Chapter 15
Mid Atlantic Bight and Chesapeake Bay

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This chapter is dedicated to research asst. professor Arthur Schwarzschild (1966–2017) who is best known for his leadership as the site director at Anheuser-Busch Coastal Research Center in Oyster, Va., which is the facility that hosts the Virginia Coastal Reserve Long Term Ecological Research program.

15.1 Migratory Lighthouses

The Mid-Atlantic Bight (MAB) off the East Coast of the United States covers the continental shelf region from Nantucket Shoals in Massachusetts to Cape Lookout in North Carolina. This indentation or concave stretch of changing coastline includes the New York Bight and important estuaries such as Long Island Sound, Great South Bay, Delaware Bay, Chesapeake Bay, and Pamlico Sound. The geography of the MAB is depicted in Fig. 15.1. The Chesapeake Bay is the largest estuary in the United States, extending nearly 321.9 km (200 miles) from the Susquehanna River in the north to its entrance between the Virginia Capes. The Pamlico Sound is the largest lagoon along the North American East Coast, extending 129 km (80 miles) in length and having widths from 24 to 48 km (15–30 miles). Storms resulting in coastal erosion along the MAB include wave developments preceding cyclogenesis, strong cold fronts with associated squall lines, intense cyclones moving northeastward, and hurricanes. The MAB rising sea level,

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which has accelerated during the past few decades in some locations, not only inundates low-lying coastal regions but also contributes to the redistribution of sediment along sandy coasts. Barrier islands respond by migrating landward (Part 2, Chap. 9). The impact is illustrated along the MAB by (1) the erosion observed on barrier islands such as Hatteras Island, NC, and glacial headlands, such as Nantucket Island's Sankaty Head and (2) ongoing engineering efforts required to safeguard the historic Cape Hatteras and Sankaty Lighthouses. While these lighthouses are located at either end of the MAB others such as the historic Montauk Point Lighthouse in New Jersey are also threatened by erosion. The rapidly increasing availability of meteorological and oceanographic data and innovative marine technologies since the 1950s has greatly improved the frequency and accuracy of numerical forecast models and other products that can be directly used to protect property or adapt to sea level rise by moving coastal structures and infrastructure away from unsuitable areas.

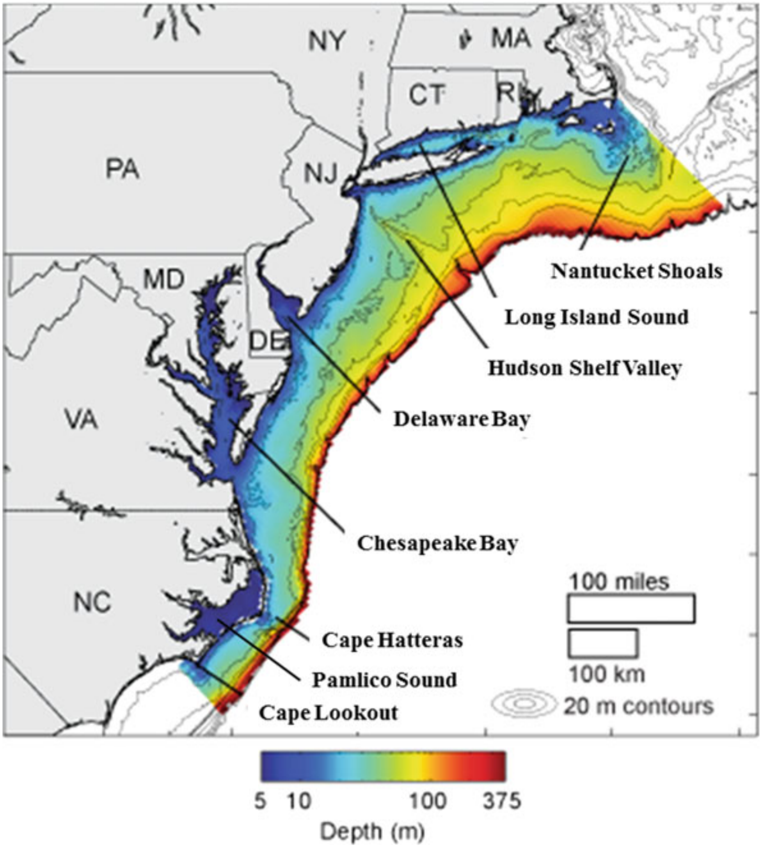


Fig. 15.1 Geography of Mid Atlantic Bight. *Source* U.S. Geological Survey

The first Cape Hatteras Lighthouse was made of sandstone and completed in 1803. Owing to modernization, a new tower was constructed in 1870 and encroachment by the sea required the lighthouse to be replaced by a steel tower in 1935. The beacon was returned to the brick tower during 1950, following considerable accretion of beach material in front of the lighthouse. From the 1960s to the 1980s, efforts were made to stabilize the beach in front of the lighthouse. During March 1980, a winter storm swept away the remains of the 1803 lighthouse and caused significant dune erosion. During September 1999, when the 61-m (200-foot) tall and 5000-ton Cape Hatteras lighthouse was just 4.6 m (15 ft) from the ocean's edge, a well-planned and executed engineering feat resulted in its movement from its original location at the edge of the ocean to a safer location approximately 460 m (1500 ft) from the shoreline. The general contractor International Chimney and Expert House Movers won the 40th Annual Outstanding Civil Engineering Achievement Award from the American Society of Civil Engineers in 1999 for their accomplishment in moving the Cape Hatteras Lighthouse, the tallest masonry structure ever moved.

During the 1850s, Sankaty Light on Nantucket Island was reportedly 85 m (280 ft) from the edge of the bluff. The bluff has reportedly lost an average of 0.9 m (3 ft) a year since 1980, but erosion is episodic. For example, approximately 5.18 m (17 ft) were lost off Sankaty Head after the Perfect Storm, also known as the No-Name Storm, of 1991. This nor'easter absorbed the remnant of Hurricane Grace and ultimately evolved back into a small unnamed hurricane late in its life cycle. With their success in moving the Cape Hatteras Lighthouse, the Buffalo, N.Y.-based company International Chimney was contracted to move the 70-foot-tall, 550-ton Sankaty Lighthouse inland during October 2007, when it was approximately 20 m (66 ft) from the edge of the bluff (Benchley and Felch 2009). The lighthouse was jacked up and slowly moved to its new location approximately 85 m (280 ft) from the cliff along steel rail tracks. In addition to being a historical landmark, Sankaty Light remains an important navigation aid.

15.2 New Jersey to Cape Charles, Virginia

The Intergovernmental Panel on Climate Change, or IPCC (2007), estimates that global sea level will rise from 0.18 to 0.59 m (7–23.23 in.) by the end of the 21st century. As sea level continues to rise along the MAB with the concomitant erosion from tides, waves, and currents, the future of coastal structures such as lighthouses and natural areas such as shorelines is uncertain.

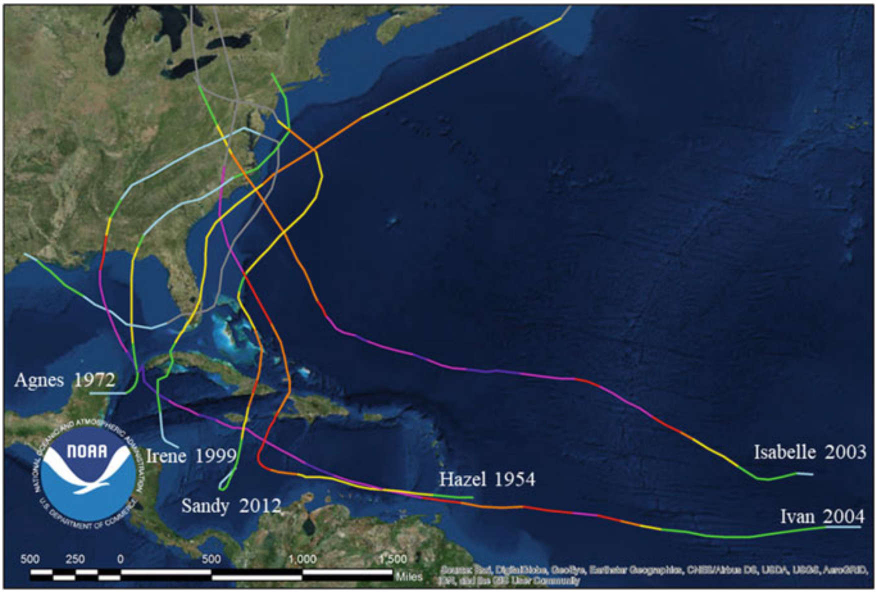
The shoreline is defined as the wider fringe of land that is geologically modified by the action of the ocean past and present. Many coastal residents in places such as Ocean City, New Jersey, and the Eastern Shore of Maryland face recurring flooding, especially during higher high tides or Spring tides and during periods when favorable winds set-up estuarine and coastal waters. The spring tides occur just after a new or full moon, when the gravitational pull of the sun is "added" to the gravitational pull of the moon on Earth. Flooding may also be caused by the combined effects of wind waves, high tides and storm surges in response to fluctuations in local and remote winds and atmospheric pressure. The term ‘surge’ refers to the pile of water pushed ashore by the strong winds. People living along coastal lagoons and estuaries need to be aware of sea-level rise rates. In the Chesapeake Bay, people living on Smith and Tangier Islands are especially susceptible to the impacts of sea level rise.

Many of the Chesapeake Bay islands have been shrinking in size for centuries, due to a combination of their low elevation, lack of rock substrate, land subsidence, storm erosion, and man-made factors, such as dredging channels through the marsh. Langland and Cronin (2003), report sediment accumulations of 25–30 m (82–98 ft) in some parts of the Bay. Further, land subsidence in some parts of the Chesapeake Bay region is caused by the pumping of ground water from unconsolidated sediment (Eggleston and Pope 2013). In order to be resilient to flooding, some coastal communities spend many millions of dollars on dredging, building new structures, such as elevated roads, and making improvements to drainage systems and pumping stations. Smith Island, located 19.3 km (12 miles) west by water from Crisfield on the Maryland Eastern Shore, was particularly devastated in 2012 by Hurricane Sandy. Residents formed the group Smith Island United to fight efforts by the State of Maryland to buy up and demolish homes that were impacted by hurricane storm surge. Smith Island United, in concert with various private and public partners, has developed plans to be resilient against future storms and eroding land. Other communities are adapting by introducing flood protection schemes that integrate habitat restoration with traditional measures, e.g., developing wetlands that store floodwaters, planting woodlands to slow flash floods, and restoring rivers to hold more water.

15.3 Rising Sea Level Along the Maryland and Virginia Chesapeake Bay Shoreline

Numerous investigators (e.g., Cronin 2005; Curtin et al. 2001; Pritchard 1951, 1952a, b, 1955; Ward et al. 1989; White 1989) have characterized physical features common to the Chesapeake Bay, a semi-enclosed body of water partially protected from the open sea, referred to as a “Type II” (moderately stratified) estuary (Pritchard 1951). Marine scientists classify the Chesapeake Bay as a drowned river valley estuary and have studied its response to notable storms such as Hurricanes Hazel (1954), Agnes (1972), Irene (1999), Isabel (2003), Ivan (2004), Sandy (2012). The area of land that drains into Chesapeake Bay includes parts of Delaware, Maryland, New York, Pennsylvania, Virginia, West Virginia, and Washington D.C. This area, known as the Delmarva Peninsula, is especially affected by cyclones that brush the East Coast. Central and Western Maryland, as well as Washington, D.C., commonly receive rainfall from the remnants of storms that make landfall elsewhere and track northward. These episodic events, which are detailed in Fig. 15.2, directly contribute to flooding and geomorphological changes such as shoreline erosion and shifting channels. As illustrated in Fig. 15.3, the Chesapeake Bay includes major tributaries such as the Susquehanna, Potomac, Rappahannock, York and James rivers, and more than 100,000 streams, creeks and rivers. The bay and its tidal tributaries include about 18,803.6 km (11,684 miles) of shoreline and have depths averaging 6.4 m (21 ft) along with deep holes that are up to 53 m (174 ft) deep.

Physical processes in the MAB, such as sea level rise, greatly influence the life cycles of marshes, submerged aquatic vegetation (SAV), marine birds, shellfish, and fish. Along with natural and anthropogenically influenced processes, sea level rise contributes to coastal erosion, driven by the movement of beach materials. Atmospheric and oceanic weather, such as El Niño, storms, winds, tides, currents, waves, and storm surges, are major factors in coastal erosion, which can be quantified by geophysical surveying and remote sensing. Discharge from rivers and water movement due to the astronomical tides also produces coastal erosion as evidenced by the sediment plumes that are depicted in Fig. 15.3. Solid particles



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Fig. 15.2 Tracks of hurricanes causing wind damage and severe flooding along the Chesapeake Bay. Numerous investigators (Blankenship 2004; Chesapeake Research Consortium, Inc. 1976; Horowitz et al. 2014; Smith 2014; and Wang et al. 2015) describe the impacts that these extreme events have caused on the Bay's rivers, wetlands, forests, and coastal communities. Tropical cyclones traversing the MAB tend to move toward the west-northwest, which brings the hurricane into the vicinity of the East Coast of the U.S. The hurricane tracks were obtained from the NOAA National Hurricane Center (see http://www.nhc.noaa.gov or https://coast.noaa.gov/hurricanes/)

Fig. 15.3 In Maryland, the National Weather Service reported rainfall totals of 613 mm (24.13 in.) in Largo, 609 mm (23.98 in.) in Forrestville, and 546 mm (21.49 in.) in Forest Heights

from eroding river banks, drainage from construction sites, and agricultural runoff are entrained in rivers such as the Susquehanna and are transported into the Chesapeake Bay. Aside from sea level rise and other natural processes, humans have contributed to coastal erosion by altering coastline transport processes with dams, groins, and jetties, which impact the supplies of sand to the shorelines.

Long-term environmental data are made available through sensors that comprise capabilities such as the National Water Level Observation Network, the U.S. Army Corps of Engineers Field Research Facility at Duck, N.C., Physical Oceanographic Real-Time Systems, and the Chesapeake Bay Interpretive Buoy System. Data from these networks indicate that water levels are rising along the North American coast due to climatic changes that expose more and more of the coastline to wave action (Sweet et al. 2017). The Chesapeake Bay's wetlands safeguard natural services of the coastal ecosystem and the temperate climate offers a fertile and diverse environment for waterfowl such as mallards (*Anas platyrhynchos*), black ducks (*Anas rubripes*), canvasbacks (*Aythya valisineria*), and redhead ducks (*Aythya americana*). Winds and rains can cause high sea states and currents that uproot bay grasses. These same SAV beds that contain species such as eelgrass (*Zostera marina*) and Widgeon grass (*Ruppia maritima*), provide food and habitat for many species of waterfowl on their migration from summer breeding grounds. The beds provide a refuge from predators for finfish such as spot (*Leiostomus xanthurus*), croaker (*Micropogonias undulatus*), and juvenile striped bass (*Morone saxatilis*). The Bay grass beds are also important for grass shrimp (*Palaemonetes pugio*) and blue crabs (*Callinectes sapidus*), especially after molting. These wetlands provide an important natural buffer for storms by temporarily storing floodwaters and filtering pollutants. Shorelines that lack adequate wetlands, beaches, and oyster reefs are highly vulnerable to forces generated by sea level rise, waves, tides, and other shallow water processes. People living in flood prone areas that lack buffers have to contend with recurring floods that enter front yards and garages, overtop docks, clog storm drains, block streets, and damage lawns and trees.

Sea level rise exacerbates the vulnerability of infrastructure to flooding from storm surges along the MAB. In the Chesapeake Bay region, port facilities, coastal roads, pipelines, and other important structures in Maryland and Virginia are especially susceptible to storm surge. Locations of recurring floods include Hampton Roads and the heavily traveled US 17 coastal highway. Flooding caused by hurricanes, tropical storms, and nor'easters occurs as a result of elevated water levels from atmospheric pressure changes and favorable wind directions associated with storm passage. Coastal communities also face flooding when sea level rise is compounded by semi-monthly spring tides, which increases coastal erosion and the weathering of roads. Wave action associated with storm surge has been responsible for the removal of beach and dune sediments in places such as Virginia Beach. One of the often overlooked dangers to motorists driving on previously flooded roads is that the inundation reduces the bearing strength of the pavement by allowing water to get into the underlying layers. This is evidenced by numerous ruts, cracks, and potholes.

There are many physical processes contributing to long and short-term variations in Chesapeake Bay water levels. Short-term variations that occur on a daily basis include waves, tides, or episodic flood events, such as those associated with winter snow melt, hurricanes or coastal storms. The majority of the Chesapeake Bay has a semidiurnal tidal period and harmonically predicted tides are made possible by a long-term water level observation network that includes more than 20 stations, which are maintained by NOAA. Areas that experience tides have two high and low waters and accompanying ebb and flood tidal currents per day in response to astronomical forces. The tidal day is 24 h and 48 min long and is the reason why tides arrive one hour later each solar day. For some species such as horseshoe crabs (*Limulus polyphemus*), spawning activities occur in synchronization with the full moon and spring tides. Currents caused by tides, winds, rains, and differences in water levels are responsible for the transport of passive drifters such as plankton, seeds, and fish larvae. Longer-term processes may occur over time scales ranging from months to several years, and may present as repeatable cycles, gradual trends, or intermittent anomalies. Seasonal weather patterns, variations in the Earth's declination, changes in Gulf Stream circulation (Ezer et al. 2013), anthropogenic influences (such as dredging), vertical land motion, and the El Niño Southern Oscillation are just a few examples of long-term fluctuations. When estimating sea level trends, a minimum of 30 years of data should be used in order to account for long-term sea level variations and to reduce errors in computing sea level trends based on monthly mean sea level. Accounting for repeatable, predictable cycles, such as tidal, seasonal, and interannual variations allows for computation of a more accurate long-term sea level trend. Changing sea levels have been documented by the Coast and Geodetic Survey, as evidenced by Fig. 15.3, which depicts historic seasonal to inter-annual cycles of sea level in the MAB area using a low-pass filter on NOAA water level records.

NOAA tide stations that measure Local Sea Level, which refers to the height of the water as measured along the coast relative to a specific point on land, are critical to understanding long term changes in sea level. According to Cooper (2016), the Eastern Shore is the third most vulnerable area to flooding behind South Florida and Louisiana. As indicated by 20th century water level records in Fig. 15.4 and references such as Cronin (2005), Maryland residents have been coping with rising sea levels and shoreline erosion for many years. The combination of sinking lands and rising sea levels has significantly eroded previously inhabited islands such as Holland Island in the Chesapeake Bay. Holland Island, which once supported a community with approximately 60 homes, a church and other buildings, was abandoned in 1922. The island, which has receded into the Bay, was located in the Holland Strait between South Marsh Island on the south and Bloodsworth Island and other smaller uninhabited low marshy islands on the north. Figure 15.5 is a

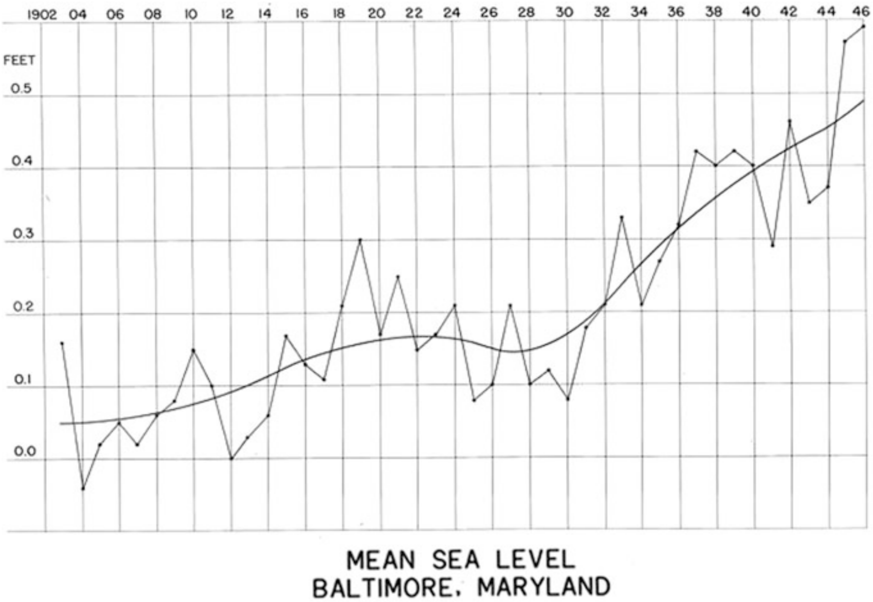


Fig. 15.4 A historic graph showing the rise in sea level in Baltimore, which includes water level fluctuations caused because the underlying land is falling with respect to the sea surface. Data from 1902 through 1946 were obtained through C&GS tide gage observations (courtesy NOAA Photo Library)

Fig. 15.5 The last house on Holland Island, which was built in 1888, collapsed into the Bay in October, 2010. This photograph of the Holland Island, which is barely discernible today, was taken on November 9, 2008 (courtesy of the Chesapeake Bay Foundation, Photo by Chuck Foster)

picture of the remaining house on Holland Island before its total collapse in October 2010. Schulte et al. (2015) hypothesizes that Tangier Island, which is located in Virginia, will have to be abandoned prior to 2100. Neighboring Smith Island residents who have been reported to say, “we live in the water,” highlight the fact that people will fight to defend the places they call home. These islands have a rich history dating back to the earliest European explorers and remain important sites for marine archaeology and anthropology.

15.4 Human Intervention

Effective solutions for shoreline protection rely on a complete understanding of the physical, financial, government permitting, and policy environments. Built-up areas that are subject to coastal erosion are expensive to protect. Most shore protection structures (e.g., jetties and sea walls) are eventually undermined and broken apart by waves. Therefore, when possible, it makes sense to allow coastal erosion to continue and to site new structures far enough back from the shoreline, dunes, or banks to minimize the need for shore protection structures. Climate change will

Fig. 15.6 Following hurricane sandy, the U.S. Army Corps of Engineers replaced roughly 6.1 million m^3 (8 million $yards^3$) of sand to repair and restore engineered beaches along the Atlantic coast of Monmouth County, NJ (courtesy of U.S. Army Corps of Engineers)

accelerate sea-level rise and erosion of beaches and necessitate building rock defenses against coastal erosion. For example, the Monmouth Seawall was heavily damaged by Hurricane Sandy after the "superstorm" made landfall in Brigantine, New Jersey on October 29, 2012. The National Weather Service reported storm surge of up to 3.35 m (11 ft) along the New Jersey Shore with wave heights in excess of 4.27 m (14 ft). Portions of the seawall have been rebuilt and new additions to the wall are being planned as indicated in Fig. 15.6. Data collected during storms such as Hurricane Sandy have been used to improve the accuracy and resolution of numerical modeling of storm effects. The ensuing street-scale forecasts have proven to be especially useful to urban planners. Blumberg et al. (2015) developed a hydrodynamic model to accurately describe Sandy's flooding along the urban coastal waters in Hoboken, New Jersey. Other solutions for shoreline protection include control of ground water pumping and development of surface water to offset the reductions of ground water pumping. Ground water recharge has also been practiced in some locations threatened by subsidence.

15.5 Wetlands Restoration

Human interactions such as heavy land development have been blamed for declines in some of the more than 3600 species of plants, fish, and animals that inhabit the Chesapeake Bay. As an example, runoff from the watershed can pick up pollutants such as nutrients, sediment, and chemical contaminants. The ensuing siltation blocks sunlight from reaching SAV beds and smothers oyster reefs, causing problems for feeding and the settling of new larvae on old shell material. Commercial, residential, and recreational development along the coast has reduced favorable habitat of the piping plover (*Charadrius melodus*), which prefers wide, flat, open, sandy beaches with very little grass or other vegetation. Besides high turbidity from siltation, diseases and invasive species have contributed to declines in sea grasses. Other factors such as the parasites MSX (*Haplosporidium nelsoni*) and Dermo (*Perkinsus marinus*), overharvesting, and loss of habitat are contributing to declines in Eastern Oyster (*Crassostrea virginica*) populations.

Programs have been implemented in the MAB to help improve water quality, prevent overfishing and reopen spawning grounds. Restoration of SAVs benefits through nitrogen removal (e.g., Reynolds et al. 2016) and oyster restoration benefits by helping to stabilize and raise shorelines (e.g., La Peyre et al. 2014). Organizations such as the Maryland Department of Natural Resources, Chesapeake Bay Foundation, and the Oyster Restoration Partnership are working to re-establish once flourishing SAV beds and oyster reefs. The reduced loading of nutrients is now contributing to a marked expansion of SAV beds throughout the Chesapeake Bay. Table 15.1 provides an example list of selected rivers and SAV species that are responding well to restoration efforts. Restoring native oysters, planting underwater grasses, and planting trees and stream buffers helps to restore the Bay's natural filters. For example, eelgrass (*Zostera marina*) with their long, ribbon-like leaves

Approximately 20 species of Chesapeake Bay marine and freshwater SAVs grow into impressive beds and provide important ecosystem services such as habitat and protection for fish, crustaceans, and mollusks. In recent years, SAVs have made an unprecedented recovery owing to restoration efforts. Some selected examples by river and species are listed below

Tributary	Common Name	Scientific Name
James River	eelgrass	*Zostera marina*
Magothy River	widgeon grass	*Ruppia maritima*
Patapsco River	wild celery	*Vallisneria americana*
Patuxent River	eelgrass	*Zostera marina*
Potomac River	eelgrass	*Zostera marina*
Rappahannock River	eelgrass	*Zostera marina*
Severn River	widgeon grass	*Ruppia maritima*
South River	sago pondweed	*Stuckenia pectinata*
Susquehanna River	wild celery	*Vallisneria americana*
York River	eelgrass	*Zostera marina*

that grow in the saltier waters of the middle and lower Chesapeake Bay, absorb CO_2 through photosynthesis. As generations of oysters settle on top of each other, they sequester carbon from the water column as they form calcium carbonate shells. The benefit of restored reefs is structured habitat for many fish species and crabs and a natural water-cleansing system, filtering the estuary's entire water volume of excess nutrients on the order of weeks rather than today's rate of more than a year. Restored SAV beds and oyster reefs help to prevent ocean acidification since they are carbon sinks that absorb carbon dioxide.

15.6 Chesapeake Bay Management

Many government agencies and industries are working to safeguard the Chesapeake Bay. As an example, the Environmental Protection Agency (EPA), the National Oceanic and Atmospheric Administration (NOAA) and the Department of Defense spend millions for restoration projects in the Chesapeake Bay watershed. EPA programs include (1) air and water pollution control, (2) toxic substances, pesticides and drinking water regulation, (3) wetlands protection, (4) hazardous waste management, (5) hazardous waste site cleanup, and (6) some regulation of radioactive materials. Activities include compliance and enforcement, inspection, engineering reviews, ambient monitoring, analysis of environmental trends, environmental planning, pollution prevention, risk assessment, and education and outreach. NOAA provides services ranging from protecting lives and property through the distribution of meteorological, hydrographic, and oceanographic information to evaluating the status and trends in stressed fisheries such as Menhaden (*Brevoortia tyrannus*). Military bases, such as the United States Army's Aberdeen Proving Grounds and the United States Navy's Naval Surface Warfare Center, Dahlgren Division, have exemplified principles of stewardship through compliance with the National Environmental Policy Act of 1969. This Act, which is generally called "NEPA," requires U.S. Federal agencies to consider environmental effects that include, among others, impacts on social, cultural, and economic resources, as well as natural resources.

Since 1983, governors from Maryland, Virginia, and Pennsylvania, along with the mayor from the District of Columbia have sponsored a Chesapeake Bay Program that reflects a shared vision for the restoration and protection of the Chesapeake Bay, one of our nation's most wonderful natural resources. The Chesapeake Bay Program is officially managed by EPA and staff from a number of federal and state agencies, non-profit organizations, and academic institutions that comprise the Chesapeake Bay Program Office. Restoration efforts sponsored by the Chesapeake Bay Program have shown that the development of intertidal oyster reefs near shorelines protects against erosion and could possibly help keep up with sea level rise. These kind of living shoreline techniques are also being applied by others in the MAB region to help stabilize coastlines, improve water quality, and reduce recurring floods and erosion. This type of green infrastructure utilizes natural materials such as plants, sand, or rock and possibly offshore sills or reefs to stabilize the shoreline.

15.7 Virginia Beach to Cape Lookout

Coastal lagoons, such as Long Island and Pamlico Sound that are connected to the sea through inlets, are common along the MAB. Numerous authors (Barnes 1980; Kjerfve and Magill 1989; FitzGerald et al. 2008; Carrasco et al. 2016) have described the formation of these estuaries as the result of rising sea level during the Pleistocene or Holocene epoch and the building of coastal barriers by marine processes. Sea level rise may contribute to the conversion of marshes to open water and increasing flows through coastal inlets. These inlets provide important commercial and military navigation links and may be spanned by bridges or crossed by ferry. These shallow estuaries are productive ecosystems and are a vital nursery area for many species from different taxa. They provide recreational opportunities for the nation and assets for the economic strength of coastal communities. Lagoons are also vulnerable to anthropogenic influences such as increased nutrient loads because of land use change, alterations to freshwater inflows and modification to tidal flushing regimens. On longer time scales, sea level rise causes changes in the exchange of water occurring between the shallow lagoon and the sea because of tides, river flow, wind, and waves. This contributes to sand sequestration in tidal deltas and erosion of adjacent barrier shorelines.

Research sites such as the Virginia Coast Reserve (VCR) provide long-term data to study coastal lagoons that extend for 110 km (63 mi.) along the Atlantic shore of the Delmarva Peninsula (e.g., Callahan 1984; Hayden et al. 1991). Erosion along coastal lagoon shorelines that includes barrier islands along what is now part of the VCR required the decommissioning and demolishment of Hog Island Light in 1948. The site where the lighthouse once stood is now nearly 1.6 km (1 mile) offshore. The VCR Long Term Ecological Research (LTER) program includes an archive of historic information, long-term data sets from sensors that provide access to real-time observations, various types of high-resolution imagery, experimental data on marshes, coastal bays and barrier islands, and numerical model output. Fundamental research at the VCR has included the integration of these data to achieve new levels of understanding on ecological systems such as SAV beds, salt marshes, and barrier islands and processes such as shoreline retreat and resilience to climate change. These data support research that has been focused on succession, disturbance, and system-state change and helps address management questions about what resources should to be protected, saved or conserved. VCR LTER contributions include large seagrass restoration and monitoring projects that can be applied by others (Orth and McGlathery 2012; McGlathery et al. 2012; Moore et al. 2014). The VCR LTER has also demonstrated the importance of educating society on climate changes through outreach and education activities that have included the full spectrum of students from elementary school to university to life-long learners.

The North Carolina Outer Banks consist of low, sandy barrier islands including Cape Hatteras National Seashore, Cape Lookout National Seashore, and Pea Island National Wildlife Refuge. The origin of the Outer Banks is likely to have been from coastal deposition and erosion along the drainage divides between late Pleistocene river valleys. This would be the geological epoch with repeated glaciations which lasted from about 2,588,000 to 11,700 years ago, also commonly called the Ice Age. The barrier island segments along the Outer Banks provide the seaward boundary of a system of large, ecologically important sounds. The Pamlico Sound is connected to the north with Albemarle Sound through passages provided by the Roanoke Sound and Croatan Sound. Core Sound is located at the Pamlico Sound's narrow southern end. Today, it is fed by the Neuse and Pamlico Rivers from the west and by the Atlantic Ocean through Oregon, Hatteras, and Ocracoke Inlets. Inman and Dolan (1989) report shoreline retreat rates along the Outer Banks to be around 1.58 m/year (5.2 ft/year). Sea level rise has caused significant loss of both wetlands and uplands at the estuarine water-land interface. Further, wave climate and longshore transport causes these barrier island inlets to migrate in a southerly direction. The process involves development of distal bar through deposition and erosion of the downdrift shore owing to the longshore current (Nichols and Williams 2009).

The cuspate forelands that comprise the Carolina coast include three major capes, Cape Hatteras to the north, Cape Lookout, and Cape Fear to the south. The formation of these capes has been attributed to the Gulf Stream, wave climate, and longshore currents. The barrier islands along the North Carolina coast are separated by coastal inlets. Most of the tidal inlets form as a result of severe storms and the passages remain open owing to the to-and-fro motion of tidal currents. Tidal inlets have played a major role in the development and maintenance of the Outer Banks. Along the Banks, three to eleven tidal inlets have cut through the barriers islands over the historical record (Stick 1958). These tidal inlets provide a connection between the ocean and bays, lagoons, marshes, and tidal creek systems. Passages such as Oregon Inlet are very important for species that travel from the ocean to estuarine areas and back and navigation by vessels from the sounds to the coastal ocean supports maritime commerce. The North Carolina Department of Transportation runs a ferry system to cross Currituck and Pamlico Sounds, and also the Cape Fear, Neuse, and Pamlico Rivers. When bridges are damaged due to storms such as Hurricanes Irene and Sandy, the ferry system provides a crucial transportation link between the barrier islands and the mainland.

Coastal inlets provide a migration path for fish larvae spawned on the continental shelf that need to return to nursery areas in the coastal lagoons. Wind drift currents facilitate the shoreward transport of fish larvae to the littoral zone, where longshore currents and associated breaking waves should facilitate their movement toward the inlets. Fry then aggregate near the inlet plume front as a result of stimuli such as olfactory cues and high turbidity until they are transported inland on flood tides. Subtidal frequency flood currents are known to jet oceanic water laden with young fish into the Pamlico Sound estuary via Oregon Inlet in related pulses. These exaggerated flood currents are caused by the set-up of water on the ocean side of the barrier islands, which also helps to retain the fry in the sounds. The hydraulic currents resulting from these seaward pressure heads that form during periods of favorable longshore winds drives water from the ocean to the sounds.

Inlets are also regions of mixing for freshwater from land drainage and salty ocean waters. Inlets that close in response to sediment transport may reduce the salt content for organisms living in the back bay. Estuarine organisms have different tolerances and responses to salinity changes. While species such as Eastern Oysters, Bay Scallops (*Argopecten irradians concentricus*) and Blue Crabs (*Callinectes sapidus*), can tolerate some change in salinity, decreased salinities beyond an acceptable range will negatively affect their growth and reproduction, and ultimately, their survival. Further, sea level rise has caused significant loss of wetland and upland habitats at the estuarine water-land interface.

Fishermen from Manteo and Wanchese, two towns on Roanoke Island, navigate through Oregon Inlet to reach fishing grounds on Diamond Shoals, also known as the Graveyard of the Atlantic. The Herbert C. Bonner Bridge, which spans Oregon Inlet, was built in 1963 and is being replaced with a new bridge to better withstand environmental loads (wind, waves, currents) and provide improved options for navigation under the bridge. For many years, watermen and local government officials lobbied for construction of twin jetties that would theoretically stabilize the inlet by blocking sand traveling along the shoreline from entering the inlet. In 1970, Congress approved a $108 million jetty project, but failed to provide construction funds. However, the Departments of the Interior and Commerce both maintained that the twin jetty project should be rejected in favor of dredging alternatives owing to environmental impacts. For example, the National Marine Fisheries Service opposed the jetties because of unresolved issues regarding the blocking of migration routes for marine fish larvae that are carried by natural currents through the inlet to estuarine nursery areas. In 2002, the White House Council on Environmental Quality announced that the jetty project was not warranted. Instead, the federal government promised Dare County and North Carolina that maintenance dredging would be accomplished to maintain a navigable tidal inlet. Navigation through Oregon Inlet, North Carolina is only recommended during good weather and calm seas.

Wave climate contributes to the southward migration of inlets found in North Carolina's Outer Banks, which is a process vital to the health of the barrier islands. Breaching of barriers by tidal inlets allows for the buildup of flood shoals on the bay side of a barrier island that increases the width of the island and provides a platform for further increase in the elevation of the barrier island superstructure and source for sand dune generation. When left to nature, tidal inlets open, migrate, add sediment to the barrier system, and then eventually close as new inlets open at other locations and capture the tidal drainage. When inlets are stabilized, as in the case of Rudee Inlet, Virginia, unintended consequences may occur, including prolonged interruption of littoral sediment supply and erosion of downdrift beaches. Rudee Inlet is located about 122 km (76 miles) to the north of Oregon Inlet.

15.8 With an Eye Toward Marine Policy

The rising population in the coastal zone is a modern phenomenon, which requires the reduction of coastal risks. Today there are many more hotels, restaurants, and shopping centers located along the shoreline than during the 1950s. This development has not always considered the impact of sea level rise and recurring storm events, which may cause major damage. Without doubt, the first step must be for the scientific community to raise awareness of coastal vulnerabilities and the value of science in understanding it. Also important is developing a broad appreciation of the notion of resilience to improve development patterns and principles. Organizations such as the Southeastern Universities Research Association (SURA) have promoted a coastal resilience workshop series to focus on essential elements such as a quantitative understanding of local erosion rates, predictions of shoreline positions for various sea-level rise scenarios, costs to maintain the shoreline in a fixed position, and increased vulnerability of beaches to storms with a rising sea level (Wright et al. 2016). Further, SURA has been instrumental in managing the development of the Coastal and Ocean Modeling Testbed (Luettich et al. 2013). This testbed has been developed to assess state-of-the-art numerical models of storm surge, wave, and coastal flooding which are needed to provide hindcasting of past hurricanes, provide real-time forecasting of current hurricanes and assess future flood risks. One recent advance in numerical modeling that has been demonstrated by this testbed is the coupling of wave models such as Simulating WAves Nearshore or SWAN that computes random, short-crested wind-generated waves with traditional models used by NOAA, such as the Sea, Lake and Overland Surges from Hurricanes (SLOSH) model that was developed by the National Weather Service to estimate storm surge heights resulting from historical, hypothetical, or predicted hurricanes. Luettich et al. (2017) demonstrated that an ensemble mean of multiple models has a higher skill predicting hypoxia than any individual model in the Chesapeake Bay. Since there are numerous numerical models with different model physics and numerics, a testbed helps organizations such as NOAA identify the best approach to ensuring a weather-ready nation.

Dynamic coastal environments can change dramatically across a range of temporal and spatial scales in response to natural processes and human modifications. Rebuilding expensive structures and homes in vulnerable areas such as flood plains located along the MAB is not sustainable. Current flood insurance policies are not in synchronization with environmental factors such as current and projected sea level rise (Dennis 2017). Today's policy makers have competing interests as they work to recover from coastal inundation, and hyperbolic and partisan rhetoric has done little to foster free public discussion of the issues without rancor and finger pointing. Short term economic gains are a critical factor in decisions as to whether a community should restore and rebuild what has been damaged by shoreline retreat rates rather than to cede to the erosion that even faces historic landmarks such as the Sankaty Head and Cape Hatteras lighthouses. However, in the case of these lighthouses, recurring nor'easters and hurricanes put these structures in imminent jeopardy of being beyond the municipality's fiscal and engineering capabilities to save. As climate change causes more intense storms, surges, and higher sea levels in areas such as the Chesapeake Bay (Boesch et al. 2013), coastal communities can respond by (1) mapping floodplains and identifying land areas less than 1.5 m (5 ft) above mean sea level, (2) identifying impacts on structures occurring during spring tides (e.g., how high the water, waves and debris reach), (3) controlling storm-water runoff to prevent erosion (e.g., plant native plants to reduce erosion and flash floods), and (4) ensuring a resilient shoreline that acts as a buffer from storm surge and waves (e.g., living shorelines that include tidal wetland vegetation). Tomorrow's coast will require new flood insurance policies with provisions to buy and destroy or move properties that are associated with repetitive claims.

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