of lagoonal silt (associated with barrier island transgression) underlies

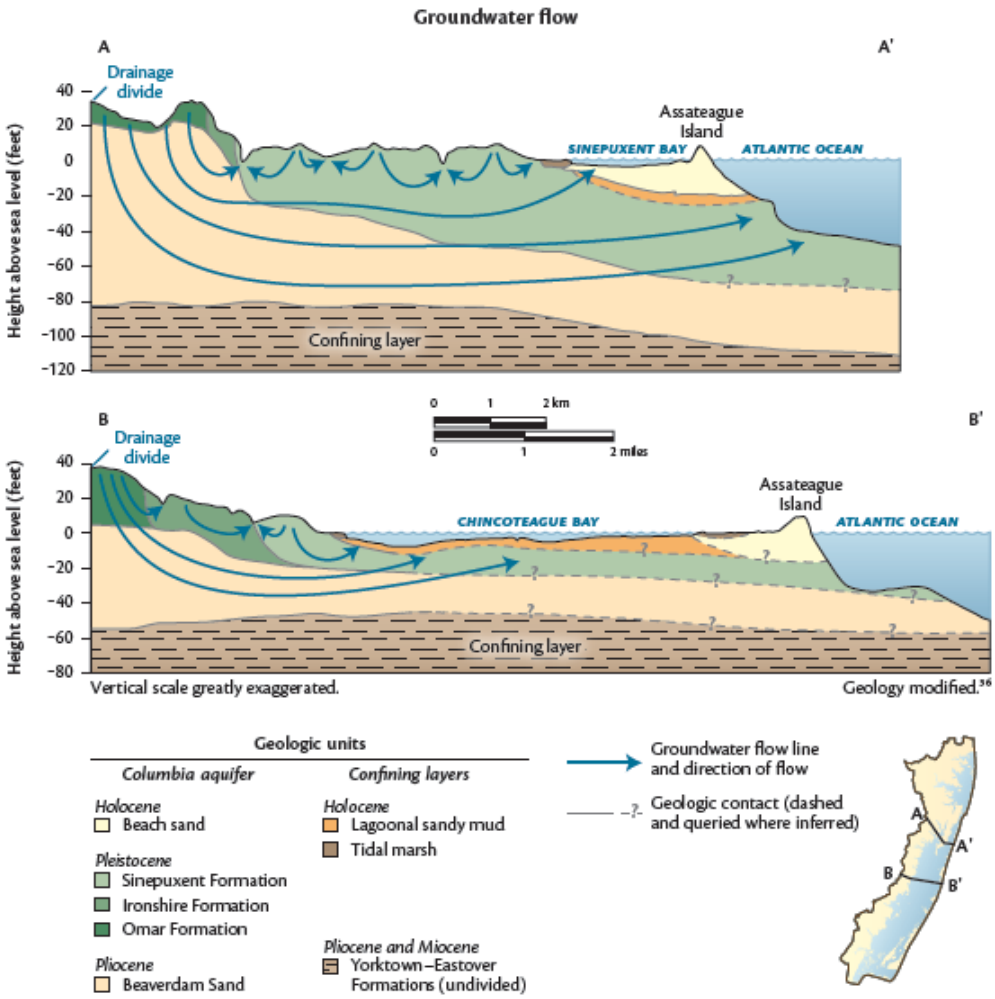


Figure 24. Schematic graphic of local and regional groundwater flow along Assateague Island. Figure from Krantz et al. (2009).

most of the island and physically limits the depth of the fresh lens (Krantz 2010). Along the perimeter of the island and in areas of former inlets, saltwater infiltrates the aquifer as a result of ocean-side overwash and bay-side flooding, leading to a much thinner and shallower (1 m [3.3 ft]) freshwater lens (Hall 2005). The ocean-side section of the island (beach, berm, and primary and secondary dune fields) has an extremely dynamic groundwater system, with alternating inputs of freshwater from precipitation and saltwater from overwash, and preferential subsurface flow of brackish groundwater following storm-created channels and swales (Krantz 2010). Freshwater availability and vegetation associated with each landform are described in more detail in the "Geologic Features and Processes" chapter.

Studies of the Coastal Bays show that fresh groundwater from the mainland flows beneath the narrow Sinepuxent Bay and Assateague Island to discharge directly to the ocean. In the broader reaches of Chincoteague Bay, the freshwater may mix with the saline groundwater beneath the bay, making the groundwater brackish. Alternatively, the freshwater may discharge into Chincoteague Bay within 1 to 2 km (0.6 to 1.2 mi) of the western shoreline and can be a significant source of freshwater to the Coastal Bays (Dillow and Greene 1999). The groundwater migrates slowly and is generally more than 50 years old (Bratton et al. 2009).

Additional insights into groundwater hydrology at Assateague Island continue to emerge as part of the USGS Sea-Level Rise Decision Support Tool study (see the "Coastal Vulnerability and Sea-Level Rise" section). In 2010, preliminary water-level data were collected from 9 of the 26 monitoring wells that were installed in pairs (one shallow well, one deep well) along five east-west trending transects (Banks et al. 2012). These data indicate that in the monitoring wells nearest to the ocean and bay shorelines, precipitation events coupled with changes in ambient sea level had the largest effect on groundwater levels (Banks et al. 2012). In wells near the center of the island, precipitation events alone had the greatest impact on shallow groundwater levels (2.2 to 3.7 m [7.2 to 12 ft] below ground level) (Banks et al. 2012). Tidal cycles appeared to have minimal influence on groundwater levels throughout the island, and observed water-level changes varied among well sites, indicating that changes in lithology may affect the response of water levels in the shallow and deeper groundwater systems throughout the island (Banks et al. 2012). This is illustrated by the data collected in the geologically older Green Run area of the island, where shallow groundwater responded regularly to evapotranspiration, with plants consuming water and decreasing the groundwater level during the daytime, while deeper groundwater (13 to 14.5 m [43to 48 ft] below ground level) responded regularly to the tidal cycle of the ocean (Larry Martin, NPS Water Resources Division, written communication to Brian Sturgis, ecologist, Assateague Island National Seashore, 3 October 2011). Additional water level data will be collected and correlated to tidal and precipitation data to gain a better understanding of the shallow and deeper groundwater systems of the island.

Several research needs were noted during the 2005 Geologic Resource Evaluation (now Geologic Resources Inventory) Scoping Meeting (Thornberry-Ehrlich 2005) and have not yet been addressed:

- Development of a groundwater monitoring protocol and installation of wells required;
- Development of a hydrogeologic model to predict groundwater response to contamination;
- Characterization of the groundwater interface between salt- and freshwater boundaries;
- Potential wildlife impacts on water quality in seasonal freshwater ponds;
- Inventory baseline level of CFCs in groundwater; and
- Inventory baseline wetland water and soil quality.

Benthic Habitats

The Geologic Resource Evaluation Scoping Meeting Summary (Thornberry-Ehrlich 2005) identified marine and estuarine benthic habitats as areas in which more information was required for management purposes. Since that time, the Assateague Island National Seashore staff has made significant progress toward mapping the island's subaqueous resources.

Marine Benthic Habitats

Although oceanic resources make up 20% of Assateague Island National Seashore's area, a lack of basic information hinders staff's ability to manage and protect its marine resources; to limit ongoing habitat destruction by commercial fishing; to assess future resource threats, such as offshore energy (wind and natural gas) infrastructure; to prepare for the impacts of sea-level rise; to evaluate changing resource conditions; and to develop long-term marine resource monitoring protocols.

Nearshore sand movement controls every aspect of the seashore, including ecosystem health; visitor use; infrastructure management; the North End Restoration Project (described in the "Inlet Impacts on Sediment Transport" section); and habitat availability for shorebirds, commercial finfish and shellfish, and federally-listed threatened and endangered species.

Nearshore benthic habitats support a diversity of marine life that is commercially, recreationally, and intrinsically valuable. Six federally-listed threatened or endangered species regularly utilize Assateague Island National Seashore waters: humpback whale (*Megaptera novaeangliae*), right whale (*Eubalaena glacialis*), sperm whale (*Physeter catodon*), green sea turtle (*Chelonia mydas*), leatherback sea turtle (*Dermochelys coriacea*), and loggerhead sea turtle (*Caretta caretta*). Two other federally-listed threatened species also depend on natural coastal processes: piping plover (*Charadrius melodus*) and seabeach amaranth (*Amaranthus pumilus*). Waters within or in the immediate vicinity of Assateague

Island National Seashore also include essential fish habitat for various life stages of fish species. Baseline understanding of benthic invertebrates provides a source of information for assessing patterns in marine biodiversity; serves as input data for evaluating biological responses to stressors associated with sediments; and provides a source of biological observations in support of long-term integrative marine observing systems; and provides a basis for monitoring the incidence and patterns of invasive species in marine and coastal waters (Federal Geographic Data Committee [FGDC] 2012).

Marine resources are threatened by ongoing and proposed commercial activities within and offshore of national seashore waters. Shellfish dredging creates biological wastelands on the seafloor (Collie et al. 2000; Løkkeborg 2004). Construction of offshore wind farms and other structures has been considered and proposed along the mid-Atlantic coast (Minerals Management Service 2007; BOEMRE 2011a). Offshore construction activities would likely cause changes in light penetration, sediment disturbance and resuspension, and the associated potential for prey disturbance and smothering of benthic organisms (Elliott 2002). The presence of offshore oil platforms and pipelines, or tens to hundreds of wind turbines and transmission cables extending onshore, could alter the existing patterns of incident waves and sediment transport. These changes, in turn, could affect the island's shoreline configuration, elevation, storm response, erosion rate, and the morphology of nearshore shoals, which serve as waterbird feeding areas, fish habitat, and migratory fish navigation cues (Diaz et al. 2004; Vasslides and Able 2008).

Bush (2009) suggested five methods and vital signs for monitoring marine features and processes: 1) the general setting of the environment, of which water depth is the primary indicator; 2) the energy of the environment, waves, and currents; 3) barriers, including reefs and other offshore barriers, which block energy; 4) seafloor composition, or substrate; and 5) water column turbidity. Long-term monitoring datasets for the Assateague Island area include those from a USACE wave gauge that measures significant marine wave height, direction, and period in 8 m (26 ft) of water off of Ocean City (USACE 2012), and a NOAA tide gauge at Lewes, Delaware (NOAA 2012) that provides predicted and actual marine water levels, although historical records indicate that high water at the Lewes gauge occurs about 1.0 hr later than at the NOAA tide gauge located within the estuary at Ocean City Inlet (Psuty et al. 2011). The assessment of summer marine water quality is also part of the national seashore's long-term monitoring program.

In 2011, a nearshore marine survey was conducted along the entire island and up to 1 km (0.6 mi) offshore of Assateague Island. Results based on acoustic data, which were ground-truthed with video and grab samples, captured the nearshore bathymetry and bedforms; seafloor sediment types, texture, distribution, and thickness; shallow subsurface structures; and benthic invertebrate distribution. The biological and physical datasets will be interpreted to create spatially explicit maps of benthic biotypes, known as habitat classification maps, in 2012. Initial results indicate that the nearshore seafloor has a variety of bottom types, including broad, flat fine-sand areas between shore-attached bars; mud and poorly sorted sands in troughs between shore-attached bars that are likely outcroppings of underlying strata; tube worm colonies; and possible outcrops of back-barrier peats (Wells 2012).

Estuarine Benthic Habitats

The estuarine waters within and adjacent to Assateague Island National Seashore compose 50% of the seashore's area, contain the majority of sensitive aquatic habitats found in the Delaware-Maryland-Virginia Coastal Bays system, and have been recognized as nationally significant through their inclusion in the Environmental Protection Agency's National Estuary Program. They serve as spawning and nursery areas for many commercial and recreational fish, hard clams, and blue crabs due to the food and habitat structure provided by seagrass and sandy bottoms. They are also important foraging habitat for migratory birds. They are crucial to the maintenance of regional biological diversity, ecosystem health, and several rare and endangered species (Boynton et al. 1996), including several state-listed and three federally-listed threatened and endangered species (piping plover, bald eagle, and loggerhead sea turtle).

The national seashore's estuaries face several threats to ecological viability, including water pollution and excessive nutrient loading from agricultural practices and residential developments; contamination of sediments by toxic non-point pollutants; increased turbidity from suspended sediments and phytoplankton blooms; destruction of aquatic and wetland habitat by land conversion and boating activity (Chaillou and Weisberg 1996); and commercial and recreational consumptive use of aquatic species, including commercial mariculture.

The most significant threat to the health and functionality of estuarine waters in the national seashore is eutrophication, a process by which excess nutrient input stimulates plant growth and leads to depletion of dissolved oxygen. The primary sources of nutrients and pollutants are agriculture and development activities related to a rapidly growing population (Wazniak et al. 2007), which in Worcester County Maryland increased by 47% between 1990 and 2010, compared to a 21% increase in the Maryland state population during the same time period (U.S. Census Bureau 2013). Water quality in the Coastal Bays is being degraded, and many areas have surpassed crucial thresholds needed to maintain important living resources (Wazniak et al. 2007). Because the estuary has a relatively high tendency to retain nutrients and contaminants, the Maryland Coastal Bays were rated as highly susceptible to pollution in a strategic assessment of East Coast estuaries (NOAA 1989). Chincoteague Bay, which is a major portion of the Coastal Bays, was recently listed in Maryland's Impaired Waters Report (Maryland Department of Environment

2011), and sub-basins of Chincoteague Bay were listed in the equivalent report for Virginia (Virginia Department of Environmental Quality and Department of Conservation and Recreation 2010).

Bathymetry and sediment characteristics control the locations of many estuarine resources. For example, submerged aquatic vegetation (SAV) provides food for waterfowl and a nursery for gamefish and shellfish (Wazniak and Hall 2005). Benthic invertebrate communities serve as an ecological health indicator due to their sensitivity to disturbance and stress (Kutz 1993; Homer et al. 1997). Clam distribution and abundance are also dependent upon benthic characteristics. Bathymetry and sediment data are necessary to identify the potential locations of these resources and to develop management tools including establishment of total maximum daily loads to reduce pollutants, habitat restoration projects, groundwater flowpath modeling, benthic habitat characterization, development of sediment contaminant maps and associated pollutant loading limits compatible with park goals, and a tidal circulation model—a critical tool for understanding bay hydrology, sediment transport, and, most importantly, the delivery, cycling, fate, and impact of nutrients.

Bathymetric data and surficial sediment samples were collected by national seashore staff and the Maryland Department of Natural Resources in the Maryland (1991–1997) and Virginia (2007) Coastal Bays, with follow-up sampling in tributaries and specific areas of interest within the Coastal Bays (2010–2011) (figs. 13 and 14). Sediments were analyzed to determine water content; bulk density; grain size (sand, silt, and clay content); and total and organic carbon, total nitrogen, total sulfur, and heavier mineral content (phosphorus, cadmium, cobalt, copper, iron, manganese, nickel, lead, and zinc). The study results are described in the "Barrier Island System Units" section of the "Geologic Features and Processes" chapter.

The assessment of estuarine water quality (monthly) and areal extent of SAV beds (annually) are also part of the national seashore's long-term monitoring program. A NOAA tide gauge at Ocean City Inlet Maryland (NOAA 2013) and two park-maintained tide gauges in the Maryland estuary (Sinepuxent Bay and Northern Chincoteague Bay) provide long-term records of estuarine water level.

Landscape and Shoreline Evolution

Assateague Island's geomorphologic evolution over several millennia has been driven by sea level, storms, and sediment supply, and controlled by the underlying geologic framework.

Overwash plays an important role in the response of barrier islands to storm events and sea-level rise by transporting sand from the beach to island interiors, replenishing back-barrier marshes and creating overwash fans (Leatherman 1979a; Kochel and Wampfler 1989), a dynamic habitat that supports rare island flora and fauna (Carruthers et al. 2011). For several millennia, Assateague Island has been migrating landward through the processes of coastal transgression and island rollover, by which sediment is eroded from the shoreface, moved on top of and across the island by overwash processes, and deposited on marsh and estuarine surfaces (fig. 7). These processes are controlled by waves, sediment supply, sea level, and the underlying geologic framework.

As described in the Introduction, multiple inlets (fig. 11) have been documented along Fenwick and Assateague islands (Hite 1924; Gawne 1966; Truitt 1968). The inlets form during storms, rework seafloor and underlying sediments, deposit new sediments on the marsh platform and in the Coastal Bays, and subsequently fill back in as a result of natural processes. Inlets may close quickly if plentiful sediment is available, but may remain open for long periods in the presence of a large tidal prism—the volume of water in the bay between high and low tide—which can generate enough tidal flow to scour sediment and maintain the inlet (Krantz et al. 2009). Although modern circulation patterns in the Coastal Bays are limited by the positions of existing inlets, they almost certainly differed in the past depending on the locations and widths of inlets at any given time (Wells and Conkwright 1999).

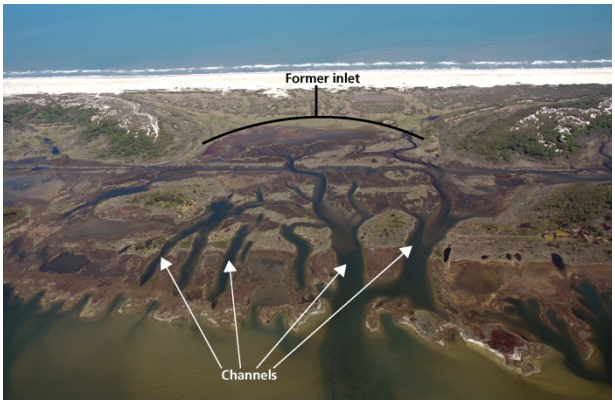


Figure 25. Photograph of former inlet. The location of a former inlet on Assateague Island, such as this one near Little Levels campground, is most commonly marked by a rounded, funnel-shaped low area on the seaward side of the island and a single deep channel or set of channels that extend from the center of the island into the back-barrier lagoon. Photograph by Jane Thomas, Integration and Application Network, University of Maryland Center for Environmental Science (http://ian.umces.edu/imagelibrary/).

Past inlets played an important role in shaping Assateague and Fenwick Islands and in the distribution and character of the bottom sediments found in the bays today (Wells 1999). The location of each former inlet on Assateague Island is most commonly marked by a rounded, funnel-shaped low area on the seaward side of the island and a single deep channel or set of channels, formed by daily tides and storm surges through the inlet, that extend from the center of the island into the back-barrier lagoon (Krantz 2010) (fig. 25). Where the tidal flow reached broader areas of the lagoon, bars and flood tidal deltas may have been deposited and reshaped by waves and currents. The seaward low area is the former mouth of the inlet that filled with sand by longshore transport as the inlet closed. Each location may also have

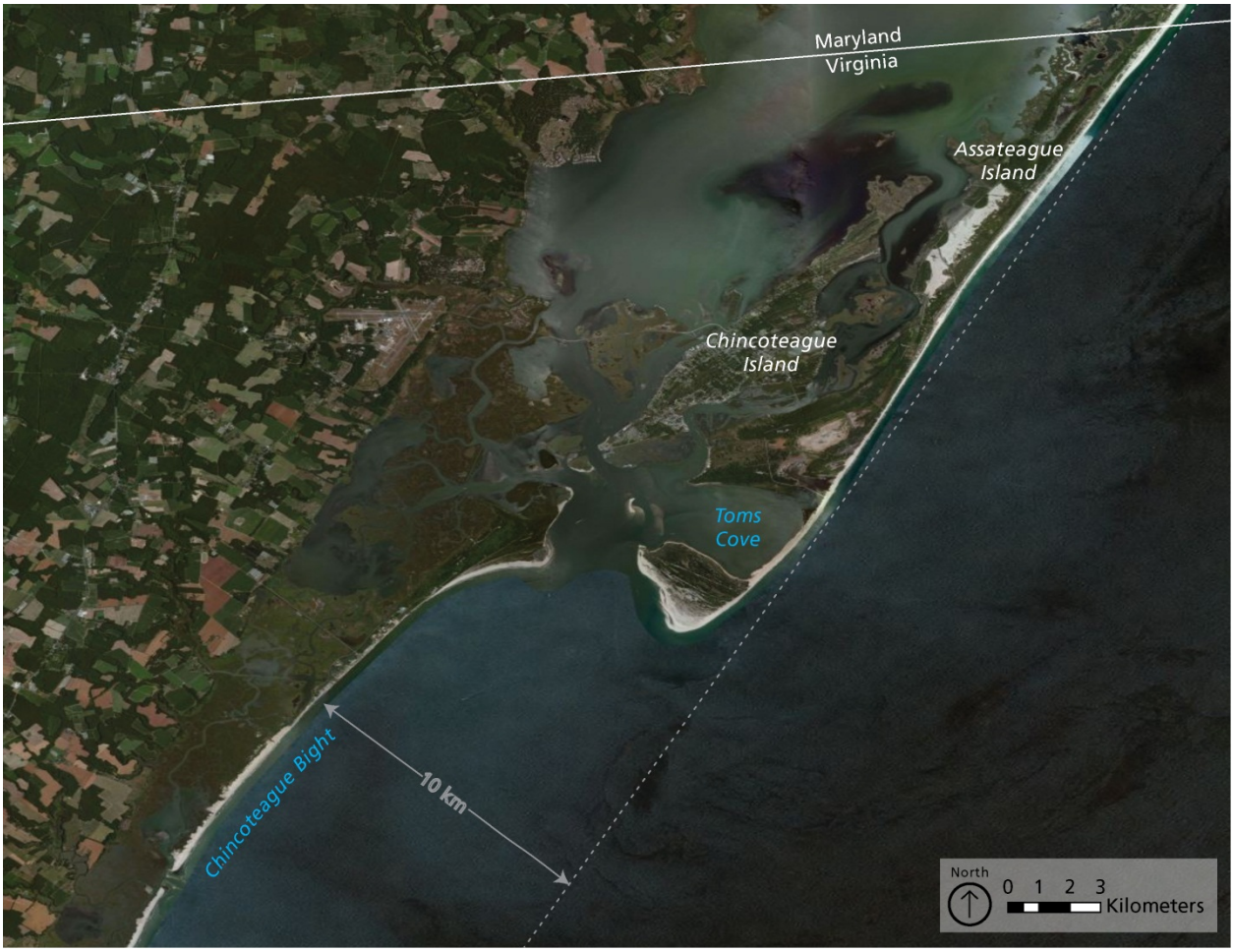


Figure 26. Aerial imagery of the southern end of Assateague Island. Assateague Island has a 10-km (6.2 mi) seaward offset from the Virginia barrier island chain to the south. The embayed area is known as the Chincoteague Bight. Graphic compiled and annotated by Rebecca Port (NPS Geologic Resources Division) using ESRI ArcGIS imagery baselayer.

inlet-closure ridges—a set of low, arcuate, nearly parallel ridges—that create a ridge and swale barricade across the former inlet mouth, as seen at the historical Green Run Inlet (Krantz 2010). Depending on the elevation and position of the remnant features, groundwater salinity and associated vegetation on these features may vary (Krantz 2010).

Assateague Island has a 10 km (6.2 mi) seaward offset from the Virginia barrier island chain to the south (fig. 26). This embayed area, known as the Chincoteague Bight, may be related to several large deep paleochannels that cut through this area. The broad valley, which may represent an ancestral Potomac River, extends across the shelf toward Washington Canyon and appears to have persisted through multiple sea level cycles (Krantz et al. 2009).

Bush and Young (2009) recommended the following methods and vital signs for monitoring coastal features and processes: 1) shoreline change, 2) coastal dune geomorphology, 3) coastal vegetation cover, 4) topography/elevation, 5) composition of beach material, 6) wetland position/acreage, and 7) coastal wetland accretion.

Long-term monitoring efforts are important components of quantifying changes in the shoreline and landscape. The national seashore staff currently surveys cross-island topography along the Maryland portion of the island twice each year, and also maps the high-water shoreline position four times per year in Maryland and twice per year along the Virginia section of the island. Island-wide coverage has been captured approximately once every 1 to 3 years by lidar elevation surveys since 1998 and orthorectified aerial photography since 1993.

The different survey types are complementary and have different sets of advantages (e.g., costs, time, coverage) but are not interchangeable. For example, a lidar-derived shoreline cannot be substituted for a ground-based shoreline survey without prior adjustments. As demonstrated by Moore and others (2006), surveying the high water line (the wet-dry line at a normal high tide) as a proxy for the shoreline position results in an offset from the actual vertical datum-based position of the Mean High Water line that it is intended to represent. This difference occurs because the high water line is a complex feature produced by a combination of tide levels and wave energy that could represent high water maxima reached over several days before the survey date

(Moore et al. 2006). This offset results in a constant shift of the calculated shoreline erosion rate, a bias that might be negligible in locations with a small proxy-datum offset or a short time period of analysis. However, the convergence of several factors, including a moderately short measurement interval and a change rate rapid enough to be significant, can cause the rate shifts to account for a substantial percentage of error in the calculation of shoreline change rates (Moore et al. 2006). Under these circumstances, and where rates will be averaged alongshore, determining the offset between shoreline indicators would allow for quantification of the rate shift and removal of the associated error (Moore et al. 2006).

Recreation and Watershed Land Use

Human impact on Assateague Island National Seashore resources includes recreation and construction and maintenance of infrastructure (roads, visitor facilities), and mainland development that impacts the sediments and water quality of the Coastal Bays. Recreation within the national seashore is predominantly low impact (camping, biking, swimming), although over-sand vehicle (OSV) use has stronger impacts.

Over-sand Vehicles

Beach driving is explicitly allowed as a traditional recreational use by Assateague Island National Seashore's general management plan (1982). OSV use is permitted along the beach and intertidal zone and on several short interior access roads in a 19-km-long (11.8 mi) area in Maryland and on Toms Cove Hook in Virginia, with some restrictions for shorebird use in the spring and summer. OSV recreation increased from 35,115 vehicles in 1993 to 79,196 vehicles in 2009 (Carruthers et al. 2011). Up to 145 vehicles are allowed at any one time along the Maryland OSV zone beach, and between 15 and 48 vehicles at any one time on Toms Cove Hook, on a "first-come, first-served" basis among annual OSV pass holders.

In the Maryland OSV zone, the widths of the foreshore and backshore vary, as does foredune size, which may be related to the anthropogenic origin of the dunes (Leatherman 1979b). Several studies have suggested that driving on the unvegetated beach may result in a net loss of sediment through the seaward displacement of sediment by each vehicle (Anders and Leatherman 1987a, 1987b). Estimates range from 119,300 m^3/year (156,040 yd^3/year) of sediment displaced (but not necessarily lost to the beach-dune system) by 45,000 vehicles annually at Fire Island National Seashore, New York (Anders and Leatherman 1987a, 1987b), to 38,018 m^3/year (49,725 yd^3/year) for every 500 cars on North Stradbroke Island, Australia (Schlacher and Thompson 2008).

In contrast, a recent study of the national seashore's OSV zone (Houser et al. 2013) has suggested that OSV use does not cause a net seaward loss of sediment from the beachface. Rather, OSV use disrupts the landward exchange of sediment between the beach and dune, which prevents post-storm dune recovery. In comparison with those in adjacent no-driving zones, the dunes in the OSV zone were found to be smaller, shorter, further landward, and more susceptible to scarping. Houser also found that dunes in the OSV zone have greater volumes of sediment on their leeward sides, which reduces their resiliency and prevents them from recovering their pre-disturbance height and elevation. These factors can accelerate shoreline retreat and island transgression in response to relative sea-level rise.

Over-sand driving can also destabilize coastal dunes through direct damage to vegetation within the backshore and embryo dunes, the precursors to larger stable dunes (e.g., Liddle and Greig-Smith 1975; Leatherman and Godfrey 1979; Anders and Leatherman 1987a). Over-sand driving within the national seashore is prohibited above the winter storm berm line, and therefore prohibited on and between existing dunes. However, embryo dunes often form in the upper beach area where sand is trapped by wrack (e.g., seaweed deposited by waves and tides) and beach vegetation, if the wrack and vegetation are not destroyed by vehicles. Even a low frequency of OSVs can cause extensive degradation of vegetation and habitat that can limit seaward growth of the dune (Anders and Leatherman 1987a). Loss of vegetation seaward of the dune can accelerate erosion at the toe of the dune, and can also steepen the seaward slope. This impact can lead to further dune erosion and scarping during storm tides. In comparison, vegetated dunes extended farther seaward and had greater protection during storms (Anders and Leatherman 1987a). In a similar study, Godfrey and Godfrey (1980) found that 50 vehicle passes on Cape Cod were enough to inhibit the seaward development of the dune and result in a scarped (rather than sloped) dune profile, and that the number of vehicles using a path makes little difference once the vegetation is impacted.

The biological impacts of over-sand driving on habitats, organisms, and ecosystems are numerous and well established (e.g., Godfrey and Godfrey 1980). On the unvegetated beach, over-sand driving limits the survival, abundance, and diversity of shorebirds and sea turtles (Leatherman and Godfrey 1979; Godfrey and Godfrey 1980; Hosier and Eaton 1980; Wolcott and Wolcott 1984; Watson et al. 1996; Williams et al. 2004; Schlacher et al. 2007, 2008) and invertebrates (Steiner and Leatherman 1981, Moss and McPhee 2006). Odum and Dueser (1982) studied the ecological effects of OSV use in the Virginia portion of Assateague Island, concluding that the vehicles were having a direct negative impact on developing dune lines at Tom's Cove Hook and a secondary impact on dunes and vegetation at Fox Hill Levels by affecting dune geomorphology, plant growth, and groundwater salinity. OSV use on Assateague Island is also known to limit the abundance of the state-listed endangered white tiger beetle (*Cicindela dorsalis media*) (Knisley and Hill 1990), and reduce the species richness and abundance of migratory shorebirds and the size and number of roosts (Forgues 2010). Migrating shorebirds

also spend less time foraging in the presence of OSVs (Forgues 2010).

Watershed Land Use

Land use along the mainland side of the estuary plays a large role in the health of waters within the national seashore, and significant areas of the mainland are protected lands and waters, although development is increasing. The Maryland Department of Natural Resources owns and manages large areas (1172 ha [2897 ac]) of the upstream watershed adjacent to Johnson Bay and Parker Bay in the E.A. Vaughn Wildlife Management Area, as well as portions (470 ha [1162 ac]) of the Chesapeake Forest in multiple parcels inland from the bays. Multiple Maryland and Worcester County programs, along with non-governmental organizations, protect 5700 ha (14,000 ac) of habitat in the watershed from land use changes. In Maryland, the Atlantic Coastal Bays Critical Area Law (106 Code of Maryland Regulations §27.01.00.01(c)) affords significant protections to the estuary indirectly, by limiting the types, density and methods of new development within the coastal margin, and directly, by requiring a 30-m (100-ft) vegetated buffer along all tidal waters to prevent the movement of pollutants into the estuary. Recent trends in watershed development and land use have increased the threat posed primarily by higher nutrient loads, and secondarily by increases in development-related pollution and sediment runoff. Carruthers et al. (2011) suggested that estuarine health, based on multiple water-quality indicators, is good but declining.

Disturbed Lands

Assateague Island has experienced human impacts over the last several centuries, before and after its protection as a national seashore and a national wildlife refuge. The first permanent American Indian settlements were established around CE (Common Era) 900, along with the advent of maize agriculture. English settlers began arriving in the mid-1650s (Carruthers et al. 2011). Hotels were established beginning in the late 1860s, including one at Green Run (Carruthers et al. 2011). Visitation to Assateague Island and private development of houses, hunting camps, and service roads increased with the beginning of ferry service in the 1950s and construction of a bridge to Chincoteague Island in 1962 and the Verrazano Bridge to northern Assateague Island in 1964.

Human impacts result from impervious surfaces, mosquito ditches, sand mining, dune construction, animal grazing, impoundments, and boat groundings.

Impervious Surface

Impervious surfaces include roads, parking lots, and rooftops that decrease infiltration, water quality, and habitat while increasing runoff. A study in coastal New Jersey revealed that a proportion of impervious surfaces as low as 2% may have significant effects on pH and specific conductance in streams, and ecosystem components such as floral and faunal communities show considerable impact when impervious surfaces comprises 10% or more of habitat area (Carruthers et al. 2011).

Since its establishment, Assateague Island National Seashore continues to maintain and repair limited infrastructure within its developed zone to support visitor services, including bathhouses, visitor contact stations, and paved roads. These impervious surfaces cover 30.7 ha (75.9 ac) (0.22%) of Assateague Island (Carruthers et al. 2011). The national seashore is also making efforts to move parking lots further inland to reduce overwash and erosion, and to replace asphalt surfaces with native materials (clam-shell surface atop a clay base) where feasible. This method has proved succesful at the Toms Cove Virginia parking lot, which is overwashed multiple times each year. The South Ocean Beach parking lot in Maryland was buried by 1.2 m (4 ft) of sand during Hurricane Sandy in October 2012, a powerful storm that also damaged park infrastructure including roads, parking lots, and the pedestrian bridge crossing Sinepuxent Bay.The storm recovery plan includes moving the South Ocean Beach parking lot landward to merge with the adjacent Life of the Dunes Trail parking lot and replacing the asphalt with clam shell. The national seashore also plans to move the Bayside parking lot away from the estuarine shoreline and inland towards the Bayside campsites (Bill Hulslander, Resources Management Chief, Assateague Island National Seashore, personal communication, 13 June 2013).

Mosquito Ditches

The ecosystem function of the island's 960 ha (2375 ac) of salt marsh has been altered by more than 140 km (87 mi) of ditches created during a 1930s-era effort to control mosquitoes (fig. 27). An estimated 90% of the salt marshes from Maine to Virginia had been modified by these parallel ditch systems by 1938 (Bourn and Cottam 1950). Although the original intent was to drain mosquito breeding depressions by lowering marsh water table levels, mosquito ditches now hold shallow water just long enough for mosquitoes to successfully breed. They also prohibit access to predatory fish species that eat the larvae. The end result is that the ditches actually allow mosquito populations to thrive (Wolfe 1996).

Although the ditches within the national seashore have not been maintained since 1939, they remain as a visible scar on the landscape and continue to impact the geomorphology and ecological structure and function of the national seashore's salt marshes. The effects of local hydrological modification, such as ditching, on accretion of salt marshes is concerning, particularly in light of sea-level rise (Kirby and Widjeskog 2013); for example, tidal aquatic habitat and nonvegetation intertidal habitat increase and there are fewer pannes on the surface of ditched marshes (Adamowicz and Roman 2005), which impacts habitat value (Erwin et al. 2006; Mitchell et al. 2006). Ditches increase the connectivity of floodwater to the wetlands, reducing the natural potential of the wetlands to store floodwater and improve its water quality. A lower water table reduces the ability of plant

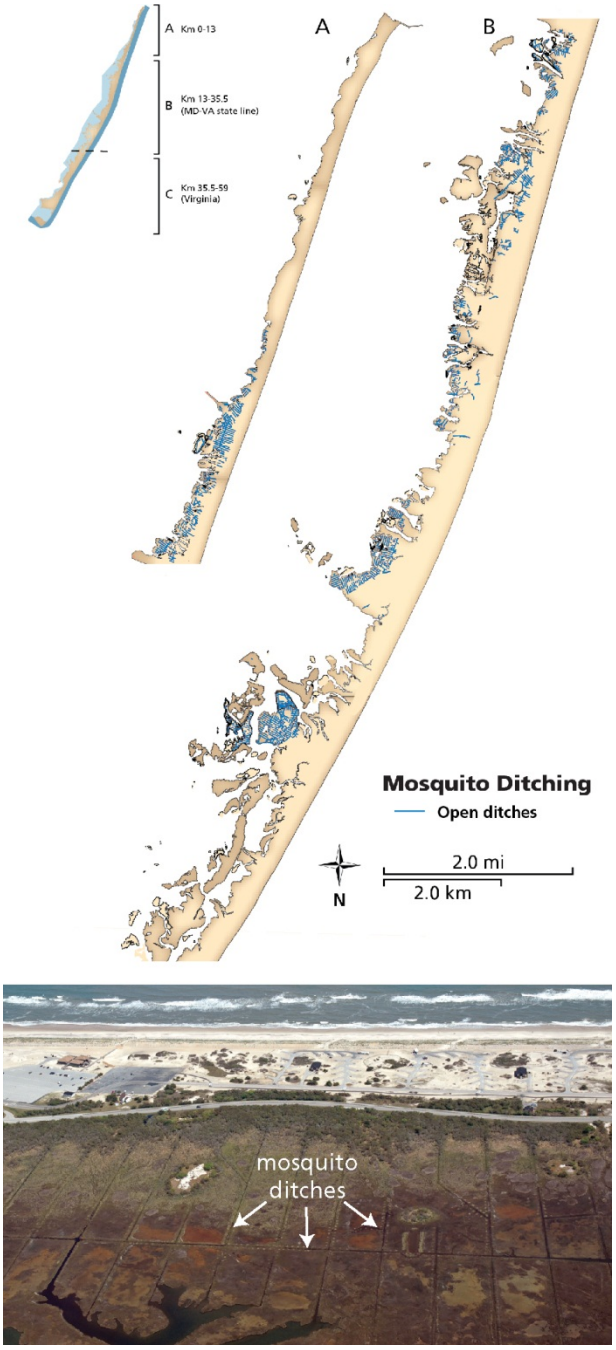


Figure 27. Map and photograph of mosquito ditches. Marsh hydrology and ecosystem function continue to be impacted by ditches built in the 1930s. Ditches were mapped along the Maryland portion of the island's estuarine shoreline in 2003. Map is figure 4.31 from Carruthers et al. (2011) using data from Assateague Island National Seashore. Photograph by Jane Thomas, Integration and Application Network, University of Maryland Center for Environmental Science (http://ian.umces.edu/imagelibrary/).

roots to intercept nutrients in groundwater. Altered tidal hydrology results in the following detrimental changes:

- Altered species composition and diversity of vegetation (Ewanchuk and Bertness 2004) and avifauna (Clark et al. 1984);
- Impacts on fish and waterbird habitat function, and other trophic components (Daiber 1986);
- Changes to soil salinity, chemistry, and aeration (e.g., leading to soil subsidence and compaction);
- Lowering of water tables;
- Reduced sediment delivery and vertical accretion (Warren and Niering 1993);
- Lower soil organic content (Portnoy 1999);
- Increased discharge of inorganic nutrients (ammonium, phosphate), dissolved and particulate organic nitrogen and carbon; and
- A suspected increased generation of ammonium and dissolved organic nitrogen within the ditches during lower tidal levels (Koch and Gobler 2009).

Changes in tidal hydrology are often followed by a change in the vegetation composition from typical native halophytic marsh plants to less salt-tolerant native and non-native plants (Roman et al. 2000). Reduced water levels and short term fluctuations in hydrology create unfavorable conditions (higher salinities and desiccation) for submerged aquatic vegetation in the shallow pond habitat of these marshes. *Phragmites australis* is an invasive reed (Daiber 1986) that is rapidly expanding in range within the national seashore, threatening terrestrial and wetland habitat biodiversity (Violi et al. 2012). To restore the hydrologic processes and salt marsh ecosystem health to a pre-ditched condition, the national seashore staff has begun to block the outlets of these ditches with biodegradable wood and then to fill the ditches with sand. Early observations indicate that hydrology is being restored; indicators include restoration of sheet flow, more water on the marsh, pannes with water, and associated vegetation changes including low salt marsh cordgrass (*Spartina alterniflora*). The staff has also installed a network of groundwater monitoring wells and an additional estuarine tide gauge to measure the response of the marsh to this effort (Brian Sturgis, ecologist, Assateague Island National Seashore, personal communication, 17 June 2013).

Sand Mining

For the marsh restoration project described above, limited quantities of sand are being removed from the OSV zone in Maryland. Sand is removed from the area between the high water line and the natural storm berm using a front-end loader, and is moved to staging areas near each ditch-filling site. The borrow site is then smoothed. The national seashore's sand borrow plan and reclamation plan have been written (ASIS 2008a, 2008b) and approved in accordance with NPS policies (NPS Director's Order Special Directive 91-6 and NPS Management Policies). Future sand mining plans should be developed using NPS guidance provided in Dallas et al. (2012).

Sediments have been dredged for decades from Sinepuxent Bay, Ocean City Inlet, and the associated ebb and flood tidal deltas to provide sediment for dune building, beach renourishment, and breach repair for Assateague Island and Ocean City. As described in the

"Sediment Transport" section, biannual mechanical sand bypassing to the North End of Assateague Island is supplied by tidal delta sediments. Other sand needs, such as large-scale Ocean City beach replenishment and the artificial foredune constructed on the national seashore in 1998 (see below), are met by dredging shoals that are farther offshore but within the state's 3-mile (4.8 km) limit (e.g., Great Gull Banks), not in federal waters.

Another major sand mining project that may impact the Assateague Island shoreline was recently approved (BOEMRE 2011b). Submerged sand shoals that lie 8 to 16 km (5 to 10 mi) off the southern end of Assateague Island will be dredged to renourish Wallops Island, which lies on the southern boundary of Chincoteague Inlet. Assateague Island National Seashore's official response to the project's proposed environmental impact statement (NASA 2010) expressed concern that the project would adversely impact the seashore in several ways:

- Reduction in the shoals' ability to shelter the seashore's eroding shoreline from wave energy, particularly waves from the southeast and east;
- Impacts on the regional sediment budget and cross-shore sediment transport pathways from the shoal and nearshore areas to the island (Thieler et al. 1995; Schwab et al. 2000a, 2000b; Hayes and Nairn 2004); and
- Degradation of habitat for pelagic fish and birds, and the benthic communities that support them (Diaz et al. 2004; Vasslides and Able 2008).

Construction of Artificial Dunes

The Ackerman/Ocean Beach Club built an artificial dune from the North End to the Virginia state line in 1950 to protect privately held developments and properties (Coburn 2009). This dune was rebuilt in 1963 following damage by the 1962 Ash Wednesday storm (Coburn 2009). The portion of the artificial dune within the national seashore's developed zone and Assateague State Park continues to be maintained to protect park roads and visitor facilities. The U.S. Fish and Wildlife Service built another artificial dune from Green Run to the southern end of the island in 1963, and dune grass was planted in 1993 to stabilize it (Coburn 2009).

A low foredune was constructed in 1998 as a temporary measure to reduce the likelihood of an island breach until the long-term North End Restoration Project could be implemented. This 2.4-km- (1.5 mi) long structure was built along an area most vulnerable to overwash to prevent imminent island breaching and its consequences on the island, the populated mainland, and inlet hydrodynamics.

The structure was intended to allow enough overwash (an estimated frequency of at least one event per year) to preclude the growth of woody plants and maintain sparse herbaceous vegetation (USACE 1998). The primary tool used to design the artificial berm was the storm-induced beach change model (Larson and Kraus 1989), a widely applied but somewhat problematic (Thieler et al. 2000) coastal engineering model that computes wave runup, overwash, and storm-induced beach erosion under various tide and wave conditions (Schupp et al. 2013). The setback of the artificial berm from the ocean was calculated with the assumption that the recent erosion rates and storm frequency would continue in the years before the long-term sand bypassing phase began (Schupp et al. 2013).

In contrast to the modeled behavior, the artificial berm proved impenetrable to overwash, due in large part to several unexpected conditions. First, the dredged sediment used in construction had a larger proportion of coarse-grained materials, including gravel, than did the native materials. Through wind winnowing, this coarse fraction blankets most of the foredune surface, limiting the ability of the underlying sediments to be mobilized during wind and storm events. Second, post-construction meteorological conditions were much calmer than the modeled storm conditions, so shoreline erosion was also unexpectedly low. Third, the long-term restoration effort, involving mechanical sand bypassing to the nearshore, began earlier than expected, so the shoreline had not eroded as far westward before the longshore sediment volume increased (Schupp et al. 2013).

As a result, by 2006, the artificial berm had gained significant volume along its flanks, had maintained its height, and had never been overwashed. By sheltering the island interior from wind and waves, the artificial berm accelerated the progression from sparsely vegetated habitat to an increasing area of herbaceous vegetation, shrub communities, and the associated growth of embryo dunes due to the sand-trapping effects of the increased vegetation. These changes reduced foraging habitat available for piping plover (*Charadrius melodus*), a federally-listed threatened species (Schupp et al. 2013).

To address these unintended impacts and to allow overwash in the project area, cross-shore depressions, or notches, were cut through the artificial berm at 14 locations in 2008 and 2009. Notch design replicated natural cross-beach overwash profiles with respect to elevation, slope, and location relative to the shoreline. As of 2011, the notches were continuing to allow overwash and restore habitat (Schupp et al. 2013). The resulting new overwash fans increased island stability by increasing the elevation of the island's interior, and also increasing areas of sparse vegetation at every notch, which is now utilized as foraging habitat by piping plover (Schupp et al. 2013). The intent is for overwash restoration to sustain the availability of foraging habitat, but future foredune modifications may be necessary to maintain or increase overwash processes and piping plover habitat in the project area (Schupp et al. 2013).

Other Human Impacts

Recreational use of the Assateague Island National Seashore estuary includes boating. Boat propellers sometimes damage seagrass beds, leaving scars that

persist for years. Two species of SAV, eel grass (*Zostera marina*) and widgeon grass (*Ruppia maritima*), play critical roles in the Coastal Bays ecology, providing habitat for a broad range of aquatic species, producing oxygen, cycling nutrients, and reducing shoreline erosion by attenuating wave energy. The waters of Assateague Island National Seashore support the largest SAV beds (by acreage) in the Maryland and Virginia Coastal Bay system, and are crucial to the maintenance of regional biological diversity.

Feral horses (*Equus caballus*) have been present on Assateague since the 1600s and are an integral part of the island's cultural history and traditions. However, they cause resource damage, including dune erosion due to heavy grazing on American beachgrass (*Ammophila brevigulata*). The beachgrass has an extensive root and rhizome system that accumulates sand, initiating dune formation and maintaining dune stability (Seliskar 1997). Overgrazing resulted in dune erosion (Seliskar 2003). Trampling by horses may also limit the ability of marshes to accumulate sediment to balance marsh erosion (Furbish and Albano 1994). Their grazing also influences plant community structure in marshes (Zervanos and Keiper 1979) and forest and shrub habitats (Sturm 2007). These issues were explored through a population viability study that used a modeling approach to identify sustainable population levels (Zimmerman et al. 2006).

In Chincoteague National Wildlife Refuge, fresh and brackish water impoundments totaling approximately 1072 ha (2,650 ac) were created for the primary purpose of providing waterfowl migration and wintering habitat (U.S. Fish and Wildlife Service [USFWS] 2012). These former water bodies or flats were altered by dikes to retain water, or are interior water bodies created by dredging below the water table (Morton et al. 2007). All but one of the impoundments were constructed in the 1950s and 1960s; the final impoundment was constructed in 1992 (USFWS 2012). The management objectives of the impoundments have broadened over time and they are now intensively managed through flooding, drawdown, disking, hydro-axing, mowing, seeding, planting, burning, and control of non-native *Phragmites* (common reed) (USFWS 2012).

Impoundments support waterfowl wintering/migratory habitat; provide food sources for waterbirds of conservation concern, such as snowy egret (*Egretta thula*), glossy ibis (*Plegadis falcinellus*), Forster's tern (*Sterna forsteri*), and gull-billed tern (*Gelochelidon nilotica*); offer shorebird migratory stopover habitat for many species of conservation concern, including short-billed dowitcher (*Limnodromus griseus*), dunlin (*Calidris alpina*), and semipalmated sandpiper (*Calidris pusilla*); and provide nesting habitat for the threatened piping plover (*Charadrius melodus)* (USFWS 2012). Impoundment vegetation also supports migrating monarch butterflies and fall migrating landbirds. Impoundments also provide valued recreational opportunities for visitors by concentrating large flocks of birds, providing wildlife viewing, photography, education, and interpretation opportunities; the associated levees and dikes are used as walking and biking trails (USFWS 2012).

All impoundments depend entirely on precipitation for their source of freshwater, and gravity or evaporation for drawdown (USFWS 2012). These structures alter groundwater hydrology and, when drained to the marsh and bay, have unknown impacts on water quality. Storm events sometimes overtop dikes, increasing salinity and water levels (USFWS 2012). As sea level continues to rise, damage to dikes and other impoundment infrastructure can be expected (USFWS 2012). Maintaining water depths at desirable levels may also become more difficult (USFWS 2012).

The 2005 Geologic Resource Evaluation Scoping Meeting (Thornberry-Ehrlich 2005) identified the following research and planning needs:

- Cooperate with local developers to minimize impacts of regional development on the national seashore;
- Collaborate with conservation groups to protect regional habitat quality and water quality;
- Promote environmentally sound methods of developing land parcels; and
- Consider remediation of the unnatural landscapes created by early settlers.

Archeological Resources

Langley (2002) compiled an inventory of all Assateague-area shipwrecks (total loss or significant damage) in recorded history (as early as 1698). Remains of eight shipwrecks are known to be within Assateague Island National Seashore, and many more are suspected. At least 156 shipwrecks occurred within the boundaries of the national seashore and a further 55 occurred in the vicinity and may be present due to drifting (Langley 2002).

Langley (2002) explained that waves and sediment movement can not only break apart and bury existing shipwrecks, but can also move the wreckage alongshore. Historic accounts of some shipwrecks involve damaged ships attempting, and failing, to limp through inlets to the calmer estuarine waters. Those that wrecked in the historic inlets have since been buried and are now within the body of the island (Langley 2002). As the island transgressed westward, shipwrecks that were in the estuary have also been buried under the island, and are sometimes exposed after large storms temporarily move sediment off of the beaches (Langley 2002) (fig. 28). In contrast, wrecks in the nearshore have been transported further away from the migrating shoreline (Langley 2002). As the Assateague Island shoreface continues to erode, artifacts from shipwrecks sometimes are washed ashore within the national seashore (Langley 2002). Additionally, artifacts from prehistoric cultures are periodically deposited on the Ocean City (Maryland) beaches, including Archaic tools (10,000 to 3,000 years old) which would have been used by people living on exposed land that is now underwater following sea-level rise (Langley 2002).

Figure 28. Photograph of shipwreck. Storm erosion sometimes uncovers shipwrecks that are buried within Assateague Island. This wreck on an 1850s two-masted schooner was uncovered by storm waves in December 1998; within three months it had been covered by up to 2.4 m (8 ft) of sand. Photograph by Assateague Island National Seashore.

Paleontological Resources

Paleontological resources (fossils) are not mentioned in Assateague Island National Seashore's enabling legislation, but are found within the seashore. A paleontological resource summary was completed as part of a network-wide summary for the Northeast and Coastal Barrier Network (Kenworthy and Santucci 2003). The fossils are likely of Pleistocene age, but whether they have washed ashore after being carried offshore by paleodrainage channels or have been eroded from the shoreface or body of the island remains unknown (Kenworthy and Santucci 2003).

The majority of these fossils are fragmentary and include oyster, angelwing, and other bivalves and shells; crabs (imprints of either *Cancer irroratus* or *Callinectes sapidus)*; tableate, cup, and tetra corals; and ammonites (Kenworthy and Santucci 2003). Some fossil bivalve shells were found on the southern end of Assateague Island and are likely Pleistocene in age, though they may date to an interglacial (high sea level) period (approximately 60,000 years old); these worn shells include *Chione cancellata*, *Crassinella lunatula parva*, *Donax variabilis*, and *Arca ponderosa*, none of which are found in the area today (Richards 1936 as cited in Kenworthy and Santucci 2003). The national seashore has 11 specimens in its museum, in addition to two non-accessioned items: a nearly complete crab and what is suspected to be the right mandible of a sea lion with one tooth. A national seashore employee reported that a mammoth tusk washed up on the Wallops Island beach approximately 13 km (8.1 mi) southwest of the national seashore (Kenworthy and Santucci 2003).

Continued discovery of fossils along the Assateague shoreline is probable. Visitors are permitted to collect up to 1 gallon of unoccupied shells per individual per visit, with the exception of shells within archeological sites (ASIS 2012a). However, NPS management policies (NPS 2006) and the 2009 Paleontological Resources Preservation Act (P.L. 111-011, Omnibus Public Land Management Act of 2009) prohibit the unpermitted collection of any paleontological resource within all national park units. To reduce misunderstanding among the visiting public and staff, the national seashore staff may want to consider developing interpretive products to increase awareness and recognition of fossil specimens.

Santucci et al. (2009) recommend five methods and vital signs for monitoring paleontological resources: 1) erosion (geologic factors), 2) erosion (climatic factors), 3) catastrophic geohazards, 4) hydrology/bathymetry, and 5) human access/public use. Although these vital signs were originally developed for in situ paleontological resources, the monitoring strategies may still be applied to areas where fossils commonly wash ashore. Brunner et al. (2010) described resource management and policy challenges associated with paleontological resource collection along NPS shorelines.

Seismicity

Very little is known about the causes of earthquakes in the eastern United States. In general, no clear association exists among seismicity, geologic structure, and surface displacement in the eastern U.S., in contrast to a common association in the western U.S. (Maryland Geological Survey 2012). Although strong earthquakes are unusual in Maryland, the state occasionally experiences perceptible earthquakes. On 23 August 2011, park visitors reported shaking, but no damage, related to a magnitude 5.8 earthquake with its epicenter in Louisa County, Virginia, 225 km (140 mi) west of Assateague Island. In the Atlantic Coastal Plain, earthquakes are now thought to be associated with nearly vertical faults that formed during the opening of the present Atlantic Ocean during the Triassic period, about 220 million years ago (Hanks 1985). Such faults would occur in the "basement" bedrock, and not in the overlying, younger Coastal Plain sediments (Maryland Geological Survey 2012).

For a given earthquake, the effective intensity will be much greater on unconsolidated (and potentially water-saturated) alluvium (such as beaches) than on consolidated bedrock. A soft surficial layer (such as the loosely consolidated sands, in combination with a high

water table, found throughout Assateague Island) can increase ground displacements by a factor of 4 to 5 and accelerations by about 1 to 1.5 (Bollinger 1978). Narrow estuarine waterways can also respond to earth motion with large wave actions (Bollinger 1978). In Virginia, the vertical configuration of the Coastal Plain sedimentary rocks is a wedge shape of soft sediments, which thickens to thousands of feet at the coastline, overlying a hard rock basement (fig. 2). This configuration can channel vibrations within the wedge, thereby amplifying the vibrations at its thin (inland) edge.

Maryland is in a zone in which seismic damage is expected to be minor, corresponding to Mercalli intensity V to VI (Maryland Geological Survey 2012), and has a very low chance of experiencing a damaging earthquake in a 50-year period. As a rough estimate, for moderate exposure times (10–100 years), the expected ground motion associated with earthquakes in this region would be of marginal interest (Algermissen et al. 1982) and would likely have a magnitude of less than 4.0 to 4.5. The difficulty in assigning maximum magnitudes is most acute where no fault is known, where seismicity is low, and where near-maximum earthquakes may not have occurred in historical times, all of which are true for most of the eastern United States (Algermissen and Perkins 1976).

Recent studies and media reports have speculated on the possibility of a tsunami striking the East Coast after being generated by an earthquake or submarine landslide on the eastern side of the Atlantic Ocean. Mega-tsunami generation, even from the larger slope failures of island stratovolcanoes, is extremely unlikely to occur, because a tsunami that would have significant far-field effects would require greater source dimensions and longer wave periods (Pararas-Carayannis 2002). Furthermore, the great width of the continental shelf along the U.S. East Coast, in addition to Atlantic seafloor bathymetry, would likely dissipate tsunami amplitude. However, impacts would be possible along the Maryland and Virginia coastline if a thrust earthquake occurred along the eastern Iberian–African plate boundary, in the Gulf of Cadiz, or west of the Madeira-Tore Rise west of Spain (Barkan et al. 2009).

A tsunami could be triggered by large-scale submarine slope failure along the continental shelf off of southern Virginia and North Carolina (Driscoll et al. 2000). Acoustic surveys indicate cracks and basinward-normal slip on these features, demonstrating a failure surface that may be the nucleus of future submarine landslides. The potential volume of such a slide could cause a tsunami up to several meters, although flooding extent would depend on the tidal stage at the time of tsunami arrival (Driscoll et al. 2000). The risk of such submarine landslides may increase with climate change; Driscoll et al. (2000) proposed that warming of bottom water during interglacial periods could cause gas hydrates in the upper several meters of sub-seafloor to melt, resulting in slope failure. Because the stability of gas hydrates is affected by pressure and temperature, lowered sea level could also cause gas hydrates to dissociate (Kvenvolden 1993).

To evaluate and monitor seismic risk, the Maryland Geological Survey has developed the Maryland Seismic Network (http://www.mgs.md.gov/seismics/local.shtml) to provide high-quality, real-time data on local earth movements and earthquakes in Maryland and other more distant earthquakes around the globe. Seismic data from the network are analyzed by the Lamont-Doherty Earth Observatory and included in the Lamont-Doherty Cooperative Seismic Network database (http://www.ldeo.columbia.edu/LCSN/index.php).

Geologic Features and Processes

Geologic resources underlie park ecosystems and geologic processes shape the landscape of every park. This chapter describes prominent and distinctive geologic features and processes in Assateague Island National Seashore.

During the scoping meeting (26–28 July 2005), a list of geologic features and processes operating in Assateague Island National Seashore was developed, including:

- Wave and Current Activity
- Wind Activity
- Tidal Activity
- Sediment Transport Processes
- Barrier Island System Units

Waves, wind, and tides shape the geomorphology of Assateague Island through various processes, including through sediment transport.

Wave and Current Activity

The ocean coastline is wave dominated (Field 1979). The wave climate is generally moderate as measured off of Ocean City Inlet Maryland (USACE 2012) (fig. 29) with a mean deep-water significant wave height of 1.2 m (3.9 ft) (determined from an 18-year record of National Data Buoy Center station 44009, Delaware Bay) (Moore et al. 2006). At Assateague Island, 92% of wave heights are less than 1.4 m (4.6 ft), but wave heights up to 3.5 m (11.5 ft) occur about once every 10 years, and heights up to 4.5 m (15 ft) once every 50 years (Krantz et al. 2009). Hurricanes and extra-tropical (northeaster) storms can produce local wave heights in excess of 8 m (26 ft), and based on the 18-year Delaware Bay record, the 50-year return wave height is estimated to be approximately 10 m (33 ft) in this region (Moore et al. 2006).

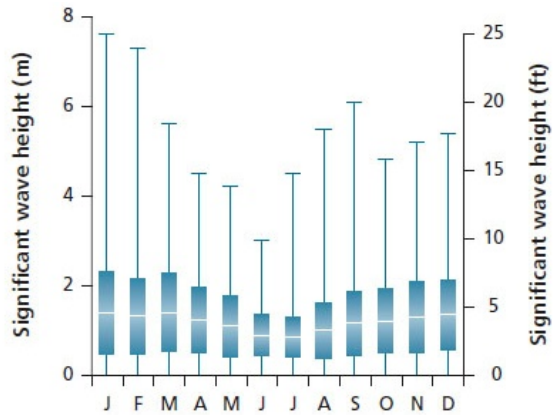


Figure 29. Graph of monthly wave heights measured offshore of Ocean City Inlet Maryland. Wave climate is generally moderate, with stronger wave energy in the winter. Data show the median value (white line), the first and third quartiles (ends of thick blue bars), and the lowest and highest values (thin blue lines). Figure 2.4 from Carruthers et al. (2011) using data available from USACE (2012).

Wind-driven waves drive the longshore current (fig. 30), which moves sediment predominantly southward, although direction varies seasonally; this process is described below in the "Sediment Transport Processes" section of this chapter. Extra-tropical storms (winter northeasters) and high wave energy create a low, flat beach with sand stored in nearshore bars, whereas summer beach profiles are steeper.

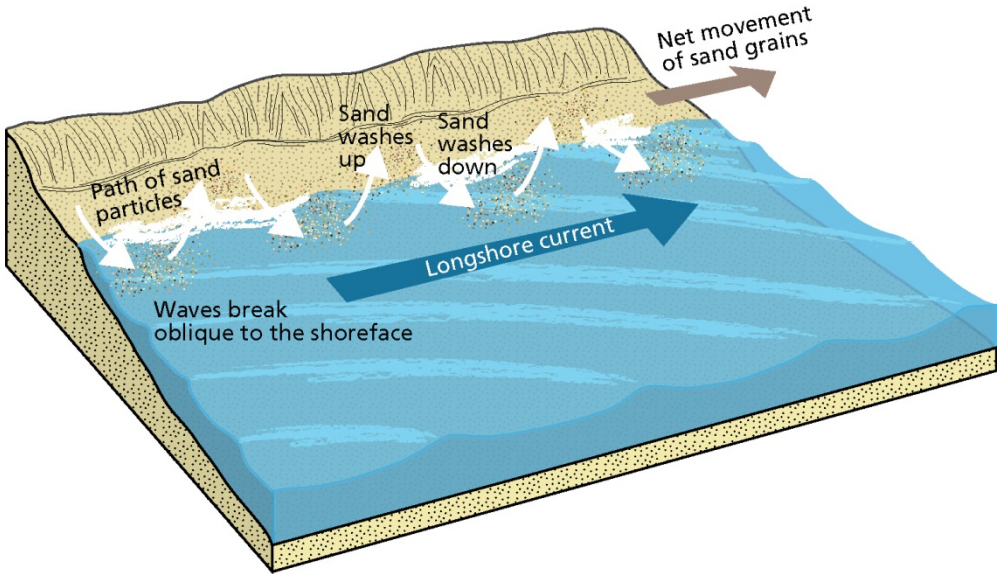


Figure 30. Schematic graphic of longshore current and sediment transport. Waves drive longshore current, which moves sediment alongshore. Figure redrafted by Trista Thornberry-Ehrlich (Colorado State University) after British Columbia Capital Regional District (http://www.crd.bc.ca/watersheds/protection/geology-processes/coastalsediment.htm).

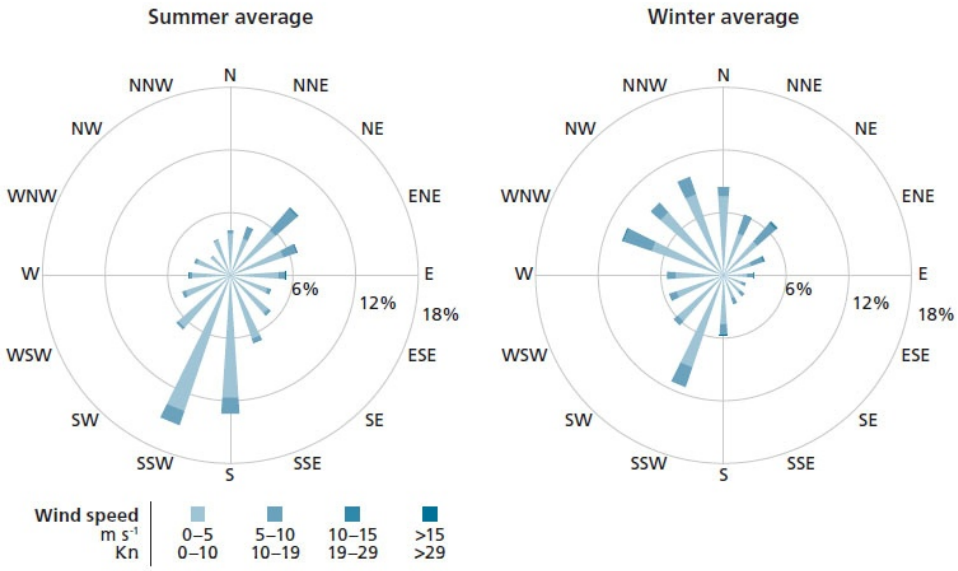


Figure 31. Rose diagrams of seasonal wind speed and direction, 1995–2006, as measured in the Green Run area of Assateague Island. Wind conditions are primarily from the south during the summer and from the west during the winter. Figure 2.3 from Carruthers et al. (2011) using data from BLM/NPS (2011).

Wind Activity

During the summer, winds are mostly from the south-southwest, predominantly from 5 to 10 m/s (11 to 22 mi/hr) whereas in winter the dominant wind direction is northwest, with wind speeds frequently greater than 10 m/s (22 mi/hr) (Carruthers et al. 2011), as measured by the weather station (BLM & NPS 2011) in the Green Run area of Assateague Island (fig. 31).

Along the western and northern margins of the bays, wind conditions have a greater effect on water levels and current velocities than do tides (Wells 1999). In Chincoteague Bay, currents are largely dominated by wind. Casey and Wesche (1981) reported negligible tidal currents but wind-generated currents up to 0.12 m/s (0.4 ft/s) at a site near Public Landing (mid-point of Chincoteague Bay). At this site, tidal amplitude was measured at 0.17 m (0.56 ft). However, during storm conditions, they observed as much as 0.63 m (2.1 ft) variation in water levels.

Winds between 10 and 17 m/s (22 to 38 mi/hr) occur about 11% of the time along the Maryland coast and can produce whitecaps and increase turbidity in the Coastal Bays by stirring up fine sediments (Krantz et al. 2009). If water level is also elevated, the wind events also create waves that erode the outer edges of the tidal marsh and undercut the root mat (Krantz et al. 2009).

Wind also transports significant quantities of sediment between the beach and dunes, into the island's interior, and into the Coastal Bays. The mechanisms of this transport are described below in the "Sediment Transport Processes" section.

Tidal Activity

The Assateague Island ocean coastline is classified as microtidal; the semi-diurnal tide has a mean range of 1.02 m (3.36 ft) and a spring range of 1.22 m (4.00 ft), as measured at the Ocean City Maryland Fishing Pier (MD) (NOAA 2007). Just south of Assateague Island, at the NOAA tide gauge along the coast of Wallops Island Virginia, the mean tide range is higher: 1.12 m (3.67 ft), with an extreme range (spring tide) of 1.33 m (4.37 ft) and a mean tide level of 0.58 m (1.89 ft) (NOAA 2007). On the basis of nearby open-coast NOAA tide gauges, the local mean high water elevation was calculated to be 0.31 m (1.0 ft) NAVD88 at the Ocean City Maryland Fishing Pier, and 0.38 m (1.2 ft) at Wallops Island Virginia (Weber et al. 2005).

In the Maryland Coastal Bays, tidal cycles exert significant control on circulation patterns and tidal ranges. Near Ocean City Inlet, currents are primarily an effect of tidal cycles and are commonly more than 2 m/s (6.5 ft/s) with amplitudes of 0.55 to 0.78 m (1.8 to 2.5 ft), according to data from tide stations in southern Isle of Wight Bay (Wells 1999). Approximately 80% of the tidal flow is directed northward into Isle of Wight Bay (Dean et al. 1978 as cited in Wells 1999) because Sinepuxent Bay is more constricted. Tidal influence diminishes rapidly with increasing distance from the inlet, and wind becomes the stronger influence (Wells 1999). Within Isle of Wight and Assawoman Bays, nominal tidal amplitudes range from 0.25 m (0.82 ft) (spring tide) to 0.16 m (0.52 ft) (neap tide), and peak ebb and flood velocities range from 0.14 m/s (0.46 ft/s) to 0.26 m/s (0.85 m/s) (Casey and Wesche 1981 as cited in Wells 1999).

Shallow bathymetry and restricted access to the ocean contribute to poor circulation and flushing in the

Maryland Coastal Bays. Reported estimates for turn-around time in Chincoteague Bay range from 200 days (Sieling 1958 as cited in Wells 1999) to 63 days (Pritchard 1960 as cited in Wells 1999).

Sediment Transport Processes

Sediment Sources

The shoreline derives sand from erosion of the shoreface and Pleistocene headlands at Rehoboth Beach and Bethany Beach, Delaware (Hobbs et al. in press). Shoreface ravinement, or the landward erosion of sedimentary layers through shoreface processes, is the primary erosional process, as scour by storm waves and longshore currents bevels Holocene back-barrier deposits exposed in the shoreface and excavates shallow Pleistocene sediments to 11 to 13 m (36 to 43 ft) below present sea level (Kraft 1971).

Longshore Transport

Along the ocean shorelines of Ocean City and Assateague Island, net longshore sediment transport (fig. 30) is southward due to strong winter northeasters. In the summer, waves from the southeast drive sand transport less vigorously northward. The net annual longshore transport is estimated to be between 115,000 m^3/year (150,400 yd^3/year) and 214,000 m^3/year (279,900 yd^3/year) toward the south (Underwood and Hiland 1995).

Depth of closure, defined as the depth beyond which sediment transport of engineering significance does not occur (Hallermeier 1981), is estimated to be –6.2 m (–20.3 ft) at Assateague Island (Stauble 1994), where it is typically found about 275 to 400 m (900 to 1300 ft) from the high tide line (Schupp et al. 2007).

Accretion at Toms Cove, Virginia

The southern end of Assateague Island, Toms Cove Spit, is an accretionary spit complex bounded by Chincoteague Inlet. It is the terminus of the regional longshore sediment transport system that moves sand southward from the Bethany headland nearly 75 km (47 mi) to the north (Oertel and Kraft 1994). It has grown by 6 km (3.7 mi) since the mid-1800s (Field and Duane 1976). This rapid growth may have been driven by the natural closure of historic inlets through Assateague Island (Green Run and Pope Island inlets) and subsequent reworking of their respective ebb-tidal deltas in the late 1800s (Halsey 1978; Demarest and Leatherman 1985; McBride 1999; Hobbs et al. in press). Chincoteague Inlet and the shoals offshore of Toms Cove serve as an extremely efficient sediment trap (Wikel 2008), allowing only about 5% of longshore transport to bypass to the south (Moffatt and Nichol 1986). Estimates of accumulation range from 165,000 to 1,100,000 m^3/year (215,800 to 1,439,000 yd^3/year) (Finkelstein 1983; Headland et al. 1987; Hobbs et al. in press). The spit continues to build southwestward at the rate of approximately 50 m (164 ft) per year, according to national seashore shoreline survey data and historic maps (fig. 32).

Sediment Transport in the Coastal Bays

Sediment transported into the Coastal Bays comes from several sources: suspended sediments transported by streams; resuspension of marine seafloor sediments during storms; erosion of the mainland shoreline; overwash across the island; and windblown sand from the island (Krantz et al. 2009). Fine-grained sediments settle quickly in the Coastal Bays areas, away from the inlets and channels (Krantz et al. 2009). Within the tidal inlet channels and flood-tidal deltas, where tidal energy is high, only larger-grained sediments (sand and gravel) can settle to the bottom.

Aeolian Transport

Wind also moves sediment onto, off of, and along the island. During storms, waves generated by onshore winds remove sediment from the upper beach, creating a wider, flatter surface with finer-grained sediment that is more easily transported by wind during later phases of the storm, when surge levels are lower (Nordstrom et al. 2006). Strong northeasters frequently bury the national seashore's parking lots with sand that can form drifts of more than 0.5 m (1.6 ft). Aeolian transport potential is controlled by sediment supply, size, and sorting (Nordstrom et al. 1986), in addition to environmental factors such as vegetation (Buckley 1987), slope, and surface moisture (Sherman and Hotta 1990), wind regime, and lag deposits (Houser and Hamilton 2009). Effects of vegetation on the rate of windblown sand transport seem to be highly localized, but bare sand areas in the dunes, even those <10 m (33 ft) wide, can provide a sufficient source width to cause high rates of transport in fine sand (Nordstrom et al. 2006).

Aeolian processes are important to beach/dune interactions, including building and maintaining dunes (Conaway and Wells 2005). Coastal dunes exist only where there is an adequate sediment supply and the wind regime is favorable (Davidson-Arnott and Law 1990). Dune growth and migration are correlated with the rate and volume of sediment transported by wind from the beach to the foredune ridge (Sherman and Bauer 1993) and may also be supplied by offshore winds carrying sediment from overwash fans (Leatherman 1979a). Where ocean waves erode the dune base, the eroded sediment can be blown inland, causing landward migration of the dune ridge (Nordstrom et al. 1986) (fig. 33).

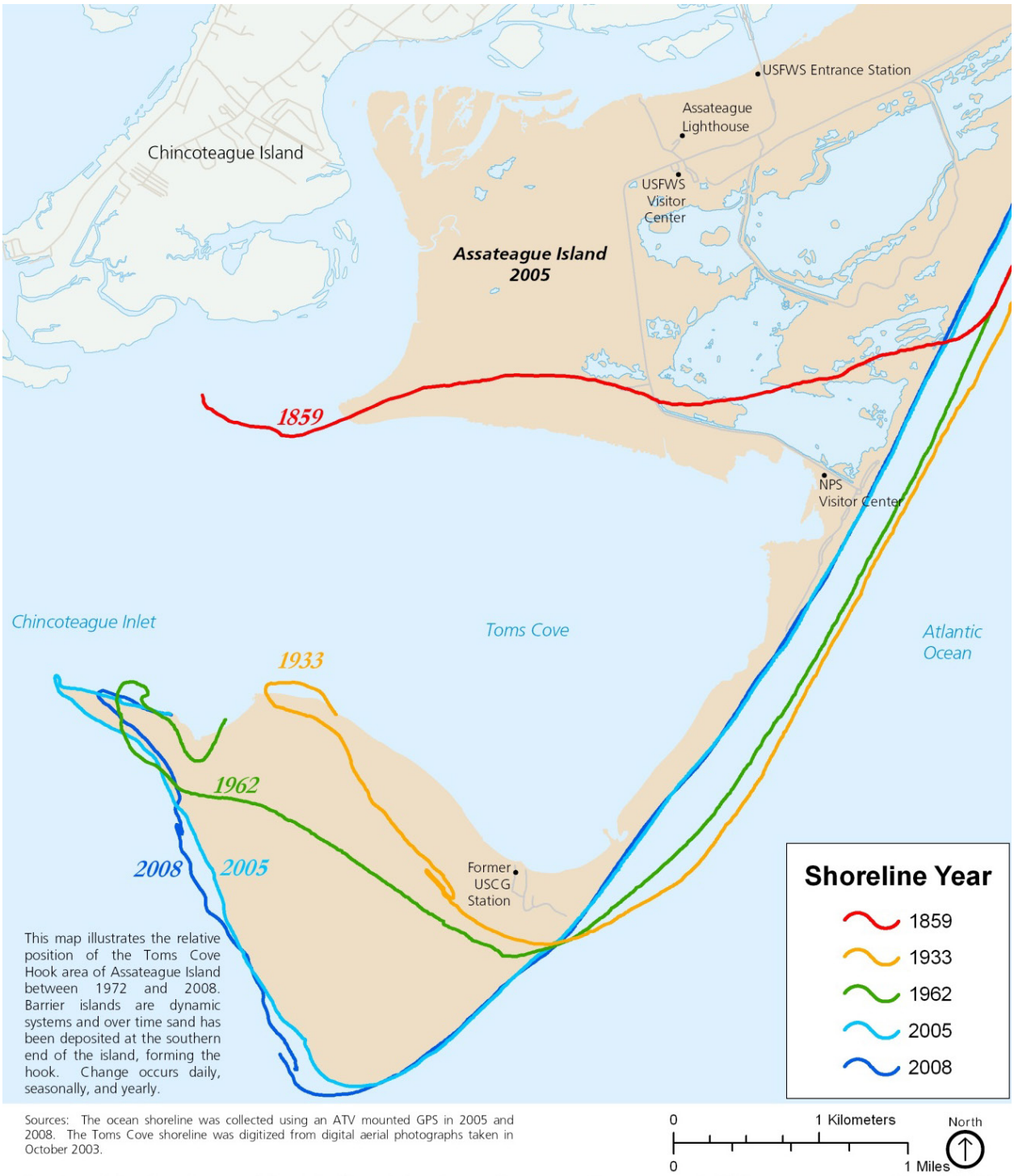


Figure 32. Map of Toms Cove location over time. Toms Cove Spit, at the southern end of Assateague Island, is accretional. Figure by Assateague Island National Seashore in March 2009.

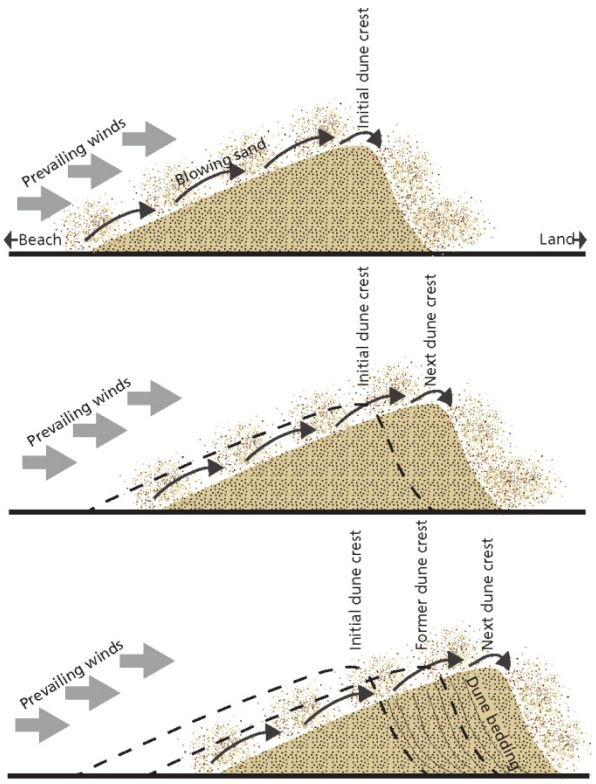


Figure 33. Schematic graphic of aeolian sand transportation process. Sand is lifted off the beach by the wind, then dropped or trapped by vegetation. Winds blowing from the ocean onto the beach gradually move the dunes landward. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

Barrier Island System Units

Assateague Island has a diversity of depositional sub-environments that are seen on other barrier islands along the middle Atlantic coast. The GRI digital geologic map presented here (see "Geologic Map Data" chapter) was developed by Morton et al. (2007) and classifies the island's surficial geomorphology into 19 units, six of which are anthropogenic in origin (artificial berm, impoundments, jetty, modified land, parking lots, reclaimed land; see Map Unit Properties Table). This map emphasizes the origins of the surficial features and serves as a basis for documenting sub-environments that are relatively stable, such as the barrier island core, andthose that are highly dynamic, such as the beach and active overwash zones (Morton et al. 2007). The landforms, hydrogeology, and biology are closely interrelated, exerting control upon each other.

Artificial Berm

This anthropogenic feature (fig. 34), built in 1998, is composed of 285,000 m^3 (373,000 yd^3) of sand, gravel, and shell dredged from an offshore shoal. It parallels the shore and functions as a low foredune in the backbeach area. Located along the island's north end, it is 2.4 km (1.5 mi) long and has an elevation up to 3.05 m (10 ft) (NAVD88). It has impeded natural overwash function on the North End, reducing foraging habitat available for piping plover (*Charadrius melodus*), a federally-listed threatened species (Schupp et al. 2013). Additional

Figure 34. Photograph of artificial berm. This photograph shows overwash at the southern tip of the constructed berm. Photograph by Assateague Island National Seashore.

information on this structure's function and impact can be found in the "Geologic Issues" chapter.

Impoundments

In Chincoteague National Wildlife Refuge, fresh and brackish water impoundments totaling approximately 1,072 ha (2,650 ac) were created beginning in the 1950s, primarily to provide waterfowl migration and wintering habitat (USFWS 2012). Now, they also provide food and habitat for multiple bird species and migrating butterflies. These structures also alter groundwater hydrology and may impact estuarine water quality. Storm events that overtop dikes also increase salinity and water levels within the impoundments. Additional information can be found in the "Geologic Issues" chapter.

Jetty

The north end of Assateague Island is bounded by Ocean City Inlet, which was stabilized with a pair of jetties in 1934 to maintain the navigation channel. The jetties, which are engineering structures that project perpendicular to the shoreline, are composed of large blocks of rock and are designed to reduce the flow of sand into a coastal navigation channel, such as a tidal inlet (Morton et al. 2007). The jetty along the north end of Assateague Island is 700 m (0.4 mi) long, 400 m (0.25 mi) of which extends seaward from the island (Schupp et al. 2013). It is regularly maintained, including work in 1938, 1956, 1963, and 1986 (Coburn 2009). The inlet and jetties disrupt southward sediment transport and have starved the North End of sediment, resulting in increased shoreline erosion rates and lowered island elevation. (Additional details can be found in the "Sediment Transport" section of the "Geologic Issues" chapter.) Two breakwaters were also built along the island's inlet shoreline, in line with the jetty, to shelter the inlet shoreline from waves; the associated sand buildup sometimes extends from the shoreline to the breakwaters.

Modified Land and Parking Lots

The developed areas of Assateague Island National Seashore and Assateague State Park in Maryland support visitor access and infrastructure, including parking lots, roads, buildings, and campground areas (fig. 35). These maintained areas are cleared and paved. They have low

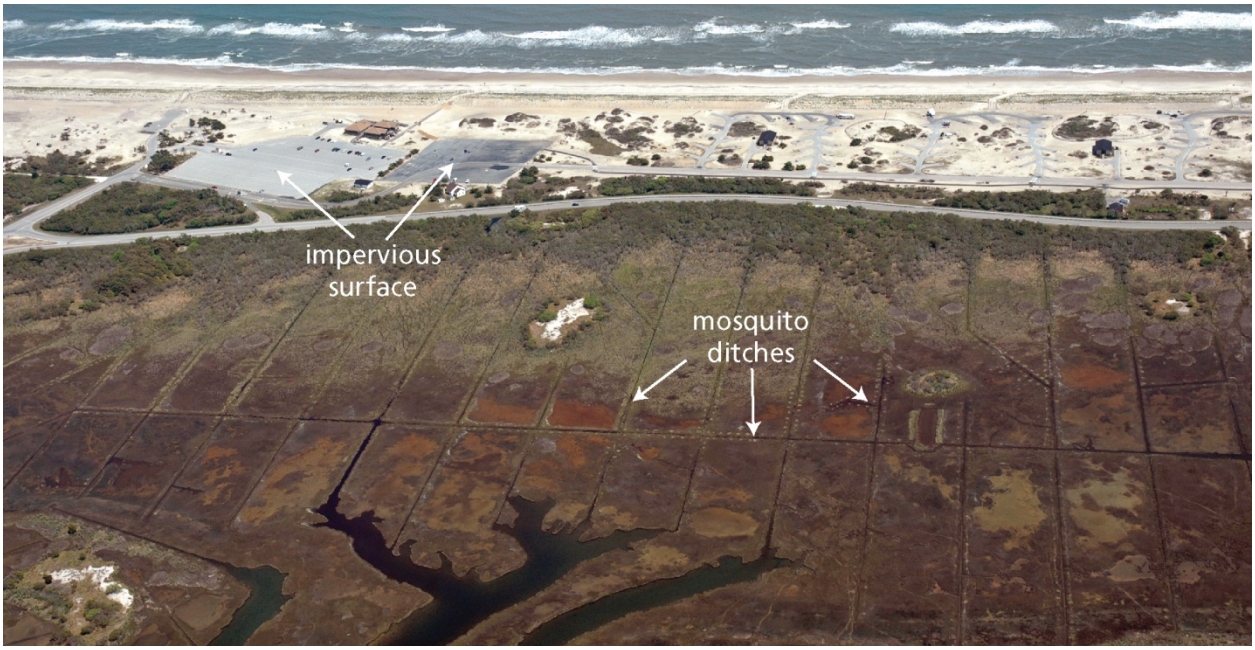


Figure 35. Photograph of modified land and parking lots. Parking lots, roads, and buildings are mapped as modified land and are impervious surfaces. The drive-in campground loops (Assateague State Park) visible in the upper right of the photograph are also mapped as modified land. This area is just south of the Verrazano Bridge in Maryland. Photograph by Jane Thomas, Integration and Application Network, University of Maryland Center for Environmental Science (http://ian.umces.edu/imagelibrary/)

habitat value due to the high level of human disturbance and the expanse of impervious surface; they also decrease infiltration, water quality, and habitat while increasing runoff.

The parking lots on the Virginia section of Assateague Island are built from shell and clay, rather than being paved. When those parking lots are damaged by storms, much of these native materials can be recollected to rebuild the parking lot, and uncollected debris blends more easily with the environment than would asphalt. The geologic map also indicates the locations of land modified for commercial and residential development along the shoreline of Chincoteague Island, Virginia, which is not managed by the national seashore.

Reclaimed Land

Reclaimed land includes Ferry Landing, built on the bay side of Assateague Island to receive the ferry from the mainland, and several dunes built from dredge spoil on the north end of the island.

The construction date of Ferry Landing is uncertain, but the deep channel dug through the marsh to reach it was used heavily in the 1950s, when developers brought prospective buyers to the island. Ferry service ended when the Verrazano Bridge was built in 1964 to connect the island to the mainland.

Spoil dunes on the north end of the island were created in association with channel dredging. Following a North End breach related to the 1962 Ash Wednesday storm, material was dredged from the inlet and Sinepuxent Bay: 16,650 m^3 (21,800 yd^3) in early 1963 to build an emergency dune (Bob Blama, project manager, USACE, personal communication, 31 May 2012), and 764,555 m^3 (1 million yd^3) of sediment to close the breach (USACE 1986). These dunes have much higher elevations than the island's natural dunes but similar vegetation: panic grass (*Panicum* spp.), seaside goldenrod (*Solidago sempervirens*), and American beachgrass (*Ammophila brevigulata*), which has an extensive root and rhizome system that promotes dune stability, but is grazed heavily by horses (Carruthers et al. 2013). The dunes also support an insect listed as endangered in Maryland (little white tiger beetle, *Cicindela lepida*) (Carruthers et al. 2013).

Accretion Mounds

Accretion mounds are low, oblong vegetated hills that formed through the concentric accumulation of sand (Morton et al. 2007). These older sections of the island are usually slightly higher-elevation features in the otherwise low-lying former inlets or areas of extensive overwash, and they have been dissected and sculpted by storm overwash (Krantz 2010). The larger mounds (wider than about 75 m [246 ft]) have series of arcuate ridges on their seaward sides that can be up to 3.5 m (11.5 ft) high. The fresh groundwater lens is thickest (3 to 4 m [10 to 13 ft]) and most stable in the center of each mound, with an abrupt shallowing immediately outside of the outer ridge. Smaller mounds have localized shallow lenses of fresh groundwater that dissipate close to the edges of the features and may be sufficient to allow growth of salt-tolerant shrubs (Krantz 2010).

Vegetation on the accretion mounds is distinctly zoned. Larger mounds are covered by maritime forest with obligate freshwater plants. The bayward side is typically occupied by low-marsh grasses and high-marsh shrubs

and grasses in a low-slope pocket protected by the wrapping storm ridges (Krantz 2010). Feral horses (*Equus caballus*), native white-tail deer (*Odocoileus virginianus*), and historically introduced sika deer (*Cervus nippon*) impact vegetation structure in these and other forest and shrub communities on the island (Sturm 2007).

Accretion Mound Swales

Accretion mound swales are topographic depressions located within accretion mounds. They may be dry or may intermittently pond freshwater after heavy rain (Morton et al. 2007), and they are also susceptible to flooding during strong to moderate storms (Krantz 2010). Commonly, the swales serve as seasonal freshwater wetlands with a distinct plant community that may include *Osmunda* ferns. Some swales that become seasonally dry support trees and shrubs, whereas others that are more persistently wet are covered predominantly by grasses (Krantz 2010).

Barrier Core

The barrier core is defined as the central part of the barrier island that commonly lies between dunes on the seaward side and marshes on the landward side, and may be vegetated with grasses or trees (Morton et al. 2007) (fig. 36). The central part of the barrier core has the most stable, deepest fresh groundwater lens, which is up to 8 m (26 ft) thick—shallower than predicted by theoretical considerations but limited in depth by the low-permeability lagoonal silt layer that underlies much of the island. This area has the most consistently fresh groundwater, with ponds that are well protected from saltwater intrusion, permanently fresh, and particularly valuable wildlife habitat (Krantz 2010). Many of the prominent storm ridges that isolate the barrier core from the overwash areas were created or expanded during the 1962 storm (Krantz 2010).

The vegetation within swales differs from the surrounding maritime forest by adaptation to hydric soils (soils that are water saturated throughout most or all of the year). Ridges higher than 2 m (6.5 ft) are covered by the oldest-growth and most diverse maritime forests on the island, largely due to the depth and stability of the fresh groundwater lens. Ridges 2.5 to 5 m (8 to 16 ft) in height have thick, unsaturated (dry) soil zones and a paucity of vegetation, in particular trees and shrubs (Krantz 2010).

This unit will likely be impacted by climate change in multiple ways. Expected increases in the rate of sea-level rise and more intense storms will likely reduce island stability, due to the increased likelihood of beach and dune erosion, overwash, inlet breaching, shoreline retreat, and island narrowing (TNC 2010). Forest and shrub communities will be among the first affected by sea-level rise, overwash, and its effects on increasing salinity of groundwater (Shao et al. 1995). Longer summer droughts and changes in groundwater level may cause species shifts.

Figure 36. Photograph of shrubland and forest. These habitats are part of the barrier core map unit. Area in photograph is in the southern porterion of the Maryland OSV zone. Photograph by Assateague Island National Seashore.

Beach

The beach is the shore-parallel area of mostly unvegetated sand that extends from the water to the seaward edge of the dunes or crest of a washover terrace (Morton et al. 2007) (fig. 9). The seaward part of the beach is regularly inundated by wave runup during high-water phases of the tidal cycle. The foreshore, the area between the low tide line and the top of the natural beach berm (or the uppermost reach of waves at high tide), has an average slope of 4° (Moore et al. 2006).

The beach is shaped by natural barrier island processes of ocean shoreline erosion and island rollover caused by the movement of sediment alongshore (net annual southward transport, with accretion at the island's southern terminus) and landward (to be deposited on the island's surface, marsh shoreline, and in the bay), resulting in the island's overall landward and southward migration (Krantz et al. 2009). In recent years (1997–2008), the shoreline has been eroding at a rate of 0.84 m/year (2.8 ft/year) along the northern 13 km (8 mi) of the island, and 0.79 m/year (2.6 ft/year) in the middle portion of the island (between km 13 and km 26). This erosion is slower than the rates calculated for the period 1849–1908 (Carruthers et al. 2013) and likely reflects the influence of the North End Restoration Project in restoring sediment to the nearshore system.

Beaches generally gain volume in summer and early fall when storm frequency is at a minimum and offshore

Figure 37. Photograph of heavy minerals on beach. Strong wind or tides can leave a layer of these minerals on the beach, such as here on the North End. Photograph by Assateague Island National Seashore.

sand is transported onto the beach. Winter storms move sand offshore into bars, alongshore, and across the island. New sediment is supplied to the island's beach from two sources: erosion of the Delmarva Headland (located between Fenwick Island and Cape Henlopen, Delaware) (Oertel et al. 2008) and erosion of the shoreface (Kraft 1971).

Assateague Island's sediments originated from the scraping of glaciers across the land surfaces of Canada and the northeastern United States more than 1.5 million years ago (see "Geologic History" chapter for additional information). The majority of Assateague Island's beach sediments are quartz and feldspar, although hornblende, pyroxene, mica, tourmaline, zircon, and garnet are also present (Langley 2002). Approximately 1.65% of beach sands are heavy minerals, mainly ilmenite, rutile, zircon, and small quantities of garnet, xenotime, horneblende, kyanite, and chlorite (Kuster 1959). Strong wind or tide events sometimes leave a dark layer of these heavy minerals on the beach surface (fig. 37).

Beach vegetation is sparse and limited to taxa specially adapted to the harsh conditions that alternate between inundation by seawater and desiccation due to the thick unsaturated zone. This habitat supports American beachgrass (*Ammophila breviligulata*), sea rocket (*Cakile edentula*), and the endangered seabeach amaranth (*Amaranthus pumilus*), which colonize organic wrack and incipient dunes (Krantz 2010), and an insect listed as endangered in Maryland (white tiger beetle, *Cicindela dorsalis media*).

Current rates of shoreline erosion are expected to be exacerbated by climate change. An additional threat to the beach environment is OSV use along 19.3 km of the national seashore beaches. The "Geologic Issues" chapter includes additional discussion of these two issues.

Beach Ridge Complex and Beach Ridge Swales

The accretionary beach ridge complex that forms Toms Cove and Toms Cove Spit comprises sets of long, continuous ridges parallel to the ocean shore, composed of sand that is deposited by a combination of wave runup and the wind (Morton et al. 2007). This complex may be covered by grasses or trees. Within the complex are beach ridge swales, topographic depressions that may be dry or may intermittently pond freshwater after heavy rain (Morton et al. 2007). For additional information about the accretionary processes of this feature, see the "Sediment Transport Processes" section of this chapter.

Dunes

Dunes are hills or ridges of wind-blown sand that form hummocky topography landward of and parallel to the beach (Morton et al. 2007). Natural dunes have formed by wind and waves (Hayes 1979), as windblown sand is trapped in tidal wrack.

Assateague Island, like other barrier islands immediately to the north, is low, wide, and flat, with dunes that extend further landward than in other regions of the U.S. Atlantic coast. Low, closely spaced, parallel dune ridges form where the sand supply is abundant and the shore is prograding. Erosion creates a steep seaward edge of the dune. Beaches with fine sand often have larger dunes because the wind can carry the sand higher. Seliskar (2003) classified dunes into four main types representing developmental stages: 1) flats are areas with no foredune and some establishing vegetation; 2) knolls are rounded hummocks resulting from sand accumulation around vegetation; 3) ridges are older dunes with some dense vegetation and extensive root systems, and 4) buttes, most likely the oldest dunes, are scarped with considerable erosion (Seliskar 2003).

The man-made dune was first built in 1950 from the island's north end southward to the Virginia state line. Currently it is maintained only along the developed zone (6 km [3.7 mi]) of the national seashore and Assateague State Park. Remnants of the old dune dot the island (fig. 38). The man-made dune restricts overwash so effectively that groundwater in the seaward section of the island that otherwise would experience intermittent or frequent overwash is fresh or only slightly brackish, rather than brackish to saline (Krantz 2010).

Climate change is expected to increase overwash, which will in turn increase disturbance to dunes, potentially converting them to beach and intertidal habitat (Griswold et al. 2012). Sea-level rise combined with

Figure 38. Photograph of remnant dune. This dune, photographed in the Maryland OSV zone, is part of a man-made dune constructed in 1950. Photograph by Assateague Island National Seashore.

major storm events occurring more than once every 3 years will affect the ability of the dunes to rebuild and will likely result in significant dune flattening (TNC 2010), particularly in the developed area where the dune/management of the developed area restricts overwash and dune transgression.

Vegetation stabilizes dunes with root and rhizome systems. Dunes may be sparsely or densely vegetated with grasses. Dune builders, such as sea beach amaranth (*Amaranthus pumilus*) and panic grass (*Panicum spp.*), grow rapidly upward after being buried, and their stems and roots stabilize growing foredunes (Carruthers et al. 2011). Burial-tolerant stabilizers, such as American beachgrass (*Ammophilia brevigulata*) and beach heath (*Hudsonia tomentosa*), withstand overwash and flooding, and their rhizomes stabilize low-lying areas affected by storm surge. Burial-intolerant stabilizers, including many woody vegetation species, are longer lived and are found in stable areas of established dunes (Griswold et al. 2012). Seaside goldenrod (*Solidago sempervirens*) is also common on dunes (Carruthers et al. 2013). Dunes are prime habitat for hognose snakes and red fox, support the rare shrub beach heath (*Hudsonia tomentosa*), and provide forage for the national seashore's feral horses.

Interdune Swales

Topographic depressions between dune ridges are known as interdune swales. They may be dry or intermittently pond freshwater after heavy rain (Morton et al. 2007), and are particularly susceptible to saltwater flooding from storm surges and freshwater flooding from intense rainfall events (Kelsey 2012). An insect listed as endangered in Maryland (little white tiger beetle, *Cicindela lepida*) colonizes interior dune habitats and dune blowouts (Carruthers et al. 2013).

Active Overwash Zones

An active overwash zone is frequently flooded by high water and ocean waves generated by storms. It is typically low lying with sparse vegetation and composed of sand with a concentrated layer of shell at the surface (Morton et al. 2007). Overwash moves sand into the island interior, raising island elevation. It sometimes reaches the bay side of the island, creating new marsh platforms.

Overwash zones may be wide in low-lying areas, or may be localized as overwash fan complexes. Overwash often flows through low areas among the dunes, can create channels, and may pond in swales, where saltwater infiltrates the surficial aquifer. This recharge of saltwater mixes with and pushes out any fresh groundwater; the brackish groundwater then flows down gradient in the subsurface. By this process, down-gradient ponds and wetlands receive brackish groundwater, although with a lag time of days to weeks after the storm (Krantz 2010).

Significant overwash events sustain vegetation diversity on barrier islands (Schroeder et al. 1979). Swales that receive overwashing seawater several times a year tend to have a distinct salt-tolerant grass community dominated by *Spartina patens*, *Juncus* and *Panicum* (Krantz 2010). Unique to barrier islands, these early successional habitats support a variety of rare ground-nesting shorebirds, colonial waterbirds, and federally-listed sea beach amaranth (*Amaranthus pumilus*) (Carruthers et al. 2013). Low wet areas support invertebrates foraged by federally-listed piping plover (*Charadrius melodus*).

Overwash may become more frequent and intense as a result of climate change impacts and sea-level rise. In the mid-Atlantic region, land subsidence and a high rate of sea-level rise are expected to result in increased coastal flooding (Najjar et al. 2000; Williams et al. 2009). See the "Geologic Issues" chapter for additional information on sea-level rise and its impacts.

Frequent overwash onto the Toms Cove visitor parking lot, on the Virginia end of the island, encouraged national seashore staff to increase the sustainability of visitor infrastructure. In 2002 and 2003, staff rebuilt the visitor parking lot using native materials (clay, clam shells) and replaced damaged and vulnerable infrastructure with facilities (bathhouses, changing rooms) that can be moved to safe areas in preparation for large storms. At least once each year, park staff must temporarily move the bathhouses out of a storm's path and rebuild the parking lot following a storm or other high water event.

Inactive Overwash Zones

An inactive overwash zone is an area that was historically overwashed by storm surge or was created by overwash (Morton et al. 2007). These areas are not flooded frequently by high water and ocean waves, but are vulnerable to flooding from extreme storms. Inactive overwash zones typically grade landward into marshes. Former inlets usually have predominantly saline to brackish groundwater because these are preferential pathways for storm overwash and subsequent groundwater flow due to the coarse, permeable channel fill (Krantz 2010).

The two major inactive overwash zones on the island were created within the last half-century. The 1962 Ash Wednesday northeaster brought a storm surge that overwashed significant portions of the island, breached the North End, and destroyed much of the private development on the island, fueling discussion of

Figure 39. Photograph of marsh. Marshes are areas of low vegetated wetlands that support plant communities tolerant of variable salinity. Photograph by Assateague Island National Seashore.

appropriate development of the island that led to the creation of the national seashore in 1965. In 1998, two strong winter northeasters overwashed much of the North End, creating overwash flats and increasing concern about an island breach. This concern led to the construction of a protective foredune on the North End and the creation of the North End Restoration Project.

Vegetation in inactive overwash zones is similar to beach vegetation, because conditions here alternate between inundation and desiccation (Krantz 2010). In areas that have not experienced overwash in years, the former overwash sand is commonly reworked into low dunes and can be densely vegetated with low woody plants.

The high, continuous man-made dune that fronts the developed zones of the national seashore and Assateague State Park prevents active overwash and subsequent infiltration of seawater in the geomorphic setting that otherwise would receive intermittent overwash during moderate storms. This profoundly affects the hydrology of the island immediately behind the maintained dune (Krantz 2010).

Marsh

A marsh is defined as an area of low vegetated wetlands that support plant assemblages tolerant of saltwater, brackish water, and freshwater, and that are typically found along the landward side of a barrier island adjacent to a lagoon or along the margins of tidal creeks (Morton et al. 2007) (fig. 39). Low marsh develops on the distal, bayward margins of the overwash platform where its elevation drops into the intertidal zone, or sometimes on the flood-tidal deltas of now-closed tidal inlets (Krantz 2010).

Flooding (from tides and storm surges) is the main mechanism of sediment delivery to the marsh platform (Griswold et al. 2012). The platform also builds by trapping inorganic sediment in dense vegetation and by deposition of organic matter as vegetation dies.

Groundwater beneath the tidal marsh is typically brackish to fully saline, although fresher groundwater recharged from the island interior may flow shallowly beneath the marsh in discrete sand beds overlain by low-permeability salt marsh peat and mud. The shallow availability of relatively lower-salinity and higher-oxygen groundwater has been shown to be a control on the distribution of saltmeadow cordgrass (or "saltmarsh hay," *Spartina patens*) (Krantz 2010). Hypersaline brines may be produced in isolated basins due to evaporation of seawater during summer (Krantz 2010).

Marshes are highly productive, with 27 plant species providing habitat for fish, wildlife, and waterfowl. They also have many ecosystem functions, such as sediment stabilization and trapping and nutrient cycling (Kennish 2001). Subtle variations in elevation are accentuated by the zonation of salt-adapted, salt-tolerant, and salt-resistant vegetation. Elevation increases of even 0.1 m (0.3 ft) allow colonization by the salt-tolerant plant community, which may result in a high-marsh grassland dominated by saltmeadow cordgrass (*Spartina patens)* with stands of saltgrass (*Distichlis spicata)* and needle rush (*Juncus roemerianus)*, or in scrubland populated by the shrubs groundsel (*Baccharis halimifolia)* and marsh elder *(Iva frutescens)*. Low marsh is dominated by low salt marsh cordgrass (*Spartina alterniflora)*. Open, unvegetated areas in the grassy plain of the marsh may indicate production of brine that killed the *Spartina*; these are classified as salt pans (Krantz 2010).

Marshes within the national seashore face current and future threats. Horses trample and compact marsh sediments (Carruthers et al. 2013) and their selective grazing changes marsh vegetation structure (Furbish and Albano 1994). Invasive common reed (*Phragmites alterniflora)* crowds out native vegetation. Since 2008, park staff has been spending considerable time and money to eradicate this reed through spraying and burning efforts (Violi et al. 2012). Aerial surveys indicate that the area of large (high-density) infestations in the national seashore decreased from a pre-treatment area of 216 ha (534 ac)down to 80 ha (200 ac) by 2010 but are expanding up to 24% per year, and ground-based surveys have identified a significant number of low-density infestations that are undetectable by aerial and traditional ground survey methods (Violi et al. 2012). Additionally, mosquito ditches dug in the 1930s continue to impact the hydrology of 960 ha (2375 ac) of marsh and a suite of dependent terrestrial and aquatic species. See the "Disturbed Lands" section of the "Geologic Issues" chapter for additional information on these threats and national seashore staff's efforts to address them.

Increased rates of sea-level rise will continue to drown lagoon and mainland marshes, converting them to intertidal mudflats or open water if vertical accretion is less than 1 cm/year (0.4 inches/year) (TNC 2010). The marshes are particularly vulnerable to accelerated sea-level rise because of their low elevation, a result of the microtidal regime. Increased storm intensity will increase edge erosion and lagoon marshes will continue to decrease in lateral extent until they are completely eroded and disappear; island fringe marshes will continue to decrease in lateral extent along the open bay margin (TNC 2010). Increases in sea level will force transgression of mainland marshes into upland areas (TNC 2010). At Assateague Island National Seashore, overwash is an important mechanism by which marshes maintain elevation.

Tidal Flats

Tidal flats are unvegetated transitional areas that are alternately inundated and exposed by the astronomical tides or intermittently by wind-driven water (Morton et al. 2007). Salt pans may form in these flats. The edge of the tidal marsh that is exposed to the open fetch of the coastal bay commonly has a rim of sand reworked by waves and built upon the marsh surface (Krantz 2010). Where sand rims form along the edge, the increased elevation allows colonization by the shrubs groundsel (*Baccharis halimifolia)* and marsh elder *(Iva frutescens)* (Krantz 2010).

Bayside beaches and mudflats are important foraging habitat, especially for young piping plover chicks (*Charadrius melodus*) (Loegering and Fraser 1995).

If sea-level rise outpaces salt marsh accretion rates, tidal flats may increase in area (Griswold et al. 2012). Greater inundation from sea-level rise and increased storm surge may increase shoreline erosion, resulting in a siltier substrate and inhibiting SAV.

Water

This unit includes three different aquatic environments: estuarine waters, nearshore marine waters, and ponds. For the geologic map, the water unit was delineated based on lidar elevation data (Morton et al. 2007).

Estuary

A study of the bathymetry, surficial sediments, and shallow sub-bottom of the Maryland portion of the Coastal Bays was performed from 1991 to 1997 (Wells 1999). It documented recent overwash and delta deposits of unknown thickness within the eastern and southern ends of the two upper bays, and modern Holocene lagoonal muds (0 to 8 m [26 ft] thick) over much of the western portions of Assawoman and Isle of Wight Bays with maximum thicknesses corresponding to the central axes of the underlying paleochannels. It also documented a prominent reflector, interpreted to represent a pre-transgression surface, portions of which formed directly on Pleistocene deposits (Sinepuxent Formation) that appear to be related to an earlier drainage system related to Greys and Roy creeks and St. Martin River. The majority of the cores revealed a coarsening-upward (grain size) trend in the shallow sediment column, reflecting the transgressive nature of the Coastal Bays. Sedimentation rates based on radiometric dating of lead isotopes (Pb-210) in the cores alone range from 14 to 35 mm/year (0.05 to 0.14 in/year).

The areal distribution of sediment type according to Shepard's (1954) classification reflects basin geometry, energy conditions, and proximity to sediment source. Based on the study's textural analyses, the Maryland Coastal Bays bottom sediment is 55% sand, 30% silt, and 15% clay (fig. 14). The trend is a westward (landward) decrease in grain size of bottom sediments (Wells 1999).

Sandy sediments are found primarily along the eastern side of the Bays and represent material carried across the barrier island as overwash or Aeolian deposits, or carried through the inlet. These sediments, which are predominately fine to very fine, well-sorted sands, cover areas that are shallower and exposed to a relatively large fetch; thus, they are subject to higher energies from wind-generated waves. Finer-grained sediments (i.e., fine silt and clay sizes) are not deposited in these higher-energy areas or are deposited and actively winnowed (Wells 1999). From the bay side of Assateague Island west toward the mid-bay area, sediments grade from fine sand (2 to 3 phi [0.125 to 0.250 mm]) to very fine sand (3 to 4 phi [0.0625 to 0.125 mm]) (Wells 1999). Larger particles tend to be deposited first, closest to the source, and smaller particles tend to be transported the farthest. The sediment is further "sorted" by the local hydraulic regime (i.e., wave activity). As a result, fine sands tend to be well-sorted (i.e., distribution within a narrow range of particle diameters) (Wells 1999). In general, clay contents diminish from north to south in the Coastal Bays, reflecting changes in the textural characteristics of the underlying strata and geomorphic differences in the bays (Wells 1999).

Sand-sized particles are generally spherical in shape, ranging from angular to well rounded, and consist primarily of quartz minerals with some mica, feldspar, and heavy minerals. Quartz is a very stable mineral and is generally inert chemically (Wells 1999). Very fine sand and silts collected from the estuary are composed primarily of quartz and micas. Although not as stable as quartz, micas are fairly chemically inert and tend to be not very cohesive.

Generally, carbon, nitrogen, phosphorus, and sulfur contents are highest in finer-grained sediments, and distribution within the bays follows that of sediment texture, increasing from east to west across the bays, and decreasing from north to south (Wells 1999). Ratios of carbon to nitrogen and carbon to phosphorus indicate that the coastal bay sediments generally are depleted of nitrogen and enriched in phosphorus (Wells 1999). Metal concentrations are within the ranges of those reported for other Atlantic coastal bays and, overall, are relatively low (Wells 1999). Correlation analyses indicate very strong relationships between clay and most metals, and among metals (Wells 1999). Except for zinc and, to a lesser extent, copper, metal concentrations in the surficial sediments fall within the range of background or historical levels. Because zinc and copper are used in a variety of products, particularly those related to the marine industry, these two metals are elevated above background levels in many Atlantic coast estuaries (Wells 1999).

In summary, sediment analyses indicate that several areas within the Maryland Coastal Bays show some effects from anthropogenic activities. Based on nutrient and metal contents and stoichiometric relationships among the various components, the sediments in these areas show higher enrichment in nutrients such as nitrogen and carbon and/or metals (Wells 1999). These areas are either more sensitive due to the higher clay content of sediments, or are "confined" and not easily flushed (Wells 1999). Many of these areas are in Isle of Wight and Assawoman Bays where the adjacent watershed area is more developed compared with the southern bays. In most other areas of the Coastal Bays, including all of Chincoteague Bay and Newport Bay, the sediment parameters measured are within background levels, suggesting that bottom sediments are pristine.

The estuary faces several threats. Coastal Bays have low tidal flushing and limited freshwater inflow, and so are highly susceptible to eutrophication (Pritchard 1960; Boynton et al. 1996; Bricker et al. 1999), which has been linked to reduced abundance of the seagrass *Zostera marina* within the Coastal Bays (Wazniak et al. 2007). Small changes in land use have large effects on water quality and sedimentation in the Coastal Bays, and development is increasing. Climate change may bring more intense storms, which may lead to sustained inlet formation, thereby increasing estuarine salinity.

Ocean

The nearshore shelf surface is medium to fine sand with outcrops of mud and gravel (Wells 2012). Shore-oblique ridges with relief of up to 10 m (33 ft) (Hobbs et al. in press) can extend tens of kilometers from the nearshore to the offshore (Swift et al. 2003). Marine benthic habitats support a diversity of marine life and are threatened by ongoing commercial shellfishing and imminent offshore energy development proposals. (Additional information can be found in the "Marine Benthic Habitats" section of the "Geologic Issues" chapter.)

Ponds

The character of the national seashore's ponds varies dramatically, depending upon position on the island, the thickness and dynamics of the fresh groundwater lens, and the relative frequency and extent of input of saltwater by overwash from the ocean or high-water flooding from the bay (Krantz 2010). Because the island has no stream other than tidal creeks in the marshes, all ponds on the island are fed by groundwater seepage (Krantz 2010). Ponds are the only source of freshwater for animal habitat and drinking on the island (fig. 40).

Figure 40. Photograph of a pond. Ponds are the only source of freshwater habitat and animal drinking water on the island. Photograph by Assateague Island National Seashore.

Impacts of climate change on ponds may include saltwater intrusion into the freshwater lens and longer drought periods in the summer, leading to a reduction in the freshwater lens and earlier drying of vernal ponds (Boesch 2008). Ponds on the ocean side can be flooded by overwash, and those on the bay side by wind-driven events. The most stable ponds are in the barrier core, where the freshwater lens is 7 to 8 m (23 to 26 ft) thick (Krantz 2009). Other ponds have variable salinity and water level depending on season, rainfall, drought, and storms.

Geologic History

This chapter describes the rocks and unconsolidated deposits that appear on the digital geologic map of Assateague Island National Seashore, the environment in which those units were deposited, and the timing of geologic events that formed the present landscape.

The geologic history of Assateague Island National Seashore continues to shape the way that the island responds to modern-day processes. The underlying geologic framework of ancestral inlet channels, layers of old marsh peats and reworked beach sands, and remnant landforms controls the island's groundwater system, habitat availability, and response to storms and sea-level rise. The geologic history reflected in sediments and landforms is primarily Holocene in origin (11,700 years ago to present), although landforms in the surrounding region date back to the late Pleistocene Epoch (125,000 years ago). The ultimate source of Assateague Island's sediments is erosion of the Appalachian Mountains.

Mesozoic Era (248 to 65.5 Million Years Ago): Freeing Mountain Sediments to Nourish Beaches

The Appalachian mountains were built throughout the Paleozoic Era and originally were tall, rugged mountains before being eroded into the relatively subdued modern topography. These mountain-building events (known as "orogenies") culminated in the assembly of the supercontinent Pangaea around 250 million years ago (fig. 41). During the late Triassic, a period of rifting began as the joined continents began to break apart from about 230 to 200 million years ago. Pangaea divided into roughly the continents that exist today. This episode of rifting or crustal fracturing initiated the formation of the current Atlantic Ocean and caused many block-fault basins to develop with accompanying volcanism (Harris et al. 1997; Southworth et al. 2008). Thick deposits of unconsolidated gravel, sand, and silt were shed from the eroding mountains. These sediments were deposited at the bases of the mountains as alluvial fans and spread eastward to become part of the Atlantic Coastal Plain (Duffy and Whittecar 1991; Whittecar and Duffy 2000; Southworth et al. 2008).

An immense amount of material has been eroded from the Appalachian Mountains, as inferred from the now-exposed metamorphic rocks. Many rocks exposed at the surface must have been at least 20 km (~10 mi) below the surface prior to regional uplift and erosion. Erosion continues today as the Potomac, Rappahannock, Rapidan, James, and Shenandoah rivers strip the Coastal Plain sediments, lower the mountains, and deposit alluvial terraces and deltas, creating the present landscape. Waves, tides, and currents of the Atlantic Ocean continually rework these sediments along the coast.

Cenozoic Era (the Past 65.5 Million Years): Isostatic Adjustment

Since the uplift of the Appalachian Mountains and breakup of Pangaea, the North American plate has continued to move westward. The isostatic adjustments that uplifted the continent after the Alleghany orogeny (the culminating Appalachian orogeny) continued at a subdued rate throughout the Cenozoic Era (Harris et al. 1997). These adjustments may be responsible for occasional seismic events felt throughout the Chesapeake Bay region.

The wedge of sedimentary deposits that form the mid-Atlantic continental shelf began to develop during the Cretaceous (more than 65.5 million years ago) and grew into the Quaternary (Hobbs et al. in press), as glacial sediments were carried down rivers. These deposits were shaped by sea level rise and fall, which also shifted the boundary between coastal plain and continental shelf back and forth. Major drops in sea level occurred during periods of growth of the Antarctic Ice Sheet, starting in the Oligocene (28 million years ago) (Hobbs et al. in press). For the past 2.5 my, the coastal plain and shelf have been sculpted by large (120-150 m) fluctuations in sea level (Hobbs et al. in press).

Pliocene-Pleistocene Epochs (5 to 1.5 Million Years Ago): Formation of the Delmarva Peninsula

Although the Atlantic coast evolved over a 250-million-year period, the Delmarva Peninsula began forming only about 5 to 1.5 million years ago during the Pliocene and early Pleistocene. During the Pleistocene ice ages, the closest continental glaciers were approximately 160 km (100 mi) to the north. Many sediments deposited on Delmarva were derived from glaciers scraping off the land surfaces of Ontario, Quebec, Pennsylvania, and New York, and dumping large volumes of water and sediment into major river systems. These sediments were then deposited as deltas and braided-river outwash plains to form the core of the Delmarva Peninsula (Krantz et al. 2009). Age control for the major depositional events is generally poor due to the lack of fossils for biostratigraphy or materials for radiometric or other geochemical dating (Hobbs et al. in press).

During the glacial (ice age)–interglacial cycles over the past 2.5 million years, sea level has varied by nearly 150 m (490 ft). During glacial lowstands of sea level in the Middle Pleistocene (1 to 0.5 million years ago), sediments were carried across the coastal plain to what is now the continental shelf. During the interglacial highstands of sea level, wave action moved these deltaic sediments westward and formed sandy shorelines. When climate cooled and glaciers formed, sea level dropped again, leaving these high shorelines stranded inland. Multiple ancestral shorelines remain along the Delmarva Peninsula, marking former highstands of sea level as long

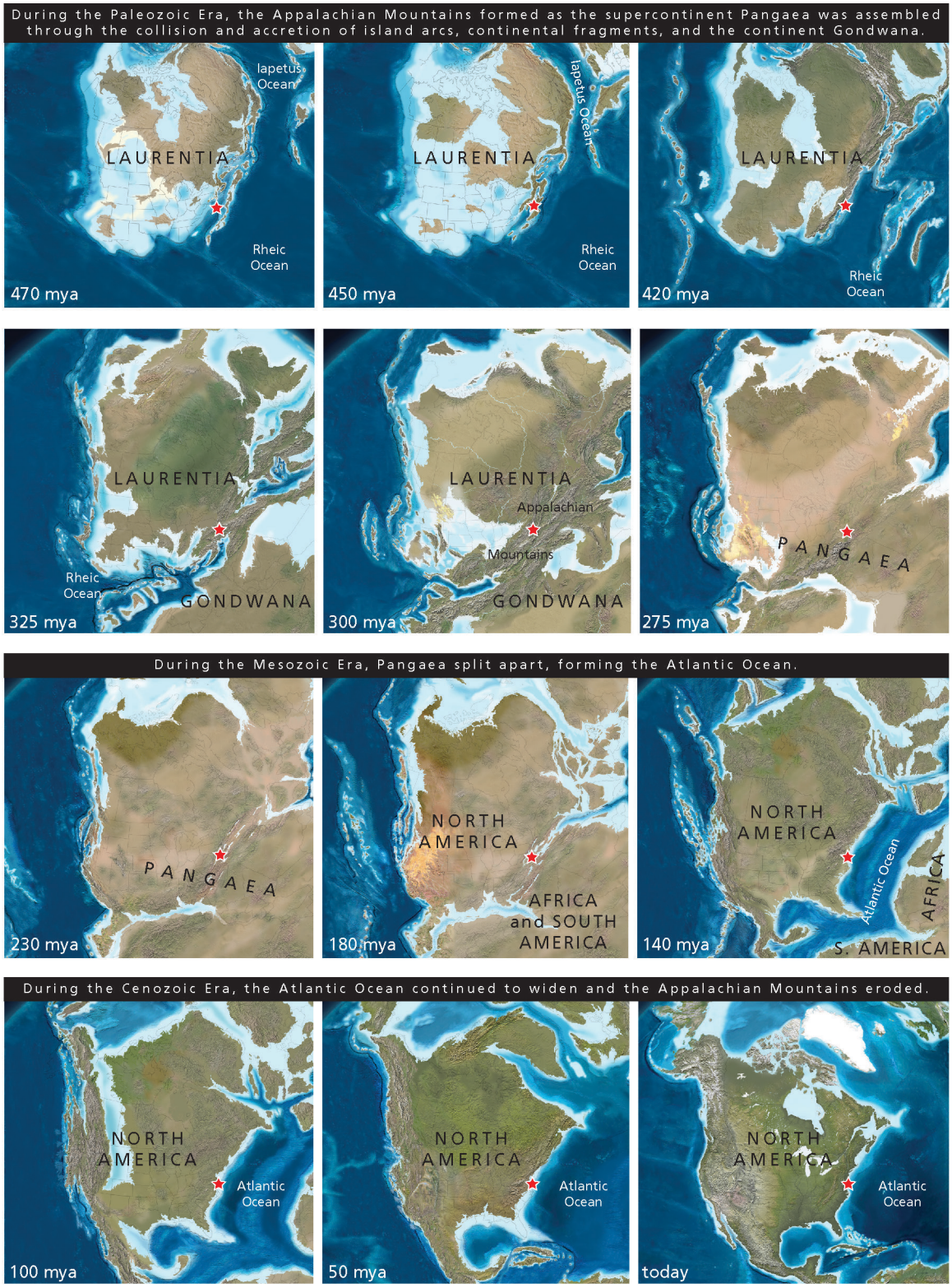


Figure 41. Paleogeographic maps of North America. The sediment that makes up Assateague Island was ultimately derived from the erosion of the Appalachian Mountains. The Appalachians were constructed during mountain-building events that culminated in the assembly of Pangaea. The Atlantic Ocean began to form when Pangaea split apart during the early Mesozoic. Today, the Atlantic Ocean continues to widen and erosion has exposed the core of the Appalachian Mountains and deposited the sediments of the Coastal Plain over more than 100 million years. Red stars indicate approximate location of Assateague Island. Graphic compiled by Jason Kenworthy (NPS Geologic Resources Division). Base paleogeographic maps by Ron Blakey (Colorado Plateau Geosystems, Inc.) and available online: http://cpgeosystems.com/paleomaps.html (accessed 23 January 2012).

linear features known as scarps and terraces (Hobbs 2004; Krantz et al. 2009).

During the most recent glacial maximum (Wisconsinan glaciation), which reached its maximum extent about 22,000 to 20,000 years ago, sea level dropped to 125 m (410 ft) below present. The modern continental shelf was exposed as a broad coastal plain with the shoreline at the edge of the shelf, approximately 97 km (60 mi) from the shoreline's present position. This drop in sea level allowed rivers and streams to incise the plain and create the basins that would later become the Coastal Bays estuary (Krantz et al. 2009).

About 18,000 years ago, the continental glaciers began melting again, increasing sea level over subsequent millennia. During several intervals between 15,000 and 10,000 years ago, sea level rose at a rate up to 10 times faster than today (Krantz et al. 2009). Sea level rose rapidly enough between 12,000 and 6,000 years ago to allow some remnants of earlier shoreline features to survive shoreface scouring (Belknap and Kraft 1985; Kraft et al 1987).

These sea level cycles have left a record in the underlying geology (figs. 5, 6, and 24). The Pliocene marine Yorktown Formation underlies most coastal areas in Virginia and Maryland, including Assateague Island. This unit contains quartz and feldspar sands mixed with lesser clays and silts and abundant fossils. The upper surface of the Yorktown Formation is erosional; in eastern Maryland, the Walston Silt and Beaverdam Sand were deposited on this surface, although only Beaverdam Sand underlies Assateague Island. Another Late Pleistocene deposit, the Accomack Member of the Omar Formation, is a widespread unit atop the Yorktown Formation but is not present under the island. Joynes Neck sand is present in Virginia coastal areas (Mixon 1985; Toscano et al. 1989).

After a period of erosion, the Sinepuxent, Wachapreague, and Ironshire Formations were deposited atop the Omar Formation during the Late Pleistocene. The Wachapreague Formation contains well-preserved paleo-sand spits and barriers. The Ironshire Formation, inland of Assateague Island, contains sand and gravel, whereas the Sinepuxent Formation, which underlies the island, contains finer-grained marginal marine sediments.

The units above the Yorktown Formation are part of a major shoreline complex deposited oblique to the current barrier island system in the Late Pleistocene (Toscano et al. 1989). These units were emplaced as terraces during periods of fluctuating sea level. Several areas exhibit a transgressive sequence comprised of basal fluvial channel deposits, paludal (pond) layers, and estuarine, marsh, lagoonal, back-barrier, and barrier facies, recording local sea-level rise (Peebles et al. 1984).

Holocene Epoch (11,700 Years Ago to Present): Rising Sea Level Pushes the Barrier Islands Westward

As sea level continued to rise, the barrier islands on the edge of the shelf migrated landward with the ocean and arrived near to their present position about 5,000 years ago, when the rate of sea-level rise slowed and the low-lying basins flooded to create the Coastal Bays (Krantz et al. 2009).

Sand is the dominant sediment type at Assateague Island National Seashore, often comprising up to 100% of sediment in samples (Toscano et al. 1989). Muddy deposits exist in local pockets throughout the area and likely represent reworked back-bay and marsh deposits. Gravel lenses in the shallow nearshore are the result of high-energy events and likely represent reworked inlet channel fills exposed on the shoreface.

The shoreline has two sediment sources: the Pleistocene Headlands to the north of Assateague Island, at Rehoboth Beach and Bethany Beach, Delaware (Hobbs et al. in press); and the Assateague shoreface, where storms and currents erode sediment as deep as 11 to 13 m (36 to 43 ft) below present sea level, freeing Holocene back-barrier deposits and shallow Pleistocene sediments (Kraft 1971).

The underlying geologic framework of the national seashore controls responses of the island's landforms, sediments, and groundwater to physical processes such as storms, waves, and sea level that continue to shape the island.

Geologic Map Data

This chapter summarizes the geologic map data available for Assateague Island National Seashore. The Geologic Map Graphic (in pocket) displays the geologic map data over imagery of the national seashore and surrounding area. The Map Unit Properties Table (in pocket) summarizes this report's content for each geologic map unit. Complete GIS data are included on the accompanying CD and are also available at the GRI publications website: http://go.nps.gov/gripubs.

Geologic Maps

Geologic maps facilitate an understanding of an area's geologic framework and the evolution of its present landscape. Using designated colors and symbols, geologic maps portray the spatial distribution and relationships of rocks and unconsolidated deposits. There are two primary types of geologic maps: surficial and bedrock. Surficial, or "geomorphic", geologic maps encompass deposits that are frequently unconsolidated and formed during the past 2.6 million years (the Quaternary Period). Surficial map units are differentiated by geologic process or depositional environment. Bedrock geologic maps encompass older, generally more consolidated sedimentary, metamorphic, and/or igneous rocks. Bedrock map units are differentiated based on age and/or rock type. For reference, a geologic time scale is included as figures 3 and 4. Surficial geologic map data and hydrogeomorphic map data are provided for Assateague Island National Seashore.

Geologic maps also may show geomorphic features, structural interpretations, and locations of past geologic hazards that may be prone to future activity. Additionally, anthropogenic features such as mines and quarries may be indicated on geologic maps. Geomorphic features and anthropogenic features are included on the Assateague Island National Seashore digital geologic data.

Source Maps

The Geologic Resources Inventory (GRI) team converts digital and/or paper source maps into GIS formats that conform to the GRI GIS data model. The GRI digital geologic map product also includes essential elements of the source maps, including unit descriptions, map legend, map notes, references, and figures. The following reference is the source for the GRI digital geologic data for Assateague Island National Seashore:

Morton, R.A., Bracone, J.E., and Cooke, B. 2008. Geomorphology and depositional sub-environments of Assateague Island, Maryland-Virginia. Scale 1:21,552. Open-file report OF-2007-1388. U.S. Geological Survey, Reston, Virginia, USA. (GRI Source Map ID 75016).

The digital geologic data also includes a hydrogeomorphic map and report.

Krantz, D. E. 2010. A hydrogeomorphic map of Assateague Island National Seashore, Maryland and Virginia. Natural resource report NPS/NRPC/GRD/NRR—2010/215. National Park Service, Fort Collins, Colorado, USA.

Geologic GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is included on the enclosed CD and is also available online (http://science.nature.nps.gov/im/inventory/geology/GeologyGISDataModel.cfm). This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI team digitized the data for Assateague Island National Seashore using data model version 2.1.

GRI digital geologic data are included on the attached CD and are available through the NPS Integrated Resource Management Applications (IRMA) portal (https://irma.nps.gov/App/Reference/Search?SearchType=Q). Enter "GRI" as the search text and select Assateague Island National Seashore from the unit list.

The following components and geology data layers are part of the data set:

- Data in ESRI geodatabase and shapefile GIS formats
- Layer files with feature symbology (see table 3)
- Federal Geographic Data Committee (FGDC)–compliant metadata
- Documents (asis_geology.pdf and asig_geology.pdf) that contain all of the ancillary map information and graphics, including geologic unit correlation tables, and map unit descriptions, legends, and other information captured from source maps.
- ESRI map document files (.mxd) that display the digital geologic data

Table 3. Geology data layers in the Assateague Island National Seashore GIS data.

Map	Data Layer	Data Layer Code	On Map Graphic?
Geomorphic (Morton et al. 2007)	Geomorphic Unit Contacts	MRPHA	Yes
	Geomorphic Units	MRPH	Yes
Hydrogeomorphic (Krantz 2010)	Hydrogeomorphic Unit Boundaries	GLGA	No
	Hydrogeomorphic Units	GLG	No

Geologic Map Graphic

The Geologic Map Graphic (in pocket) displays the GRI digital geologic data for Morton et al. (2007) draped over aerial imagery of the national seashore and surrounding area. For graphic clarity and legibility, not all GIS feature classes may be visible on the overview, as indicated in table 3. Cartographic elements and basic geographic information have been added to the overview. Aerial imagery and geographic information, which are part of the overview graphic, are not included with the GRI digital geologic GIS data for the national seashore, but are available online from a variety of sources.

Map Unit Properties Table

The geologic units listed in the Map Unit Properties Table (in pocket) correspond to the accompanying digital geologic data from Morton et al. (2007). Following the structure of the report, the table summarizes the geologic issues, features, and processes, and geologic history associated with each map unit. The table also lists the geologic time period, map unit symbol, and a simplified geologic description of the unit. Connections between geologic units and park stories are also summarized.

Use Constraints

Graphic and written information provided in this report is not a substitute for site-specific investigations. Ground-disturbing activities should neither be permitted nor denied based upon the information provided here. Minor inaccuracies may exist regarding the location of geologic features relative to other geologic or geographic features on the overview graphic. Based on the source map scale (1:21,552 for Morton et al. 2007) and U.S. National Map Accuracy Standards, geologic features represented in the geologic map data are horizontally within 11 m (36 ft) of their true location.

Please contact GRI with any questions.

Glossary

This glossary contains brief definitions of geologic terms used in this report. Not all geologic terms used are listed. Definitions are based on those in the American Geological Institute Glossary of Geology *(fifth edition; 2005). Additional definitions and terms are available at: http://geomaps.wr.usgs.gov/parks/misc/glossarya.html.*

accretion. The gradual addition of new land to old by the deposition of sediment or emplacement of landmasses onto the edge of a continent at a convergent margin.

aeolian. Describes materials formed, eroded, or deposited by or related to the action of the wind. Also spelled "eolian."

aggradation. The building-up of Earth's surface by depositional processes, specifically the upbuilding performed by a stream in order to establish or maintain uniformity of grade or slope.

alkalic. Describes rocks that are enriched in sodium and potassium.

alluvial fan. A fan-shaped deposit of sediment that accumulates where a hydraulically confined stream flows to a hydraulically unconfined area. Commonly out of a mountainous area into an area such as a valley or plain.

alluvium. Stream-deposited sediment.

amphibole. A common group of rock-forming silicate minerals. Hornblende is the most abundant type.

amphibolite. A metamorphic rock consisting mostly of the minerals amphibole and plagioclase with little or no quartz.

apatite. A group of variously colored phosphate minerals. Tooth enamel and bones contain minerals from the apatite group.

aquiclude. See "confining bed."

aquifer. A rock or sedimentary unit that is sufficiently porous that it has a capacity to hold water, sufficiently permeable to allow water to move through it, and currently saturated to some level.

barchan dune. A crescent-shaped dune with arms or horns of the crescent pointing downwind. The crescent or barchan type is most characteristic of inland desert regions.

barrier island. A long, low, narrow island formed by a ridge of sand that parallels the coast.

basalt. A dark-colored, often low-viscosity, extrusive igneous rock.

basement. The undifferentiated rocks, commonly igneous and metamorphic, that underlie rocks exposed at the surface.

basin (sedimentary). Any depression, from continental to local scales, into which sediments are deposited.

beach. A gently sloping shoreline covered with sediment, commonly formed by the action of waves and tides.

beach face. The section of the beach exposed to direct wave and/or tidal action.

bed. The smallest sedimentary strata unit, commonly ranging in thickness from one centimeter to a meter or two and distinguishable from beds above and below.

bedding. Depositional layering or stratification of sediments.

bedrock. A general term for the rock that underlies soil or other unconsolidated, surficial material.

berm. A low, impermanent, nearly horizontal or landward-sloping bench, shelf, or ledge on the backshore of a beach.

depth of closure. The depth of closure for a given time interval is the most landward depth seaward of which there is no significant change in bottom elevation and no significant net sediment transport between the nearshore and the offshore.

dune. A low mound or ridge of sediment, usually sand, deposited by wind. Common dune types include "barchan," "longitudinal," "parabolic," and "transverse" (see respective listings).

electrical resistivity survey. A measure of the difficulty with which electric current flows through unconsolidated sediment and rock.

electromagnetic survey (method). An electrical exploration method based on the measurement of alternating magnetic fields associated with currents artificially or naturally maintained in the subsurface.

embryo dunes. Sand deposits stabilized by wrack and pioneer plants, which can be destroyed by storms but may develop into larger dune structures in calmer weather.

entrainment. The process of picking up and transporting sediment, commonly by wind or water.

eolian. Describes materials formed, eroded, or deposited by or related to the action of the wind. Also spelled "Aeolian."

ephemeral stream. A stream that flows briefly only in direct response to precipitation in the immediate locality and whose channel is at all times above the water table.

estuary. The seaward end or tidal mouth of a river where freshwater and seawater mix; many estuaries are drowned river valleys caused by sea-level rise (transgression) or coastal subsidence.

eutrophication. The process by which excess nutrient input stimulates plant growth and leads to depletion of dissolved oxygen.

eustatic. Relates to simultaneous worldwide rise or fall of sea level.

facies (sedimentary). The depositional or environmental conditions reflected in the sedimentary structures, textures, mineralogy, fossils, etc. of a sedimentary rock.

fault. A break in rock along which relative movement has occurred between the two sides.

feldspar. A group of abundant (more than 60% of Earth's crust), light-colored to translucent silicate minerals found in all types of rocks. Usually white and gray to pink. May contain potassium, sodium, calcium, barium, rubidium, and strontium along with aluminum, silica, and oxygen.

floodplain. The surface or strip of relatively smooth land adjacent to a river channel and formed by the river. Covered with water when the river overflows its banks.

foredune. Shore-parallel dune ridge formed on the top of the backshore by Aeolian sand deposition within vegetation.

formation. Fundamental rock-stratigraphic unit that is mappable, lithologically distinct from adjoining strata, and has definable upper and lower contacts.

garnet. A hard mineral that has a glassy luster, often with well defined crystal faces, and a variety of colors, dark red being characteristic. Commonly found in metamorphic rocks.

geology. The study of Earth including its origin, history, physical processes, components, and morphology.

glauconite. A green mineral, closely related to the micas. It is an indicator of very slow sedimentation.

granite. An intrusive igneous (plutonic) rock composed primarily of quartz and feldspar. Mica and amphibole minerals are also common. Intrusive equivalent of rhyolite.

highstand. The interval of time during one or more cycles of relative change of sea level when sea level is above the shelf edge in a given local area.

hinge line. A line or boundary between a stable region and one undergoing upward or downward movement.

hornblende. The most common mineral of the amphibole group. Hornblende is commonly black and occurs in distinct crystals or in columnar, fibrous, or granular forms.

hydraulic conductivity. Measure of permeability coefficient.

hydrogeologic. Refers to the geologic influences on groundwater and surface water composition, movement and distribution.

incision. The process whereby a downward-eroding stream deepens its channel or produces a narrow, steep-walled valley.

isotopic age. An age expressed in years and calculated from the quantitative determination of radioactive elements and their decay products; "absolute age" and "radiometric age" are often used in place of isotopic age but are less precise terms.

kaolinite. A common clay mineral with a high aluminum oxide content and white color.

lag gravel. An accumulation of coarse material remaining on a surface after the finer material has been blown away by winds.

lamination. Very thin, parallel layers.

landslide. Any process or landform resulting from rapid, gravity-driven mass movement.

liquefaction. The transformation of loosely packed sediment into a more tightly packed fluid mass.

lithic. A sedimentary rock or pyroclastic deposit that contains abundant fragments of previously formed rocks.

lithification. The conversion of sediment into solid rock.

lithify. To change to stone or to petrify; especially to consolidate from a loose sediment to a solid rock through compaction and cementation.

lithofacies. A lateral, mappable subdivision of a designated stratigraphic unit, distinguished from adjacent subdivisions on the basis of rock characteristics (lithology).

lithology. The physical description or classification of a rock or rock unit based on characters such as its color, mineral composition, and grain size.

lithostratigraphy. The element of stratigraphy that deals with the lithology of strata, their organization into units based on lithologic characteristics, and their correlation.

littoral. Pertaining to the benthic ocean environment or depth zone between high water and low water.

littoral zone. The benthic ocean environment or depth zone between high water and low water.

longshore current. A current parallel to a coastline caused by waves approaching the shore at an oblique angle.

lowstand. The interval of time during one or more cycles of relative change of sea level when sea level is below the shelf edge.

marine terrace. A narrow coastal strip of deposited material, sloping gently seaward.

marker bed. A distinctive layer used to trace a geologic unit from one geographic location to another.

member. A lithostratigraphic unit with definable contacts; a member subdivides a formation.

mica. A prominent rock-forming mineral of igneous and metamorphic rocks. It has perfect basal cleavage meaning that it forms flat sheets.

microcrystalline. A rock with a texture consisting of crystals only visible with a microscope.

micrographic. Describes the graphic texture of an igneous rock, distinguishable only with a microscope.

microplate. A small lithospheric plate.

mid-ocean ridge. The continuous, generally submarine and volcanically active mountain range that marks the divergent tectonic margin(s) in Earth's oceans.

mineral. A naturally occurring, inorganic crystalline solid with a definite chemical composition or compositional range.

muscovite. A mineral of the mica group. It is colorless to pale brown and is a common mineral in metamorphic rocks such as gneiss and schist, igneous rocks such as granite, pegmatite, and sedimentary rocks such as sandstone.

orogeny. A mountain-building event.

outcrop. Any part of a rock mass or formation that is exposed or "crops out" at Earth's surface.

overwash. Flow of water over low portions of barrier islands or spits during high tides or storms.

paleogeography. The study, description, and reconstruction of the physical landscape from past geologic periods.

paleontology. The study of the life and chronology of Earth's geologic past based on the fossil record.

paralic. Describes intertongued marine and continental deposits laid down on the landward side of a coast or in shallow water subject to marine inundation.

passive margin. A margin where no plate-scale tectonism is taking place; plates are not converging, diverging, or sliding past one another. An example is the east coast of North America (compare to "active margin").

pebble. Generally, small rounded rock particles from 4 to 64 mm (0.16 to 2.52 in) in diameter.

perched aquifer. An aquifer containing unconfined groundwater separated from an underlying main body of groundwater by an unsaturated zone.

permeability. A measure of the relative ease with which fluids move through the pore spaces of rocks or sediments.

piedmont. An area, plain, slope, glacier, or other feature at the base of a mountain.

plagioclase. An important rock-forming group of feldspar minerals.

plate tectonics. The concept that the lithosphere is broken up into a series of rigid plates that move over Earth's surface above a more fluid asthenosphere.

plateau. A broad, flat-topped topographic high (terrestrial or marine) of great extent and elevation above the surrounding plains, canyons, or valleys.

platform. Any level or nearly-level surface, ranging in size from a terrace or bench to a plateau or peneplain.

porosity. The proportion of void space (e.g., pores or voids) in a volume of rock or sediment deposit.

porphyry. An igneous rock consisting of abundant coarse crystals in a fine-grained matrix.

potassium feldspar. A feldspar mineral rich in potassium (e.g., orthoclase, microcline, sanidine, adularia).

potentiometric surface. A surface representing the total head of groundwater and defined by the levels to which water will rise in tightly cased wells. The water table is a particular potentiometric surface.

principle of original horizontality. The concept that sediments are originally deposited in horizontal layers and that deviations from the horizontal indicate post-depositional deformation.

principle of superposition. The concept that sediments are deposited in layers, one atop another, i.e., the rocks on the bottom are oldest with the overlying rocks progressively younger toward the top.

principle of uniformity. The assumption of uniformity of causes or processes throughout time and space; the uniformity of natural laws. Not synonymous with the uniformitarianism of Charles Lyell, who constrained throughout geologic time both the intensity and frequency and the kinds of processes seen today.

prodelta. The part of a delta below the level of wave erosion.

progradation. The seaward building of land area due to sedimentary deposition.

provenance. A place of origin. The area from which the constituent materials of a sedimentary rock were derived.

pyroxene. A common rock-forming mineral. It is characterized by short, stout crystals.

quartzite. Metamorphosed quartz sandstone.

radioactivity. The spontaneous decay or breakdown of unstable atomic nuclei.

radiometric age. An age expressed in years and calculated from the quantitative determination of radioactive elements and their decay products.

recharge. Infiltration processes that replenish groundwater.

reflection survey. Record of the time it takes for seismic waves generated from a controlled source to return to the surface. Used to interpret the depth to the subsurface feature that generated the reflections.

regression. A long-term seaward retreat of the shoreline or relative fall of sea level.

relative dating. Determining the chronological placement of rocks, events, or fossils with respect to the geologic time scale and without reference to their numerical age.

ripple marks. The undulating, approximately parallel and usually small-scale ridge pattern formed on sediment by the flow of wind or water.

riprap. A layer of large, durable, broken rock fragments irregularly thrown together in an attempt to prevent erosion by waves or currents and thereby preserve the shape of a surface, slope, or underlying structure.

roundness. The relative amount of curvature of the "corners" of a sediment grain.

runup. The advance of water up the foreshore of a beach or structure, following the breaking of the wave.

saltation. A mode of sediment movement, driven by wind or water, whereby materials move through a series of intermittent "leaps" or "jumps."

sand. A clastic particle smaller than a granule and larger than a silt grain, having a diameter in the range of 1/16 mm (0.0025 in) to 2 mm (0.08 in).

sand sheet. A large irregularly shaped plain of eolian sand, lacking the discernible slip faces that are common on dunes.

scarp. A steep cliff or topographic step resulting from displacement on a fault, or by mass movement, or erosion. Also called an "escarpment."

sediment. An eroded and deposited, unconsolidated accumulation of rock and mineral fragments.

sedimentary rock. A consolidated and lithified rock consisting of clastic and/or chemical sediment(s). One of the three main classes of rocks—igneous, metamorphic, and sedimentary.

sequence. A major informal rock-stratigraphic unit that is traceable over large areas and defined by a sediments associated with a major sea level transgression-regression.

shoreface. The zone between the seaward limit of the shore and the more nearly horizontal surface of the offshore zone; typically extends seaward to storm wave depth or about 10 m (32 ft).

shoreface ravinement. The truncation of paralic layers due to erosion by shoreface processes.

silicate. A compound whose crystal structure contains the SiO_4 tetrahedra.

silicic. Describes a silica-rich igneous rock or magma.

silt. Clastic sedimentary material intermediate in size between fine-grained sand and coarse clay (1/256 to 1/16 mm [0.00015 to 0.002 in]).

slope. The inclined surface of any geomorphic feature or measurement thereof. Synonymous with "gradient."

soil. Surface accumulation of weathered rock and organic matter capable of supporting plant growth and often overlying the parent material from which it formed.

strata. Tabular or sheet-like masses or distinct layers of rock.

stratification. The accumulation, or layering of sedimentary rocks in strata. Tabular, or planar, stratification refers to essentially parallel surfaces. Cross-stratification refers to strata inclined at an angle to the main stratification.

stratigraphy. The geologic study of the origin, occurrence, distribution, classification, correlation, and age of rock layers, especially sedimentary rocks.

stream. Any body of water moving under gravity flow in a clearly confined channel.

stream channel. A long, narrow depression shaped by the concentrated flow of a stream and covered continuously or periodically by water.

subaerial. Describes conditions and processes that exist or operate in the open air on or immediately adjacent to the land surface.

subsidence. The gradual sinking or depression of part of Earth's surface.

supertidal. Describes features or processes at elevations higher than normal tidal range on a give shoreface.

system (stratigraphy). The group of rocks formed during a period of geologic time.

terrestrial. Relating to land, Earth, or its inhabitants.

terrigenous. Derived from the land or a continent.

thalweg. The line connecting the lowest or deepest points along a stream bed; the line of maximum depth.

topography. The general morphology of Earth's surface, including relief and locations of natural and anthropogenic features.

transgression. Landward migration of the sea as a result of a relative rise in sea level.

transverse dune. Dune elongated perpendicular to the prevailing wind direction. The leeward slope stands at or near the angle of repose of sand whereas the windward slope is comparatively gentle.

trend. The direction or azimuth of elongation of a linear geologic feature.

unconfined groundwater. Groundwater that has a water table; i.e., water not confined under pressure beneath a confining bed.

unconformity. An erosional or non-depositional surface bounded on one or both sides by sedimentary strata. An unconformity marks a period of missing time.

undercutting. The removal of material at the base of a steep slope or cliff or other exposed rock by the erosive action of falling or running water (such as a meandering stream), of sand-laden wind in the desert, or of waves along the coast.

uplift. A structurally high area in the crust, produced by movement that raises the rocks.

water table. The upper surface of the saturated zone; the zone of rock in an aquifer saturated with water.

weathering. The physical, chemical, and biological processes by which rock is broken down.

Literature Cited

This chapter lists references cited in this report. Contact the Geologic Resources Division for assistance in obtaining these documents.

Adamowicz, S.C. and C.T. Roman. 2005. New England salt marsh pools: a quantitative analysis of and geographic features. Wetlands 25(2):279–288.

Algermissen, S. T., D. M. Perkins, P. C. Thenhaus, S. L. Hanson, and B. L. Bender. 1982. Probabilistic estimates of maximum acceleration and velocity in rock in the contiguous United States. Open-File Report 82-1033. U.S. Geological Survey, Reston, Virginia, USA. http://pubs.er.usgs.gov/publication/ofr821033 (accessed 17 June 2013).

Algermissen, S. T. and D. M. Perkins. 1976. Probabilistic estimate of maximum acceleration in rock in the contiguous United States. Open-File Report 76-416. U.S. Geological Survey, Reston, Virginia, USA.

Anders, F., and S. Leatherman. 1987a. Disturbance of beach sediment by off-road vehicles. Environmental Geology 9:183–189.

Anders, F. J., and S. Leatherman. 1987b. Effects of off-road vehicles on coastal foredunes at Fire Island, New York, USA. Environmental Management 11:45–52.

Assateague Island National Seashore (ASIS). 1982. Assateague Island National Seashore General Management Plan. National Park Service Denver Service Center, Denver, Colorado, USA.

Assateague Island National Seashore (ASIS). 2008a. Reclamation plan for sand extraction sites on over-sand vehicle beach. Unpublished report, Assateague Island National Seashore, Berlin, Maryland, USA.

Assateague Island National Seashore (ASIS). 2008b. Sand borrow plan for Assateague Island National Seashore. Unpublished report, Assateague Island National Seashore, Berlin, Maryland, USA.

Assateague Island National Seashore (ASIS). 2012a. Superintendent's compendium of designations, closures, permit requirements and other restrictions imposed under discretionary authority. Assateague Island National Seashore, Berlin, Maryland, USA. Updated 2013 version: http://www.nps.gov/asis/parkmgmt/upload/2013-superintendents-compendium.pdf (accessed 3 September 2013).

Assateague Island National Seashore (ASIS). 2012b. Climate Change Projections for Assateague Island NS. Supporting documentation for draft General Management Plan. Assateague Island National Seashore, Berlin, Maryland, USA. http://parkplanning.nps.gov/document.cfm?parkID=207&projectID=26140&documentID=42252 accessed 10 July 2012).

Banks, W.S.L., J.P. Masterson, and C.D. Johnson. 2012. Well network installation and hydrogeologic data collection, Assateague Island National Seashore, Worcester County, Maryland, 2010. U.S. Geological Survey Scientific Investigations Report 2012–5079. http://pubs.usgs.gov/sir/2012/5079/ (accessed 17 June 2013).

Barkan, R., U. S. ten Brink, and J. Lin. 2009. Far field tsunami simulations of the 1755 Lisbon earthquake: implications for tsunami hazard to the U.S. East Coast and the Caribbean. Marine Geology 264:109–122.

Belknap, D. F., and J. C. Kraft. 1985. Influence of antecedent geology on stratigraphic preservation potential and evolution of Delaware's barrier systems. Marine Geology 63(1):235-262.

Biggs, R. B. 1970. The origin and geologic history of Assateague Island, Maryland and Virginia. Pages 8–41 *in* University of Maryland Natural Resources Institute, editor. Assateague ecological studies final report, part 1. Contribution no. 446. University of Maryland Natural Resources Institute, College Park, Maryland, USA.

Boesch, D. F., editor. 2008. Global warming and the free state: comprehensive assessment of climate change impacts in Maryland, report of the scientific and technical working group of the Maryland Commission on Climate Change. University of Maryland Center for Environmental Science, Cambridge, Maryland, USA. http://www.umces.edu/sites/default/files/pdfs/global_warming_free_state_report.pdf (accessed 24 September 2012).

Bollinger, G. A. 1978. Seismic Hazard in Virginia. Virginia Minerals 24(4): 29-35. http://www.dmme.virginia.gov/dgmr/pdf/vamin/VAMIN_VOL24_NO04.PDF (accessed 13 August 2013).

Bourn, W. S. and C. Cottam. 1950. Some Biological Effects of Ditching Tidewater Marshes. U.S. Fish and Wildlife Service Research Report 19. U.S. Department of the Interior, Washington, DC, USA.

Boynton, W. R., L. Murray, J. Hagy, C. Stokes, and W. M. Kemp. 1996. A comparative analysis of eutrophication patterns in a temperate coastal lagoon. Estuaries 19(2B): 408–421.

Bratton, J. F., J. K. Böhlke, D. E. Krantz, and C. R. Tobias. 2009. Flow and geochemistry of groundwater beneath a back-barrier lagoon: the subterranean estuary at Chincoteague Bay, Maryland, USA. Marine Chemistry 113:78–92.

Bratton, J. F., J. K. Böhlke, F. T. Manheim, and D. E. Krantz. 2004. Ground water beneath coastal bays of the Delmarva Peninsula: ages and nutrients. Ground Water 42(7):1021–1034.

Bricker, S. B., C. G. Clement, D. E. Pirhalla, S. P. Orlando, and D. R. G. Farrow. 1999. National estuarine eutrophication assessment: effect of nutrient enrichment in the nation's estuaries. National Oceanic and Atmospheric Administration, National Ocean Service, Special Projects Office and the National Centers for Coastal Ocean Science, Silver Spring, Maryland, USA.

Browder, A. G., and J. E. McNinch. 2006. Linking framework geology and nearshore morphology: correlation of paleo-channels with shore-oblique sandbars and gravel outcrops. Marine Geology 231:141–162.

Brunner, J., J. Kenworthy, and V. Santucci. 2010. Unauthorized fossil collecting from National Park Service Shorelines: Servicewide policy and perspectives. George Wright Forum 27(1):319-323. https://irma.nps.gov/App/Reference/Profile/2197610 (accessed 29 August 2013).

Buckley, R. 1987. The effect of sparse vegetation on the transport of dune sand by wind. Nature 325:426–428.

Bureau of Land Management (BLM) and National Park Service (NPS). 2011. Weather Conditions for site ASTM2 (Assateague Island). MesoWest Interagency Remote Automatic Weather Stations network. Online dataset: http://raws.wrh.noaa.gov/cgi-bin/roman/meso_base.cgi?stn=ASTM2 (accessed 17 June 2013).

Bureau of Ocean Energy Management, Regulation, and Enforcement (BOEMRE). 2011a. Commercial renewable energy transmission on the outer continental shelf (OCS) offshore mid-Atlantic states, notice of proposed grant area and request for competitive interest (RFCI) in the area of the Atlantic wind connection proposal. Docket No. BOEM-2011-0023. Federal Register Document 2011-32277. Federal Register 76(245): 79206-79209. http://www.gpo.gov/fdsys/pkg/FR-2011-12-21/html/2011-32277.htm (accessed 27 September 2012).

Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE). 2011b. Use of OCS sand resources in NASA's Wallops Flight Facility shoreline restoration and infrastructure program. Record of Decision. Herndon, Virginia, USA.

Bush, D. M. 2009. Marine features and processes. Pages 163–188 *in* R. Young and L. Norby, editors. Geological Monitoring. Geological Society of America, Boulder, Colorado, USA. http://nature.nps.gov/geology/monitoring/marine.cfm (accessed 10 July 2012).

Bush, D. M., and R. Young. 2009. Coastal features and processes. Pages 47–67 *in* R. Young and L. Norby, editors. Geological Monitoring. Geological Society of America, Boulder, Colorado, USA. http://nature.nps.gov/geology/monitoring/coastal.cfm (accessed 10 July 2012).

Buttolph, A.M., W. G. Grosskopf, G. P. Bass, and N. C. Kraus. 2006. Natural Sand Bypassing and Response of Ebb Shoal to Jetty Rehabilitation, Ocean City Inlet, MD, USA. Pages 3344-3356 in Proceedings 30th Coastal Engineering Conference. American Society of Civil Engineers, Reston, Virginia, USA.

Carruthers, T., K. Beckert, B. Dennison, J. Thomas, T. Saxby, M. Williams, T. Fisher, J. Kumer, C. Schupp, B. Sturgis, and C. Zimmerman. 2011. Assateague Island National Seashore natural resource condition assessment: Maryland, Virginia. Natural resource report NPS/ASIS/NRR—2011/405. National Park Service, Fort Collins, Colorado, USA. http://nature.nps.gov/water/nrca/assets/docs/ASIS_NRCA.pdf (accessed 10 July 2012).

Carruthers, T. J., K. Beckert, W. C. Dennison, J. P. Kumer, T. Saxby, C. A. Schupp, B. Sturgis, J. Thomas, M. Williams, T. Fisher, and C. S. Zimmerman. 2012. Improving management of a mid-Atlantic coastal barrier island through assessment of habitat condition. Estuarine, Coastal, and Shelf Science 116:74-86. http://www.sciencedirect.com/science/article/pii/S0272771412003204 (accessed 1 October 2012).

Casey, J., and A. Wesche. 1981. Marine benthic survey of Maryland's coastal bays: part I, spring and summer periods, 1981. Maryland Department of Natural Resources, Annapolis, Maryland, USA.

Chaillou, J. C., and S. B. Weisberg. 1996. Assessment of the ecological condition of the Delaware and Maryland Coastal Bays. Office of Research and Development, U.S. Environmental Protection Agency, Washington, DC, USA.

Christensen, J. H., B. Hewitson, A. Busuioc, A. Chen, X. Gao, R. Held, R. Jones, R. K. Kolli, W. K. Kwon, R. Laprise, V. Magana Rueda, L. Mearns, C. G. Menendez, J. Räisänen, A. Rinke, A. Sarr, P. Whetton, R. Arritt, R. Benestad, M. Beniston, D. Bromwich, D. Caya, J. Comiso, R. de Elia, and K. Dethloff. 2007. Regional Climate Projections, Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. S. D. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller, editors. Cambridge University Press, Cambridge, United Kingdom and New York, New York, USA. http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm (accessed 10 July 2012).

Clark, J. A., B. A. Harrington, T. Hruby, and F. Wasserman. 1984. The effect of ditching for mosquito control on salt marsh use by birds in Rowley, Massachusetts. Journal of Field Ornithology 55:160–180.

Coburn, A. 2009. Assateague Island National Seashore coastal engineering inventory. Program for the study of developed shorelines (PSDS), Western Carolina University, North Carolina, USA. Digital dataset (unpublished).

Collie, J. S., G. A. Escanero, and P. C. Valentine. 2000. Photographic evaluation of the impacts of bottom fishing on benthic epifauna. ICES Journal of Marine Science 57:987–1001.

Conaway, C. A., and J. T. Wells. 2005. Aeolian dynamics along scraped shorelines, Bogue Banks, North Carolina. Journal of Coastal Research 21(2):242–254.

Cooper, J. A. G., and O. H. Pilkey. 2004. Sea-level rise and shoreline retreat: time to abandon the Bruun Rule. Global and Planetary Change 43(3-4):157–171.

Daiber, F. C. 1986. Conservation of tidal marshes. Van Nostrand Reinhold Co., New York, New York, USA.

Dallas, K. L., J. Eshleman, and R. Beavers. 2012. National Park Service beach nourishment guidance. Natural resource technical report NPS/NRSS/GRD/NRTR—2012/581. National Park Service, Fort Collins, Colorado, USA. https://irma.nps.gov/App/Reference/Profile/2185115 (accessed 25 September 2012).

Davidson-Arnott, R. G. D., and M. N. Law. 1990. Seasonal patterns and controls on sediment supply to coastal foredunes, Long Point, Lake Erie. Pages 117–200 *in* K. F. Nordstrom, N. P. Psuty, and R. W. G. Carter, editors. Coastal dunes: form and process. Wiley, Chichester, England.

Dean, R. G., and M. Perlin. 1977. Coastal engineering study of Ocean City Inlet, Maryland. Pages 520–540 *in* American Society of Civil Engineers, editor. Proceedings of Coastal Sediments '77. American Society of Civil Engineers, Reston, Virginia, USA.

Dean, R. G., M. Perlin, and B. Daly. 1978. A coastal engineering study of shoaling in Ocean City Inlet. Report for U.S. Army Corps of Engineers Baltimore District, March 1978, by University of Delaware Department of Civil Engineering ,Newark, Delaware, USA.

Demarest, J. M., and S. P. Leatherman. 1985. Mainland influence on coastal transgressions: Delmarva Peninsula. Marine Geology 63(1-4):19–33.

Diaz, R. J., G. R. Cutter, Jr., and C. H. Hobbs III. 2004. Potential impacts of sand mining offshore of Maryland and Delaware: part 2—biological considerations. Journal of Coastal Research 20(1):61–69.

Dillow, J. J. A., and E. A. Greene. 1999. Ground water discharge and nitrate loadings to the coastal bays of Maryland. Water Resources Investigations Report 99-4167. U.S. Geological Survey, Baltimore, Maryland, USA. http://md.water.usgs.gov/publications/wrir-99-4167/ (accessed 3 September 2013).

Dillow, J. J. A., W. S. L. Banks, and M. J. Smigaj. 2002. Ground-water quality and discharge to Chincoteague and Sinepuxent Bays adjacent to Assateague Island National Seashore, Maryland. Water Resources Investigations Report 02-4029. U.S, Geological Survey, Baltimore, Maryland, USA. http://pubs.usgs.gov/wri/wri024029/ (accessed 3 September 2013).

Dolan, R., H. Lins, and J. Stewart. 1980. Geographical Analysis of Fenwick Island, Maryland, a Middle Atlantic Coast Barrier Island. U.S. Geological Survey Professional Paper 1177-A. U.S. Geological Survey, Reston, Virginia, USA. http://pubs.er.usgs.gov/publication/pp1177A (accessed 3 September 2013).

Dolan, R. and R. E. Davis. 1992. An Intensity Scale for Atlantic Coast Northeast Storms. Journal of Coastal Research 8(4): 840-853.

Douglas, B. C. 1997. Global sea rise, a redetermination. Surveys in Geophysics 18:279–292.

Driscoll, N. W., J. K. Weissel, and J. A. Goff. 2000. Potential for large-scale submarine slope failure and tsunami generation along the U.S. mid-Atlantic coast. Geology 28(5):407–410.

Duffy, D. F., and G. R. Whittecar. 1991. Geomorphic development of segmented alluvial fans in the Shenandoah Valley, Stuarts Draft, Virginia. Geological Society of America Abstracts with Programs 23(1).

Elliott, M. 2002. The role of the DPSIR approach and conceptual models in marine environmental management: an example for offshore wind power. Marine Pollution Bulletin 44:iii-vii.

Engelhart, S. E., B. P. Horton, and A. C. Kemp. 2011. Holocene sea level changes along the United States' Atlantic Coast. Oceanography 24(2):70–79.

Erwin, R.M. G.M. Sanders, D.J. Prosser, and D.R. Cahoon. 2006. High tides and rising seas: potential effects on estuarine waterbirds. Studies in Avian Biology 32:214–228.

Ewanchuk, P. J., and M. D. Bertness. 2004. Structure and organization of a northern New England salt marsh plant community. Journal of Ecology 92(1):72-85.

Fairbanks, R.G. 1989. A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. Nature 342:637-642. http://people.uncw.edu/grindlayn/GLY550/Fairbanks-Sealevel-1989.pdf (accessed 13 June 2013).

Federal Geographic Data Committee (FGDC). 2012. Coastal and Marine Ecological Classification Standard. FGDC-STD-018-2012. Marine and Coastal Spatial Data Subcommittee, Federal Geographic Data Committee, Reston, Virginia, USA. http://www.csc.noaa.gov/digitalcoast/publications/cmecs (accessed 30 January 2013).

Field, M. E. 1979. Sediments, shallow subbottom structure, and sand resources of the inner continental shelf, central Delmarva Peninsula. CERC-TP-79-2. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, USA.

Field, M. E., and D. B. Duane. 1976. Post-Pleistocene history of the United States inner continental shelf: significance to origin of barrier Islands. Geological Society of America Bulletin 87:691–702.

Finkelstein, K. 1983. Cape formation as a cause of erosion on adjacent shorelines. Pages 620–640 *in* O.T. Magoon and H. Converse, editors, Coastal zone '83: proceedings of the Third Symposium on Coastal and Ocean Management. American Society of Civil Engineers, Reston, Virginia, USA.

Fisher, J. S., S. P. Leatherman, and F. C. Perry. 1974. Overwash processes on Assateague Island. Pages 1194–1211 *in* American Society of Civil Engineers, editor. Proceedings of 14th Conference on Coastal Engineering. American Society of Civil Engineers, New York, New York, USA.

FitzGerald, D. M., I. V. Buynevich, and B. A. Argow. 2006. Model of tidal inlet and barrier island dynamics in a regime of accelerated sea-level rise. Journal of Coastal Research Special Issue 39:789–795.

FitzGerald, D. M., M. S. Fenster, B. A. Argow, and I. V. Buynevich. 2008. Coastal impacts due to sea-level rise. Annual Reviews of Earth and Planetary Sciences 36:601–647.

Forgues, K. 2010. The effects of off-road vehicles on migrating shorebirds at a barrier island in Maryland and Virginia. Master's Thesis. Trent University, Peterborough, Ontario, Canada.

Furbish, C. E., and M. Albano. 1994. Selective herbivory and plant community structure in a mid-Atlantic salt marsh. Ecology 75(4):1015–1022.

Gawne, C. E. 1966. Shore changes on Fenwick and Assateague Islands, Maryland and Virginia. Bachelor's Thesis. University of Illinois, Urbana, Illinois, USA.

Godfrey, P., and M. Godfrey. 1980. Ecological effects of off-road vehicles on Cape Cod. Oceanus 23:56–67.

Griswold, M., J. Hawkey, and H. Kelsey. 2012. Climate change effects on Assateague Island morphology, habitats, and species. Report to Assateague Island National Seashore. Integration & Application Network, University of Maryland Center for Environmental Science, Horn Point, Maryland, USA.

Grothe, P. R., L. A. Taylor, B. W. Eakins, R. R. Warnken, K. S. Carignan, E. Lim, R. J. Caldwell, and D. Z. Friday. 2010. Digital elevation model of Ocean City, Maryland: procedures, data sources and analysis. NOAA Technical memorandum NESDIS NGDC-37. Department of Commerce, Boulder, Colorado, USA. http://www.ngdc.noaa.gov/dem/squareCellGrid/download/381 (accessed 18 September 2012).

Gutierrez, B. T., S. J. Williams, and E. R. Thieler. 2007. Potential for shoreline changes due to sea-level rise along the U.S. Mid-Atlantic region. Open-file report 2007-1278. U.S. Geological Survey, Woods Hole, Massachusetts, USA. http://woodshole.er.usgs.gov/pubs/of2007-1278/ (accessed 28 January 2013).

Gutierrez, B. T., S. J. Williams, and E. R. Thieler. 2009. Ocean coasts. Pages 141–188 *in* J. G. Titus (Coordinating Lead Author), K. E. Anderson, D. R. Cahoon, D. B. Gesch, S. K. Gill, B. T. Gutierrez, E. R.Thieler, and S. J. Williams (Lead Authors), Coastal sensitivity to sea level rise: a focus on the mid-Atlantic region. Synthesis and assessment product 4.1. U.S. Environmental Protection Agency, Washington, DC, USA. http://library.globalchange.gov/sap-4-1-coastal-sensitivity-to-sea-level-rise-a-focus-on-the-mid-atlantic-region (accessed 10 July 2012).

Hall, S. Z. 2005. Hydrodynamics of freshwater ponds on a siliciclastic barrier island, Assateague Island National Seashore, Maryland. Master's Thesis. University of Maryland Eastern Shore, Princess Anne, Maryland, USA.

Hallermeier, R. J. 1981. A profile zonation for seasonal sand beaches from wave climate. Coastal Engineering 4:253–277.

Halsey, S. D. 1978. Late Quaternary geologic history and morphologic development of the barrier island system along the Delmarva Peninsula of the mid-Atlantic Bight. PhD Dissertation. University of Delaware, Newark, Delaware, USA.

Hanks, T. C. 1985. The national earthquake hazards reduction program scientific status. Bulletin 1059. U.S. Geological Survey, Reston, Virginia, USA.

Harris, A. G., E. Tuttle, and S. D. Tuttle. 1997. Geology of National Parks. Kendall/Hunt Publishing Company, Dubuque, Iowa, USA.

Hayes, M. O. 1979. Barrier island morphology as a function of tidal and wave regime. Pages 1–25 *in* S. P. Leatherman, editor. Barrier islands from the Gulf of St. Lawrence to the Gulf of Mexico. Academic Press, New York, New York, USA.

Hayes, M. O., and R. B. Nairn. 2004. Natural Maintenance of sand ridges and linear shoals on the U.S. Gulf and Atlantic continental shelves and the potential impacts of dredging. Journal of Coastal Research 20(1):138–148.

Headland, J. R., L. Vallianos, and J. G. Sheldon. 1987. Coastal processes at Wallops Island, Virginia. Pages 1305–1320 *in* N.C. Kraus, editor, Coastal Sediments '87: Proceedings of a Specialty Conference on Advances in Understanding of Coastal Sediment Processes. American Society of Civil Engineers, New York, New York, USA.

Hite, M. P. 1924. Some observations of storm effects on ocean inlets. American Journal of Science Series 5(7):319–326.

Hobbs, C.H., III. 2004. Geological history of Chesapeake Bay, USA. Quaternary Science Reviews 23:641-661. http://dx.doi.org/10.1016/j.quascirev.2003.08.003 (accessed 17 June 2013).

Hobbs, C. H., D. E. Krantz, and G. L. Wikel. In press. Coastal processes and offshore geology. *In* C. Bailey, editor. The geology of Viginia. The College of William and Mary, Williamsburg, Virginia, USA. http://www.eeescience.utoledo.edu/Faculty/Krantz/download_files/Virginia_Coast.Hobbs_Krantz_&_Wikel.2008.pdf (accessed 9 July 2012).

Homer, M. L., M. L. Tarnowski, R. Bussell, and C. Rice. 1997. Coastal Bays shellfish inventory. Final report to Coastal Zone Management Division, Maryland Department of Natural Resources, contract no. 14-96-134-CZM010, grant no. NA570Z0301. Annapolis, Maryland, USA.

Honeycutt, M. G., and D. E. Krantz. 2003. Influence of geologic framework on spatial variability in long-term shoreline change, Cape Henlopen to Rehoboth Beach, Delaware. Journal of Coastal Research Special Issue 38:147–167.

Horton, B. P., W. R. Peltier, S. J. Culver, R. Drummond, S. E. Engelhart, A. C. Kemp, D. Mallinson, E. R. Thieler , S. R. Riggs, D. V. Ames, and K. H. Thomson. 2009. Holocene sea-level changes along the North Carolina Coastline and their implications for glacial isostatic adjustment models. Quaternary Science Reviews 28:1725–1736.

Hosier, P. E., and T. E. Eaton. 1980. The impact of vehicles on dune and grassland vegetation on a south-eastern North Carolina barrier beach. Journal of Applied Ecology 17:173–182.

Houser, C., and S. Hamilton. 2009. Sensitivity of post-hurricane beach and dune recovery to event frequency. Earth Surface Processes and Landforms 34:613–628.

Houser, C., B. Labude, L. Haider, and B. Weymer. 2013. Impacts of driving on the beach: Case studies from Assateague Island and Padre Island Seashores. Ocean & Coastal Management 71: 33-45. http://dx.doi.org/10.1016/j.ocecoaman.2012.09.012 (accessed 8 January 2013).

Intergovernmental Panel on Climate Change (IPCC). 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. S. D. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller, editors. Cambridge University Press, Cambridge, United Kingdom and New York, New York, USA. http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm (accessed 10 July 2012).

Karl, T. R., J. M. Melillo, and T. C. Peterson, editors. 2009. Global climate change impacts in the United States. Cambridge University Press, New York, New York, USA. http://globalchange.gov/publications/reports/scientific-assessments/us-impacts (accessed 19 September 2012).

Kennish, M. J. 2001. Coastal salt marsh systems in the U.S.: a review of anthropogenic impacts. Journal of Coastal Research 17(3):731–748.

Kenworthy, J., and V. Santucci. 2003. Paleontological resource inventory and monitoring study of the Northeast and Coastal Barrier Network. TIC# D-340. National Park Service, Denver, Colorado, USA.

Kirby, R.E. and L.E. Widjeskog. 2013. Sediment Redistributed by Coastal Marsh Mosquito Ditching in Cape May County, New Jersey, U.S.A. Journal of Coastal Research 29(1):86-93.

Knisley, C. B. and J. M. Hill. 1990. Distribution and abundance of two tiger beetles *Cicindela dorsalis media* and *C. lepida* at Assateague Island, Maryland, 1990. Final report to Maryland Department of Natural Resources, Natural Heritage Program, Annapolis, Maryland, USA.

Koch, F., and C. J. Gobler. 2009. The effects of tidal export from salt marsh ditches on estuarine water quality and plankton communities. Estuaries and Coasts 32(2):261–275.

Kochel, R. C., and L. A. Wampfler. 1989. Relative role of overwash and Aeolian processes on washover fans, Assateague Island, Virginia- Maryland. Journal of Coastal Research 5(3):453–475.

Kraft, J. C. 1971. Sedimentary facies patterns and geologic history of a Holocene marine transgression. Geological Society of America Bulletin 82: 2131–2158.

Kraft, J. C. 1976. Radiocarbon dates in the Delaware coastal zone. Delaware sea grant report DEL-SG-19-76. College of Marine Studies, University of Delaware, Newark, Delaware, USA.

Kraft, J. C., M. J. Chrzastowski, D. F. Belknap, M. A. Toscano, and C. H. Fletcher. 1987. The transgressive barrier-lagoon coast of Delaware: morphostratigraphy, sedimentary sequences and responses to relative rise in sea level. Pages 129–143 *in* D. Nummedal, O. H. Pilkey, and J. D. Howard, editors. Sea-level fluctuation and coastal evolution. Special publication 41. Society for Sedimentary Geology, Tulsa, Oklahoma, USA.

Krantz, D. 2010. A hydrogeomorphic map of Assateague Island National Seashore, Maryland and Virginia. Natural resource report NPS/NRPC/GRD/NRR-2010/215. National Park Service, Fort Collins, Colorado, USA. http://nature.nps.gov/geology/inventory/gre_publications.cfm (accessed 10 July 2012).

Krantz, D. K., C. A. Schupp, C. C. Spaur, J. E. Thomas, and D. V. Wells. 2009. Dynamic systems at the land-sea interface. Pages 211–248 *in* W. C. Dennison, J. E. Thomas, C. J. Cain, T. J. B. Carruthers, M. R. Hall, R. V. Jesien, C. E. Wazniak, and D. E. Wilson, editors. Shifting sands: environmental and cultural change in Maryland's Coastal Bays. IAN Press, University of Maryland Center for Environmental Science, Cambridge, Maryland, USA.

Kraus, N. C. 2000. Reservoir model of ebb-tidal shoal evolution and sand bypassing. Journal of Waterway, Port, Coastal, and Ocean Engineering 126(6):305–313.

Kuster, W. V. 1959. Titanium minerals in the heavy sand deposits of Assateague Island, MD. Report of investigations 5512. U.S. Department of the Interior Bureau of Mines, Washington, DC, USA. http://digital.library.unt.edu/ark:/67531/metadc38679/m2/1/high_res_d/metadc38679.pdf (accessed 10 July 2012).

Kutz, F. W. 1993. 1993 Delaware and Maryland bays benthic assessment by site. U.S. Environmental Protection Agency Region III, Fort Meade, Maryland, USA.

Kvenvolden, K.A., 1993, Gas hydrates: Geological perspective and global change. Reviews of Geophysics 31:173–187. http://eesc.columbia.edu/courses/w4937/Readings/Kvenvolden.1993.pdf (accessed 16 June 2013).

Langley, S. B. M. 2002. Archeological overview and assessment of maritime resources in Assateague Island National Seashore Worcester County, Maryland & Accomack County, Virginia. Report submitted to Assateague Island National Seashore. Maryland State Historic Preservation Office, Crownsville, Maryland, USA.

Larson, M., and N. C. Kraus. 1989. SBEACH: Numerical Model for Simulating Storm-Induced Beach Change. Report DRP-92-5. U.S. Army Corps of Engineers CERC, Vicksburg, Mississippi, USA.

Leatherman, S. P. 1976. Barrier island dynamics: overwash processes and eolian transport. Pages 1958–1974 *in* American Society of Civil Engineers, Coastal Engineering 1976, Proceedings of the 15th International Conference, Honolulu, Hawaii. American Society of Civil Engineers, New York, New York, USA.

Leatherman, S. P., 1979a. Beach and dune interactions during storm conditions. Quarterly Journal of Engineering Geology and Hydrogeology 12:281–290.

Leatherman, S. P. 1979b. Migration of Assateague Island, Maryland, by inlet and overwash processes. Geology 7:104–107.

Leatherman, S.P. 1984. Shoreline evolution of North Assateague Island, Maryland. Shore and Beach 52(3):3–10.

Leatherman, S. P., and P. J. Godfrey. 1979. The impact of off-road vehicles on coastal ecosystems in Cape Cod National Seashore: an overview. Report no. 34. University of Massachusetts and National Park Service Cooperative Research Unit, University of Massachusetts, Amherst, Massachusetts, USA.

Liddle, M.J. and P. Greig-Smith. 1975. A survey of tracks and paths in a sand dune ecosystem. II. Vegetation. Journal of Applied Ecology 12:909-930.

Loegering, J. P., and J. D. Fraser. 1995. Affecting piping plover chick survival in different brood-rearing habitats. The Journal of Wildlife Management 59(4):646–655.

Løkkeborg, Svein. 2004. Impacts of trawling and scallop dredging on benthic habitats and communities. FAO fisheries technical paper 472. United Nations Food and Agriculture Organization Fisheries Department, Rome, Italy. http://www.fao.org/docrep/008/y7135e/y7135e00.htm (accessed 27 September 2012).

Maryland Department of Environment. 2011. The 2010 integrated report of surface water quality in Maryland. Report submitted to the U.S. Environmental Protection Agency in accordance with sections 303(d), 305(b) and 314 of the Clean Water Act. Maryland Department of Environment, Baltimore, Maryland, USA. http://www.mde.state.md.us/programs/Water/TMDL/Integrated303dReports/Pages/Final_approved_2010_ir.aspx (accessed 24 September 2012).

Maryland Geological Survey. 2012. Earthquakes and Maryland. Baltimore, Maryland, USA. http://www.mgs.md.gov/esic/brochures/earthquake.html (accessed 4 June 2012).

Matias, A., Ó. Ferreira, A. Vila-Concejo, B. Morris, and J. A. Dias. 2009. Foreshore and hydrodynamic factors governing overwash. Journal of Coastal Research 56:636-640. http://w3.ualg.pt/~jdias/JAD/papers/09_JCR_si56_636_AM.pdf (accessed 30 January 2013).

McBride, R. A. 1999. Spatial and temporal distribution of historical and active tidal inlets: Delmarva Peninsula and New Jersey, USA. Pages 1505–1521 *in* N. C. Kraus and W. G. McDougal, editors. Coastal Sediments '99: Proceedings of the 4th International Symposium on Coasting Engineering and Science of Coastal Sediment Processes. American Society of Civil Engineers, Reston, Virginia, USA.

McBride, R. A., and T. F. Moslow. 1991. Origin, evolution and distribution of shoreface sand ridges, Atlantic inner shelf, U.S.A. Marine Geology 97:57–85.

Meehl, G. A., T. F. Stocker, W. D. Collins, P. Friedlingstein, A. T. Gaye, J. M. Gregory, A. Kitoh, R. Knutti, J. M. Murphy, A. Noda, S. C. B. Raper, I. G. Watterson, A. J. Weaver, and Z.-C. Zhao. 2007. Global Climate Projections, Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. S. D. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller, editors. Cambridge University Press, Cambridge, United Kingdom and New York, New York, USA. http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm (accessed 10 July 2012).

Minerals Management Service. 2007. Establishment of an OCS alternative energy and alternate use program. Record of decision. Department of the Interior Minerals Management Service, Washington, DC, USA. http://ocsenergy.anl.gov/documents/docs/OCS_PEIS_ROD.PDF (accessed 27 September 2012).

Mitchell, L.R., S. Gabrey, P.P. Marra, and R.M. Erwin. 2006. Impacts of marsh management on coastal marsh-bird habitats. Studies in Avian Biology 32:155–175.

Miselis, J. L., and J. E. McNinch. 2006. Calculating shoreline erosion potential using nearshore stratigraphy and sediment volume, Outer Banks, North Carolina. Journal of Geophysical Research 111: F02019.

Mixon, R. B. 1985. Stratigraphic and geomorphic framework of uppermost Cenozoic deposits in the southern Delmarva Peninsula, Virginia and Maryland. US Government Printing Office, Washington, DC, USA.

Moffatt & Nichol. 1986. Wallops Island Shore Protection Study. Report to NASA/Goddard Space Flight Facility, Wallops Island, Virginia.

Moore, L. J., J. H. List, S. J. Williams, and D. Stolper. 2010. Complexities in barrier island response to sea-level rise: insights from numerical model experiments, North Carolina Outer Banks. Journal of Geophysical Research 115:27.

Moore, L. J., P. Ruggiero, and J. H. List. 2006. Comparing mean high water and high water line shorelines: should proxy-datum offsets be incorporated into shoreline change analysis? Journal of Coastal Research 22(4):894–905.

Morton, R. A., and A.H. Sallenger. 2003. Morphological impacts of extreme storms on sandy beaches and barriers. Journal of Coastal Research 19(3):560–573.

Morton, R. A., J. E. Bracone, and B. Cooke. 2007. Geomorphology and depositional sub-environments of Assateague Island, Maryland-Virginia. Scale 1:21552. Open-file report OF-2007-1388. U.S. Geological Survey, Reston, Virginia, USA. NPS GRI source map ID 75016. http://pubs.usgs.gov/of/2007/1388/index.html (accessed 10 July 2012).

Moser, S.C., S.J. Williams and D.F. Boesch. 2012. Wicked challenges at land's end: Managing coastal vulnerability under climate change. Annual Reviews of Environment and Resources (37):51-78.

Moss, D., and D. McPhee. 2006. The impacts of recreational four-wheel driving on the abundance of the ghost crab (*Ocypode cordimanus*) on a subtropical sandy beach in SE Queensland. Coastal Management 34:133–140.

Munger, S. and N.C. Kraus. 2010. Frequency of extreme storms based on beach erosion at northern Assateague Island, Maryland. Shore and Beach 78(2):3–11.

Najjar, R. G., H. A. Walker, P. J. Anderson, E. J. Barron, R. J. Bord, J. R. Gibson, V. S. Kennedy, C. G. Knight, J. P. Megonigal, R. E. O'Connor, C. D. Polsky, N. P. Psuty, B. A. Richards, L. G. Sorenson, E. M. Steele, and R. S. Swanson. 2000. The potential impacts of climate change on the mid-Atlantic coastal region. Climate Research 14(3):219–233.

National Aeronautics and Space Administration (NASA). 2010. Wallops Flight Facility shoreline restoration and infrastructure protection program. Draft programmatic environmental impact statement. Wallops Island, Virginia, USA.

National Oceanic and Atmospheric Administration (NOAA). 1989. Susceptibility of East Coast estuaries to nutrient discharges: Passamaquoddy Bay to Chesapeake Bay. Strategic Assessment Branch, Ocean Assessments Division, Office of Oceanography and Marine Assessment, National Ocean Service, National Oceanic and Atmospheric Administration, Rockville, Maryland USA.

National Oceanic and Atmospheric Administration (NOAA). 2007. NOAA tides and currents, Tidal Station Locations and Ranges. http://tidesandcurrents.noaa.gov/tides08/tab2ec2b.html#42 (accessed 13 June 2013).

National Oceanic and Atmospheric Administration (NOAA). 2012. NOAA tides and currents, station 8557380, Lewes, Delaware. Digital dataset. http://tidesandcurrents.noaa.gov/data_menu.shtml?stn=8557380%20Lewes,%20DE&type=Historic%20Tide%20Data (accessed 11 April 2012).

National Oceanic and Atmospheric Administration (NOAA). 2013. NOAA tides and currents, station 8570283, Ocean City Inlet, Maryland. Digital dataset. http://tidesandcurrents.noaa.gov/data_menu.shtml?stn=8570283%20Ocean%20City%20Inlet,%20MD&type=Historic%20Tide%20Data (accessed 15 June 2013).

The Nature Conservancy (TNC). 2010. Effects of global climate change at the Virginia Coast Reserve: report from the Virginia Coast Reserve climate change threats workshop. The Nature Conservancy, Arlington, Virginia, USA.

Nordstrom, K. F., N. L. Jackson, A. H. F. Klein, D. J. Sherman, and P. A. Hesp. 2006. Offshore Aeolian transport across a low foredune on a developed barrier island. Journal of Coastal Research 22(5):1260–1267.

Nordstrom, K. F., J. M. McCluskey, and P. S. Rosen. 1986. Aeolian processes and dune characteristics of a developed shoreline: Westhampton Beach, New York. Pages 131–147 *in* W. G. Nickling, editor. Aeolian geomorphology. Allen and Unwin, Boston, Massachusetts, USA.

Odum, W. E., and R. Dueser. 1982. Natural and recreational influences on Fox Hill Levels and Toms Cove Hook, Assateague Island, Va. Draft final report. Assateague Island National Seashore, Berlin, Maryland, USA.

Oertel, G. F., and J. C. Kraft, 1994. New Jersey and Delmarva barrier islands. Pages 207–232 *in* R. A. Davis, editor. Geology of Holocene barrier island systems. Springer-Verlag, Berlin, Germany.

Oertel, G. F., T. R. Allen, and A. M. Foyle. 2008. The influence of drainage hierarchy on pathways of barrier retreat: an example from Chincoteague Bight, Virginia, U.S.A. Southeastern Geology 45(3):179–201.

Owens, J.P., and C.S. Denny. 1979. Upper Cenozoic deposits of the Central Delmarva Peninsula, Maryland and Delaware. U.S. Geological Survey Professional Paper 1067-A. U.S. Geological Survey, Reston, Virginia, USA.

Pararas-Carayannis, G. 2002. Evaluation of the threat of mega tsunami generation from postulated massive slope failures of island stratovolcanoes on La Palma, Canary Islands, and on the island of Hawaii. Science of Tsunami Hazards 20(5):251-277.

Peebles, P. C., G. H. Johnson, and C. R. Berquist. 1984. The middle and late Pleistocene stratigraphy of the outer coastal plain, southeastern Virginia. Virginia Minerals 30(2):13-22.

Pendleton, E. A., S. J. Williams, and E. R. Thieler. 2004. Coastal vulnerability assessment of Assateague Island National Seashore (ASIS) to sea-level rise. Open-File report 2004-1020. U.S. Geological Survey, Woods Hole, Massachusetts. http://pubs.usgs.gov/of/2004/1020/ (accessed 3 June 2012).

Portnoy, J. W. 1999. Salt marsh diking and restoration: biogeochemical implications of altered wetland hydrology. Environmental Management 24(1):111–120.

Psuty, N. P., T. M. Silveira, and D. Soda. 2011. Shoreline change monitoring at Assateague Island National Seashore: 2005-2010 trend report. Natural Resource Technical Report NPS/NCBN/NRTR—2011/509. National Park Service, Fort Collins, Colorado, USA. http://www.nature.nps.gov/geology/monitoring/files/ASIS_ShorelineChange_TrendReport_.pdf (accessed 15 June 2013).

Public law 89-195. (79 Stat. 824; Date: 21 September 1965; enacted S. 20). Text from: United States Public Laws. http://www.nps.gov/history/history/online_books/asis/adhiaa.htm (accessed 30 January 2013).

Public law 94-578: An Act to provide for increases in appropriation ceilings and boundary changes in certain units of the National Park System, and for other purposes. (90 Stat. 2732; Date: 21 October 1976). Text from: United States Public Laws. http://www.nps.gov/history/history/online_books/asis/adhiaa.htm (accessed 30 January 2013).

Pritchard, D. W. 1960. Salt balance and exchange rate for Chincoteague Bay. Chesapeake Science 1:48–57.

Rahmstorf, S. 2007. A semi-empirical approach to projecting future sea-level rise. Science 315(5810):368–370.

Reed, D. J., D. Bishara, D. Cahoon, J. Donnelly, M. Kearney, A. Kolker, L. Leonard, R. A. Orson, and J. C. Stevenson. 2008. Site-specific scenarios for wetlands accretion as sea level rises in the mid-Atlantic region. Pages 134–174 *in* J. G. Titus and E. M. Strange, editors. Background documents supporting climate change science program synthesis and assessment product 4.1: Coastal elevations and sensitivity to sea level rise. EPA 430R07004. U.S. Environmental Protection Agency, Washington, DC, USA. http://epa.gov/climatechange/effects/coastal/background.html (accessed 10 July 2012).

Richards, H. G. 1936. Fauna of the Pleistocene Pamlico Formation of the Southern Atlantic Coastal Plain. Bulletin of the Geological Society of America 47:1611–1656.

Roman, C. T., N. Jaworski, F. Short, S. Findlay, and R. S. Warren. 2000. Estuaries of the northeastern United States: habitat and land use signatures. Estuaries 23:743–764.

Roman, C.T., and K. F. Nordstrom. 1988. The effect of erosion rate on vegetation patterns of an east coast barrier island. Estuarine, Coastal and Shelf Science 26:233–242.

Rosati, J. D., and B. A. Ebersole. 1996. Littoral impact of Ocean City Inlet, Maryland, USA. Pages 2779–2792 *in* B. L. Edge, editor. Coastal engineering 1996: proceedings of the 25th International Conference. American Society of Civil Engineers, Reston, Virginia, USA.

Sallenger, A.H., K.S. Doran, and P.A. Howd. 2012. Hotspot of accelerated sea-level rise on the Atlantic coast of North America. Nature Climate Change (advanced online publication, 24 June 1012). http://dx.doi.org/10.1038/nclimate1597 (accessed 25 October 2012).

Santucci, V. L., J. P. Kenworthy, and A. L. Mims. 2009. Monitoring in situ paleontological resources. Pages 189–204 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado, USA. http://nature.nps.gov/geology/monitoring/paleo.cfm (accessed 10 July 2012).

Schlacher, T.A., L. Thompson, and S. Price. 2007. Vehicles versus conservation of invertebrates on sandy beaches: mortalities inflicted by off-road vehicles on ghost crabs. Marine Ecology 28:354-367.

Schlacher, T. A., and L. M. C. Thompson. 2008. Physical impacts caused by off-road vehicles to sandy beaches: spatial quantification of car tracks on an Australian barrier island. Journal of Coastal Research 24:234–242.

Schlacher, T., D. Richardson, and I. McLean. 2008. Impacts of off-road vehicles (ORVs) on macrobenthic assemblages on sandy beaches. Environmental Management 41:878–892.

Schroeder, P. M., B. Hayden, and R. Dolan. 1979. Vegetation changes along the United States east coast following the great storm of March 1962. Environmental Management 3(4):331–338.

Schupp, C. A., G. P. Bass, and W. G. Grosskopf. 2007. Sand bypassing restores natural processes to Assateague Island National Seashore. Pages 1340–1353 *in* N. C. Kraus and J. D. Rosati, editors. Proceedings of Coastal Sediments '07. American Society of Civil Engineers, Reston, Virginia, USA.

Schupp, C. A., J. E. McNinch, and J. H. List. 2006. Shore-oblique bars, gravel outcrops and correlation to shoreline hotspots. Marine Geology 233(1-4):63–79.

Schupp, C. A., N. T. Winn, T. L. Pearl, J. P. Kumer, T. J. B. Carruthers, and C. S. Zimmerman. 2013. Restoration of overwash processes creates piping plover (*Charadrius melodus*) habitat on a barrier island (Assateague Island, Maryland). Estuarine, Coastal, and Shelf Science 116:11-20. http://www.sciencedirect.com/science/article/pii/S0272771412002648 (accessed 1 October 2012).

Schwab, W. C., E. R. Thieler, J. F. Denny, and W. W. Danforth. 2000a. Seafloor sediment distribution off southern Long Island, New York. Open-file report 00-243. U.S. Geological Survey, Woods Hole, Massachusetts, USA.

Schwab, W. C., E. R. Thieler, J. R. Allen, D. S. Foster, B. A. Swift, and J. F. Denny. 2000b. Influence of inner-continental shelf geologic framework on the evolution and behavior of the barrier-island system between Fire Island Inlet and Shinnecock Inlet, Long Island, New York. Journal of Coastal Research 16(2):408–422.

Seliskar, D. 1997. The effect of grazing by feral horses on American beachgrass at Assateague Island National Seashore. Final report. University of Delaware, Newark, Delaware, USA.

Seliskar, D.M. 2003. The response of Ammophila brevigulata and Spartina patens (Poaceae) to grazing by feral horses on a dynamic mid- Atlantic barrier island. American Journal of Botany 90(7):1038-1044.

Shao, G. F., H. H. Shugart, and D. R. Young. 1995. Simulation of transpiration sensitivity to environmental-changes for shrub (Myrica-Cerifera) thickets on a Virginia barrier-island. Ecological Modeling 78:235–248.

Shennan, I., and B. P. Horton. 2002. Relative sea-level changes and crustal movements of the UK. Journal of Quaternary Science 16:511–526.

Shepard, F. P. 1954. Nomenclature based on sand-silt-clay ratios: Journal of Sedimentary Petrology 24:151-158.

Sherman, D. J., and B. O. Bauer. 1993. Dynamics of beach-dune systems. Progress in Physical Geography 17:413–447.

Sherman, D. J., and S. Hotta. 1990. Aeolian sediment transport: theory and measurement. Pages 17–37 *in* K. F. Norddstrom, N. P. Psuty, and R. W. G. Carter, editors. Coastal dunes: form and process. Wiley, Chichester, England.

Sieling, F. W. 1958. Low salinity and unusual biological conditions noted in Chincoteague Bay. Maryland Tidewater News 14(4):15–16.

Southworth, S., D. K. Brezinski, R. C. Orndorff, J. E. Repetski, and D. M. Denenny. 2008. Geology of the Chesapeake and Ohio Canal National Historical Park and Potomac River Corridor, District of Columbia, Maryland, West Virginia, and Virginia. Professional Paper 1691. U.S. Geological Survey, Reston, Virginia, USA. http://pubs.usgs.gov/pp/1691/ (accessed 3 September 2013).

Stanley, D. J., and A. G. Warne. 1994. Worldwide initiation of Holocene marine deltas by deceleration of sea-level rise. Science 265(5169):228–231.

Stauble, D. K. 1994. A physical monitoring plan for northern Assateague Island, Maryland. U.S. Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, Vicksburg, Mississippi, USA.

Stauble, D. K. 1997. Appendix A: ebb and flood shoal evolution. Ocean City, Maryland, and vicinity water resources study, draft integrated feasibility report and environmental impact statement. U.S. Army Corps of Engineers Baltimore District, Baltimore, Maryland, USA.

Steiner, A.J., and S. P. Leatherman. 1981. Recreational impacts on the distribution of ghost crabs *Ocypode quadrata Fab*. Biological Conservation 20:111-122.

Sturm, M. 2007. Assessment of the effects of feral horses, sika deer and white-tailed deer on Assateague Island's forest and shrub habitat. Assateague Island National Seashore, Berlin, Maryland, USA.

Swift, D. J. P., B. S. Parsons, A. M. Foyle, and G. F. Oertel. 2003. Beds and sequences: stratigraphic organization at intermediate scales in the Quaternary of the Virginia Coast, U.S.A. Sedimentology 50:81–111.

Thieler, E. R., A. L. Brill, W. J. Cleary, C. H. Hobbs III, and R. A. Gammisch. 1995. Geology of the Wrightsville Beach, North Carolina shoreface: implications for the concept of shoreface profile of equilibrium. Marine Geology 126:271–287.

Thieler, E. R., O. H. Pilkey Jr, R. S. Young, D. M. Bush, and F. Chai. 2000. The use of mathematical models to predict beach behavior for US coastal engineering: a critical review. Journal of Coastal Research 16(1):48–70.

Thornberry-Ehrlich, T. 2005. Assateague Island National Seashore geologic resource management issues scoping summary. National Park Service and Colorado State University, Denver, Colorado, USA. http://nature.nps.gov/geology/inventory/gre_publications.cfm (accessed 10 July 2012).

Toscano, M. A., R. T. Kerhin, L. L. York, T. M. Cronin, and S. J. Williams. 1989. Quaternary stratigraphy of the inner continental shelf of Maryland. Report of Investigation 50. Maryland Geological Survey, Baltimore, Maryland, USA.

Truitt, R. V. 1968. High winds–high tides: a chronicle of Maryland's coastal hurricanes. Educational series no. 77. University of Maryland Natural Resource Institute, College Park, Maryland, USA.

Underwood, S. G., and M. W. Hiland. 1995. Historical development of Ocean City Inlet ebb shoal and its effect on northern Assateague Island. U.S. Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, Vicksburg, Mississippi, USA.

U.S. Army Corps of Engineers (USACE). 1986. History of coastal engineering projects at Ocean City and Assateague Island, Maryland. Baltimore District Corps of Engineers, Department of the Army, Baltimore, Maryland, USA.

U.S. Army Corps of Engineers (USACE). 1998. Appendix D: restoration of Assateague Island. Ocean City, Maryland, and vicinity water resources study final integrated feasibility report and environmental impact statement. U.S. Army Corps of Engineers Baltimore District, Baltimore, Maryland, USA.

U.S. Army Corps of Engineers (USACE). 2008. Extremal statistic of water level and wave height, Ocean City Inlet and Northern Assateague Island, MD. Memorandum (CEERD-HV-B), 8 April 2008. U.S. Army Corps of Engineers Baltimore District, Baltimore, Maryland, USA.

U.S. Army Corps of Engineers (USACE). 2012. Measurements for Ocean City, MD, south site, station MD002. Online dataset. http://sandbar.wes.army.mil/public_html/pmab2web/htdocs/md002.html (accessed 11 April 2012).

U.S. Census Bureau. 2013. Population Estimates Program. http://www.census.gov/popest/index.html (accessed 15 June 2013).

U.S. Fish and Wildlife Service (UWFWS). 2012. Draft comprehensive conservation plan for Chincoteague National Wildlife Refuge. Chincoteague National Wildlife Refuge, Chincoteague, Virginia, USA.

Vasslides, J. M., and K. W. Able. 2008. Importance of shoreface sand ridges as habitat for fishes off the northeast coast of the United States. Fishery Bulletin 106(1):93–107.

Violi, H., S. Bailey, and A. LaPlant. 2012. 2011 Phragmites Project Summary. Unpublished report, Assateague Island National Seashore, Berlin, Maryland, USA.

Virginia Department of Environmental Quality and Department of Conservation and Recreation. 2010. Virginia 305(b)/303(d) water quality integrated report to Congress and the EPA Administrator for the period January 1, 2003 to December 31, 2008. Richmond, Virginia, USA. http://www.deq.virginia.gov/Programs/Water/WaterQualityInformationTMDLs/WaterQualityAssessments/2010305b303dIntegratedReport.aspx (accessed 24 September 2012).

Warren, R. S., and W. A. Niering. 1993. Vegetation change on a northeast tidal marsh: interaction of sea-level rise and marsh accretion. Ecology 74:96–103.

Watson, J. J., G. I. H. Kerley, and A. McLachlan. 1996. Human activity and potential impacts on dune breeding birds in the Alexandria Coastal Dunefield. Landscape & Urban Planning 34:315–322.

Wazniak, C. E., and M. R. Hall, editors. 2005. Maryland's Coastal Bays: ecosystem health assessment 2004. DNR-12-1202-0009. Maryland Department of Natural Resources, Tidewater Ecosystem Assessment, Annapolis, Maryland, USA.

Wazniak, C., M. Hall, C. Cain, D. Wilson, R. Jesien, J. Thomas, T. Carruthers, and W. Dennison. 2004. State of the Maryland Coastal Bays 2004. University of Maryland Center for Environmental Science, Horn Point, Maryland, USA. http://ian.umces.edu/press/reports/publication/48/state_of_the_maryland_coastal_bays_2004_2004-08-16/ (accessed 9 July 2012).

Wazniak, C. E., M. R. Hall, T. J. B. Carruthers, B. Sturgis, W. C. Dennison, and R. J. Orth. 2007. Linking water quality to living resources in a mid-Atlantic lagoon system, USA. Ecological Applications 17(5S):64–78.

Weber, K.M., J.H. List, and L.M.M. Morgan. 2005. An Operational Mean High Water Datum for Determination of Shoreline Position from Topographic Lidar Data. U.S. Geological Survey Open File Report 2004-1027. U.S. Geological Survey, Woods Hole, Massachusetts, USA. http://pubs.usgs.gov/of/2005/1027/ (accessed 13 June 2013).

Wells, D. V. 1994. Non-energy resources and shallow geologic framework of the inner continental margin off Ocean City, Maryland. Coastal and Estuarine Geology Open-File Report 16. Maryland Geological Survey, Baltimore, Maryland, USA. http://www.mgs.md.gov/coastal/pub/ofr16.pdf (accessed 10 July 2012).

Wells, D. V., and R. Conkwright. 1999. The Maryland Coastal Bays sediment mapping project - physical and chemical characteristics of the shallow sediments: synthesis report and atlas. File report 99-5, HTML-format on CD-ROM. Maryland Department of Natural Resources, Maryland Geological Survey, Coastal & Estuarine Geology Program, Baltimore, Maryland, USA. http://www.mgs.md.gov/coastal/vmap/czmatlas/index.html (accessed 10 July 2012).

Wells, D. V., E. L. Hennessee, and J. M. Hill. 2002. Shoreline erosion as a source of sediments and nutrients, northern coastal bays, Maryland. Coastal and estuarine geology file report no. 02-05. Maryland Geological Survey, Baltimore, Maryland, USA. http://www.mgs.md.gov/coastal/pub/NCB_FinalRpt.pdf (accessed 10 July 2012).

Wells, D. V., E. L. Hennessee, and J. M. Hill. 2003. Shoreline erosion as a source of sediments and nutrients, middle coastal bays, Maryland. Coastal and estuarine geology file report no. 03-07. Maryland Geological Survey, Baltimore, Maryland, USA. http://www.mgs.md.gov/coastal/pub/mcbfinal.pdf (accessed 30 January 2013).

Wells, D. V. 2012. Inventory benthic habitats and ocean resources, and protect recreational fishing synopsis of data and initial results. Status report submitted to ASIS 17 February 2012. Maryland Geological Survey, Baltimore Maryland, USA.

Whittecar, G. R., D. F. Duffy. 2000, Geomorphology and stratigraphy of late Cenozoic alluvial fans, Augusta County, Virginia, U.S.A. Southeastern Geology 39(3-4): 259-279.

Wikel, G. L. 2008. Variability in geologic framework and shoreline change: Assateague and Wallops islands, eastern shore of Virginia. Masters Thesis. Virginia Institute of Marine Science, The College of William and Mary, Williamsburg, Virginia, USA.

Williams, J. A., V. L. Ward, and L. G. Underhill. 2004. Waders respond quickly and positively to the banning of off-road vehicles from beaches in South Africa. Wader Study Group Bulletin 104:79–81.

Williams, S. J., B. T. Gutierrez, J. G. Titus, S. K. Gill, D. R. Cahoon, E. R. Thieler, K. E. Anderson, D. FitzGerald, V. Burkett, and J. Samenow. 2009. Sea-level rise and its effects on the coast. Pages 11–24 *in* J. G. Titus, K. E. Anderson, D. R. Cahoon, D. B. Gesch, S. K. Gill, B. T. Gutierrez, E. R. Thieler, and S. J. Williams, editors. Coastal sensitivity to sea-level rise: a focus on the mid-Atlantic region. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. U.S. Environmental Protection Agency, Washington, DC, USA. http://library.globalchange.gov/sap-4-1-coastal-sensitivity-to-sea-level-rise-a-focus-on-the-mid-atlantic-region (accessed 10 July 2012).

Williams, S. J. 2013 (In Review). Sea-level rise implications for Coastal Regions. Journal of Coastal Research Special Issue 63.

Wolcott, T. G., and D. L. Wolcott. 1984. Impact of off-road vehicles on macroinvertebrates of a mid-Atlantic beach. Biological Conservation 29: 217–240.

Wolfe, R.J. 1996. Effects of open marsh water management on selected tidal marsh resources: a review. Journal of the American Mosquito Control Association 12:701-712.

World Bank. 2012. Turn Down the Heat: Why a 4°C Warmer World Must be Avoided. A Report for the World Bank by the Potsdam Institute for Climate Impact Research and Climate Analytics. The World Bank, Washington, DC. http://climatechange.worldbank.org/sites/default/files/Turn_Down_the_heat_Why_a_4_degree_centrigrade_warmer_world_must_be_avoided.pdf (accessed 8 January 2013).

Zervanos, S. M., and R. R. Keiper. 1979. Winter activity patterns and carrying capacities of Assateague Island feral ponies. Final report for contract no. PX2000-8-D045. Assateague Island National Seashore, Berlin, Maryland, USA.

Zimmerman, C., M. Sturm, J. Ballou, and K. Traylor-Holzer, editors. 2006. Horses of Assateague Island population and habitat viability assessment: final report. IUCN/SSC Conservation Breeding Specialist Group, Apple Valley, Minnesota, USA.

Additional References

This chapter lists additional references, resources, and websites that may be of use to resource managers. Web addresses are current as of August 2013.

Geology of National Park Service Areas

National Park Service Geologic Resources Division (Lakewood, Colorado): http://nature.nps.gov/geology/

NPS Geologic Resources Inventory: http://www.nature.nps.gov/geology/inventory/gre_publications.cfm

Harris, A. G., E. Tuttle, and S. D. Tuttle. 2003. Geology of national parks. Sixth edition. Kendall/Hunt Publishing Co., Dubuque, Iowa, USA.

Kiver, E. P., and D. V. Harris. 1999. Geology of U.S. parklands. John Wiley and Sons, Inc., New York, New York, USA.

Lillie, R. J. 2005. Parks and plates: the geology of our national parks, monuments, and seashores. W.W. Norton and Co., New York, New York, USA.

NPS Geoscientist-in-the-Parks (GIP) internship and guest scientist program: http://www.nature.nps.gov/geology/gip/index.cfm

NPS Views Program (geology-themed modules are available for Geologic Time, Paleontology, Glaciers, Caves and Karst, Coastal Geology, Volcanoes, and a variety of geologic parks): http://www.nature.nps.gov/views/layouts/Main.html#/Views/.

NPS Resource Management Guidance and Documents

1998 National Parks Omnibus Management Act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf

NPS 2006 Management Policies (Chapter 4; Natural Resource Management): http://www.nps.gov/policy/mp/policies.html#_Toc157232681

NPS-75: Natural Resource Inventory and Monitoring Guideline: http://www.nature.nps.gov/nps75/nps75.pdf

NPS Natural Resource Management Reference Manual #77: http://www.nature.nps.gov/Rm77/

Geologic Monitoring Manual: Young, R., and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado, USA. http://nature.nps.gov/geology/monitoring/index.cfm

NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): http://etic.nps.gov/

Geological Surveys and Societies

Maryland Geological Survey: http://www.mgs.md.gov/

Maryland Seismic Network: http://www.mgs.md.gov/seismics/local.shtml

Virginia Division of Geology and Mineral Resources: http://www.dmme.virginia.gov/divisionmineralresources.shtml

U.S. Geological Survey: http://www.usgs.gov/

Geological Society of America: http://www.geosociety.org/

American Geosciences Institute: http://www.agiweb.org/

Association of American State Geologists: http://www.stategeologists.org/

Lamont-Doherty Cooperative Seismographic Network: http://www.ldeo.columbia.edu/LCSN/index.php

U.S. Geological Survey Reference Tools

U.S. Geological Survey National Geologic Map Database (NGMDB): http://ngmdb.usgs.gov/

U.S. Geological Survey Geologic Names Lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html

U.S. Geological Survey Geographic Names Information System (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/

U.S. Geological Survey GeoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on "Map Locator")

U.S. Geological Survey Publications Warehouse (USGS publications, many available online): http://pubs.er.usgs.gov

U.S. Geological Survey Tapestry of Time and Terrain (descriptions of physiographic provinces): http://tapestry.usgs.gov/Default.html

Appendix A: Scoping Meeting Participants

The following people attended the GRI scoping meeting for Assateague Island National Seashore, held on 26–28 July 2005. Discussions during this meeting supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm).

Name	Affiliation	Position
Bruce Heise	NPS, Geologic Resources Division (GRD)	Geologist
Lindsay McClelland	NPS, GRD	Geologist, Washington liaison to GRD
Melanie Ransmeier	NPS, GRD	Geologist
Trista Thornberry-Ehrlich	Colorado State University	Geologist, CSU-NPS cooperative
Beth Johnson	NPS, Northeast Regional Office	Regional coordinator, Inventory and Monitoring Network
John Karish	NPS, Northeast Regional Office	Chief scientist
Mark Duffy	NPS, Northeast Coastal Barrier Network (NCBN)	Cartographer
Bryan Milstead	NPS, NCBN	Coordinator, Inventory and Monitoring Network
Sara Stevens	NPS, NCBN	Data manager
Carl Zimmerman	NPS, Assateague Island National Seashore (ASIS)	Chief, Division of Resource Management
Courtney Schupp	NPS, ASIS	Geologist
Cheryl Hapke	USGS Biological Resources Division	Geologist
Doug Levin	National Oceanic and Atmospheric Administration (NOAA)	Habitat specialist
Darlene Wells	Maryland Geological Survey	Geologist
David Krantz	University of Toledo	Professor of geology

Appendix B: Geologic Resource Laws, Regulations, and Policies

The Geologic Resources Division developed this table to summarize laws, regulations, and policies that specifically apply to National Park Service minerals and geologic resources. The table does not include laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, National Environmental Policy Act, or National Historic Preservation Act). The table does include the NPS Organic Act when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available. Information is current as of February 2013. Contact GRD for detailed guidance or a complete list of laws, regulations, and policies for all geologic resources. This appendix is abridged to those resources applicable to Assateague Island National Seashore.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Paleontology	**National Parks Omnibus Management Act of 1998, 16 USC. § 5937** protects the confidentiality of the nature and specific location of paleontological resources and objects. **Paleontological Resources Preservation Act of 2009**, **16 USC. § 470aaa *et seq.***, provides for the management and protection of paleontological resources on federal lands.	**36 C.F.R. § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof. **36 C.F.R. § 13.35** prohibition applies even in Alaska parks where the surface collection of other geologic resources is permitted. Regulations in association with 2009 PRPA are being finalized (February 2013).	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.1** emphasizes I & M, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.
Rocks and Minerals	**NPS Organic Act**, **16 USC. § 1 *et seq.*** directs the NPS to conserve all resources in parks (which includes rock and mineral resources) unless otherwise authorized by law. **Exception: 16 USC. § 445c (c) – Pipestone National Monument enabling statute**. Authorizes Native American collection of catlinite (red pipestone).	**36 C.F.R. § 2.1** prohibits possessing, destroying, disturbing mineral resources…in park units. **Exception: 36 C.F.R. § 7.91** allows limited gold panning in Whiskeytown. **Exception: 36 C.F.R. § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, and Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Park Use of Sand and Gravel	**Materials Act of 1947, 30 USC. § 601** does not authorize the NPS to dispose of mineral materials outside of park units. **Exception:** 16 USC. §90c 1(b) the non-wilderness portion of Lake Chelan National Recreation Area, where sand, rock and gravel may be made available for sale to the residents of Stehekin for local use as long as such sale and disposal does not have significant adverse effects on the administration of the National Recreation Area.	None applicable.	**Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and: - Only for park administrative uses. - After compliance with NEPA & other federal, state, and local laws, and a finding of non-impairment. - After finding the use is park's most reasonable alternative based on environment and economics. - Parks should use existing pits and create new pits only in accordance with park-wide borrow management plan. - Spoil areas must comply with Part 6 standards - NPS must evaluate use of external quarries. Any deviations from this policy require written waiver from the Secretary, Assistant Secretary, or Director.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Coastal Features and Processes	**NPS Organic Act, 16 USC. § 1 *et. seq.*** authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights). **Coastal Zone Management Act, 16 USC. § 1451 *et. seq.*** requires Federal agencies to prepare a consistency determination for every Federal agency activity in or outside of the coastal zone that affects land or water use of the coastal zone. **Clean Water Act, 33 USC. § 1342/Rivers and Harbors Act, 33 USC. 403** require that dredge and fill actions comply with a Corps of Engineers Section 404 permit. **Executive Order 13089** (coral reefs) (1998) calls for reduction of impacts to coral reefs. **Executive Order 13158** (marine protected areas) (2000) requires every federal agency, to the extent permitted by law and the maximum extent practicable, to avoid harming marine protected areas.	**36 C.F.R. § 1.2(a)(3)** applies NPS regulations to activities occurring within waters subject to the jurisdiction of the US located within the boundaries of a unit, including navigable water and areas within their ordinary reach, below the mean high water mark (or OHW line) without regard to ownership of submerged lands, tidelands, or lowlands. **36 C.F.R. § 5.7** requires NPS authorization prior to constructing a building or other structure (including boat docks) upon, across, over, through, or under any park area.	**Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.8.1** requires NPS to allow natural geologic processes to proceed unimpeded. NPS can intervene in these processes only when required by Congress, when necessary for saving human lives, or when there is no other feasible way to protect other natural resources/ park facilities/historic properties. **Section 4.8.1.1** requires NPS to: - Allow natural processes to continue without interference, - Investigate alternatives for mitigating the effects of human alterations of natural processes and restoring natural conditions, - Study impacts of cultural resource protection proposals on natural resources, - Use the most effective and natural-looking erosion control methods available, and - Avoid putting new developments in areas subject to natural shoreline processes unless certain factors are present.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Upland and Fluvial Processes	**Rivers and Harbors Appropriation Act of 1899, 33 USC. § 403** prohibits the construction of any obstruction, on the waters of the united states, not authorized by congress or approved by the USACE. **Clean Water Act 33USC. § 1342** requires a permit from the USACE prior to any discharge of dredged or fill material into navigable waters (waters of the US (including streams)). **Executive Order 11988** requires federal agencies to avoid adverse impacts to floodplains. (see also D.O. 77-2) **Executive Order 11990** requires plans for potentially affected wetlands (including riparian wetlands). (see also D.O. 77-1)	None Applicable.	**Section 4.1** requires NPS to manage natural resources to preserve fundamental physical and biological processes, as well as individual species, features, and plant and animal communities; maintain all components and processes of naturally evolving park ecosystems. **Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.6.4** directs the NPS to (1) manage for the preservation of floodplain values; [and] (2) minimize potentially hazardous conditions associated with flooding **Section 4.6.6** directs the NPS to manage watersheds as complete hydrologic systems and minimize human- caused disturbance to the natural upland processes that deliver water, sediment, and woody debris to streams **Section 4.8.1** directs the NPS to allow natural geologic processes to proceed unimpeded. Geologic processes…include…erosion and sedimentation…processes. **Section 4.8.2** directs the NPS to protect geologic features from the unacceptable impacts of human activity while allowing natural processes to continue.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Soils	**Soil and Water Resources Conservation Act, 16 USC. §§ 2011 – 2009** provides for the collection and analysis of soil and related resource data and the appraisal of the status, condition, and trends for these resources. **Farmland Protection Policy Act, 7 USC. § 4201 *et. seq.*** requires NPS to identify and take into account the adverse effects of Federal programs on the preservation of farmland; consider alternative actions, and assure that such Federal programs are compatible with State, unit of local government, and private programs and policies to protect farmland. NPS actions are subject to the FPPA if they may irreversibly convert farmland (directly or indirectly) to nonagricultural use and are completed by a Federal agency or with assistance from a Federal agency. Applicable projects require coordination with the Department of Agriculture's Natural Resources Conservation Service (NRCS).	**7 C.F.R. Parts 610 and 611**are the US Department of Agriculture regulations for the Natural Resources Conservation Service. Part 610 governs the NRCS technical assistance program, soil erosion predictions, and the conservation of private grazing land. Part 611 governs soil surveys and cartographic operations. The NRCS works with the NPS through cooperative arrangements.	**Section 4.8.2.4** requires NPS to: - Prevent unnatural erosion, removal, and contamination. - Conduct soil surveys. - Minimize unavoidable excavation. - Develop/follow written prescriptions (instructions).

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

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