Part I Overview: The Physical Environment

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The first part of this report examines the physical and environmental impacts of sea-level rise on the natural environments of the mid-Atlantic region. Rising sea level over the next century will have a range of effects on coastal regions, including land loss and shoreline retreat from erosion and inundation, intrusion of saltwater into coastal freshwater aquifers, and an increase in flooding frequency and storm-surge elevation from coastal storms (Williams *et al.*, 1991; Morton, 2003). The sensitivity of a coastal region to sea-level rise depends both on the physical aspects (shape and composition) of a coastal landscape and also the ecological setting. One of the most obvious impacts is that there will be land loss as coastal areas are inundated and eroded. On a more detailed level, rising sea level will not just inundate the landscape but will be a driver of change to the coastal landscape. These impacts will have large effects on human development in coastal regions (see Part II of this report) as well as effects on natural environments such as coastal wetland ecosystems (Williams, 2003). Making long-term predictions of coastal change is difficult because of the multiple, interacting factors that contribute to that change. Given the large potential impacts to human and natural environments, there is a need to improve our ability to conduct long-term predictions.

Part I of this report describes the physical settings of the mid-Atlantic coast as well as the processes that influence shoreline change and land loss in response to sea-level rise. Part

I also provides an assessment of shoreline changes that can be expected over this century as well as the consequences of those changes on coastal habitats and the important flora and fauna they support. Chapter 1 provides a rough estimate of the extent of low-lying lands that may be at risk from future sea-level rise. There are, however, many limitations to this approach since sea-level rise will not only inundate the coastal landscape but also cause changes to coastal landforms and ecosystems. Also, even predicting the extent of inundation is uncertain due to limitations of the existing topographic data in the coastal zone. Chapter 2 provides an assessment of the impacts of sea-level rise on the coastal landforms of the Mid-Atlantic, such as beaches and barrier islands that make up the ocean coast of the Mid-Atlantic, in order to identify some of the factors and processes that influence their behavior. Chapter 3 provides an assessment of the vulnerability of coastal wetlands to future sea-level rise. Chapter 4 reviews the potential impacts of sea-level rise on coastal habitats and species within this region.

I.1 COASTAL ELEVATIONS

Chapter 1 summarizes available information on coastal land elevations for the mid-Atlantic region in order to identify and estimate the extent of land area threatened by future sea-level rise. These coastal elevation data are also used to estimate the land potentially available for wetland migration in response to sea-level rise, and the sea-level rise impacts to the human built environment (see Chapter 6).

I.2 OCEAN COASTS

Chapter 2 summarizes the factors and processes controlling the dynamics of ocean coasts. The major factor affecting the location and shape of coasts at centennial and longer time scales is global sea-level change, which is linked to the Earth's climate. These close linkages are well documented in the scientific literature from field studies conducted over the past few decades (*e.g.*, Muhs *et al.*, 2004; Kraft, 1971; Carter and Woodroffe, 1994). The details of the process-response relationships, however, are the subject of active, ongoing research. The general characteristics and shape of the coast (coastal morphology) reflects complex and ongoing interactions between the physical processes that act on the coast (hydrodynamic climate – *e.g.*, waves and tidal characteristics), the availability of sediment (sediment supply) transported by waves and tidal currents at the shore, and the geological substrate on which the coast is situated (geological framework). Variations in these three factors are responsible for the different coastal landforms and environments occurring in the coastal regions of the U.S.

A range of coastline types can be identified along the coastline of the continental United States including cliff or bluff shorelines, sandy shorelines, wetland shorelines, coral reef shorelines, and mudflat shores (Walker and Coleman, 1987). The majority of the U.S. coast consists of sandy shores. Wetland coasts occur intermittently mainly on the west coast of Florida and along the Louisiana coast. Wetlands also occur extensively on the inner coasts along bays and estuaries, especially on the Atlantic coast. Coral reefs occur in tropical waters in south Florida, Hawaii, Puerto Rico and the Virgin Islands. Muddy shores occur predominantly along the Louisiana and the northeastern coast of the Gulf of Mexico in Florida.

The mid-Atlantic coast of the United States is primarily composed of barrier islands, with intervening stretches made up of coastal headlands and coastal spits (See Chapter 2). Many of these barrier islands front coastal lagoons which commonly harbor coastal wetlands and are host to a range of species. In addition, the gentle slope of the Atlantic margin is characterized by incised river valleys that are lined with many low-lying areas, diverse shoreline settings, and extensive coastal wetlands. Chapter 2 considers the effect of rising sea level on the mid-Atlantic open coast settings.

I.3 WETLAND SUSTAINABILITY

Chapter 3 describes the vulnerability of coastal wetlands in the mid-Atlantic region to current and future sea-level rise. The fate of coastal wetlands in the Mid-Atlantic are determined in large part by the way in which wetland vertical development processes change with climate drivers. Chapter 3 identifies the important climate drivers affecting the vertical development of wetlands in the mid-Atlantic region. In addition, the processes by which wetlands build vertically vary by geomorphic setting. Thus, Chapter 3 examines wetland responses to sea-level rise for five primary geomorphic settings with several sub-settings for the coastal wetlands of the Mid-Atlantic, based on a geomorphic classification developed by Reed *et al.* (2008):

- Tidal Fresh Forests (FF)
- Tidal Fresh Marsh (FM)

- Estuarine/Brackish Channelized Marshes (ES)
    - Meander
    - Fringing
    - Island
- Back Barrier Lagoon Marsh (BB)
    - Back barrier/Other
    - Active flood tide delta
    - Lagoonal fill
- Saline Marsh Fringe (SF)

FF and FM are distinguished based on vegetative type (forested vs. herbaceous) and the salinity of the area. ES marshes are brackish and occur along channels rather than open coasts. ES Meander marshes would be those bordering meandering tidal rivers while ES Fringing are those bordering wider open channels where tidal flow is not focused in a specific thalweg. ES Island marshes are, as the term implies, marsh islands within tidal channels. BB marshes occupy fill within transgressive back barrier lagoons. Where the fill is attached to barrier islands, the marshes are Back Barrier/Other, and Flood Tide Deltas are marshes forming landward of tidal inlets. Lagoonal fill is frequently abandoned flood tide deltas where the inlet is closed and marsh is not supplied with sediment directly from the inlet. SF marshes are transgressive salt marshes bordering uplands, mostly on the landward side of tidal lagoons.

The information on climate drivers, wetland vertical development, and geomorphic settings, combined with local sea-level rise trends, was synthesized and assessed using an expert decision process to determine wetland vulnerability for each geomorphic setting in each subregion of the mid-Atlantic region.

I.4 IMPACTS ON PLANTS AND ANIMALS

Chapter 4 summarizes the potential impacts to biota as a result of habitat change or loss driven by sea-level rise. Habitat quality, extent, and spatial distribution will change as a result of shore erosion, wetland loss, and shifts in estuarine salinity gradients. Of particular concern is the loss of wetland habitats and the important ecosystem functions they provide, which include critical habitat for wildlife, the trapping of sediments, nutrients, and pollutants, the cycling of nutrients and minerals, the buffering of storm impacts on coastal environments, and the exchange of materials with adjacent ecosystems.

PART I OVERVIEW REFERENCES

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Chapter 1. Coastal Elevations

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KEY FINDINGS

The lands that could be inundated by rising sea level include tidal wetlands, nontidal wetlands, and dry land. While the shores of the Mid-Atlantic are composed mainly of sandy beaches which respond to sea-level rise by a combination of erosion and inundation, identifying and quantifying the low-lying land the Mid-Atlantic is critical to addressing the risk posed by future sea-level rise. The low-lying land in the mid-Atlantic region includes more than 5000 km^2 of tidal wetlands.

- The elevation data currently available for the mid-Atlantic region have been collected from a variety of sources over the past several decades and consequently are of variable vertical resolution and horizontal accuracy. Thus, with the exception of high-resolution data (*e.g.*, lidar), the data can only be used for generalized depictions of low-lying land vulnerable to sea-level rise.
- Based on an analysis of existing data approximately 900-2100 km^2 (350-800 mi^2) of dry land, half of which is in North Carolina, is within 50 cm (20 in) above spring high water.
- For a larger rise, the amount of vulnerable dry land is roughly proportional to elevation, although the percentage uncertainty is somewhat less. For example, 4900-6500 km^2 of dry land are within 200 cm above spring high water.

- Including dry land and nontidal wetlands, the Mid-Atlantic has 5,500-7,500 km^2 of land within one meter above spring high water — an area the size of Delaware. Approximately half of this land is within 50 cm above spring high water.
- Including tidal and nontidal wetlands, the Mid-Atlantic has 18,000-20,700 km^2 of land within 3 m above spring high water — an area the size of New Jersey.
- The area of dry land that may potentially be available for wetland migration is less than one-sixth the current area of tidal wetlands.

1.1 INTRODUCTION

Elevation maps are critical to understanding and characterizing vulnerability to sea-level rise. Coastal managers, federal, state and local policy makers, researchers and the public rely on this type of information, along with other data, to plan and prepare for rising sea level. Studies estimating the amount of land potentially inundated by rising sea level have long been challenged by the need to estimate the impacts of a rise in sea level that is less than the vertical precision of the topographic maps available for a particular study area (Table 1.1). Sea-level rise scenarios have often ranged between 50-100 cm, yet the available topographic maps along the Atlantic Coast generally have contour intervals of 1.5, 3, and even 6-meters. Along the U.S. Pacific Coast and in most other nations, the vertical resolution of available maps is even less. For more than two decades, however, studies have met the challenge by obtaining the best available data and interpolating between the available contours using a few different methods (*e.g.*,Schneider and Chen, 1980; Kana *et al.*, 1984).

Box 1.1 Elevation and Vulnerability

Elevation of coastal land is a critical determinant of the coastal land area that is vulnerable to sea-level rise. However, elevation is not the only factor that determines vulnerability. For example, a 50cm sea level rise would not submerge all land within 50cm above high water. Several factors influence submergence, including the possibility of future shoreline protections measures, wetland vertical development, barrier island migration, and others.

Conversely, land that is currently higher than the projected sea level rise may also be vulnerable in certain locations or circumstances. For example higher ground could experience significant storm surge and coastal erosion.

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Table 1.1 summarizes some previous studies that mapped the land vulnerable to inundation as sea level rises. Schneider and Chen (1980) estimated the nationwide land, structures, and population potentially vulnerable to a 5-7 meter (15-25 foot) rise from a disintegration of the West Antarctic Ice Sheet. The authors estimated the area below specific contours on printed USGS topographic maps. Although maps were available with contour intervals of 1.5 to 6 m (5 to 20 ft) for most of the United States, maps with poorer quality were also used. By contrast, Kana *et al.* (1984), created inundation maps for the vicinity of Charleston, SC, an area small enough to allow the researchers to digitize available USGS maps, which had a 1.5-m (5-ft) contour interval. A digital terrain model interpolating between the contours was necessary, however, because the study created maps of the spring-high-water shoreline in 25-year increments for sea-level-rise scenarios ranging from 5 to 20 mm/yr.

Advances in technology have improved the quality of some elevation data to assess which lands are vulnerable to sea-level rise. Two important developments have been the systematic conversion of pre-existing information into a digital elevation data set, and the development of high-resolution data such as lidar[1]. Digital elevation data have been collected for a number of years by Federal and State agencies for a range of applications (Osborn *et al.*, 2001). The most commonly used data are from the National Elevation Dataset (Gesch *et al*., 2002). These data estimate the elevation at particular locations within 2.2 meters (95% confidence interval). Thus, they cannot reliably identify specific locations that would be inundated from a sea-level rise of 1 or 2 meters. Nevertheless, they can generally depict low-lying land vulnerable to sea-level rise.

Digital elevation data have many applications other than assessing vulnerability to sea-level rise. The primary applications have included the rectification of aerial photography, extraction of drainage basins, modeling water flow, and visualizations. For coastal zone management, however, the most important use has been creation of maps depicting flood hazards. Like sea-level rise studies, these efforts also require the synthesis of elevation data from a diverse set of sources with varying resolution and accuracy. FEMA and its local partners use elevation data to create flood insurance rate maps, which depict floodplain boundaries and flood surge heights to the nearest 30 cm (1 ft). (See Chapter 8). FEMA (2008) requires that the topographic data must have a contour of 1.5 m (5 feet) or better. Another example is NOAA's National Geophysical Data Center (NGDC, 2008). NGDC has initiated a tsunami inundation gridding project which integrates bathymetric, topographic and shoreline data from various sources, resolutions, accuracies and with

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[1] LIDAR (Light Detection and Ranging) is a remote sensing system used to collect topographic data. LIDAR data are collected with aircraft-mounted lasers capable of recording elevation measurements at a rate of 2,000 to 5,000 pulses per second and have a vertical precision of 15 cm. After a baseline data set has been created, follow-up flights can be used to detect shoreline changes. Many federal, state, and local agencies are obtaining LIDAR to better characterize land elevations. This technology is also being used by NOAA, USGS, and NASA scientists to document topographic changes along shorelines of the mid-Atlantic.

disparate reference datums to produce a digital elevation model (DEM) for use in the tsunami forecast system. They are used to provide baseline DEM's for models to simulate tsunami generation, propagation, and inundation. USACE regularly assembles elevation data to estimate flooding and flood damages when planning for possible structural flood protection projects.

The need for high resolution elevation data in the coastal zone can be met by the use of airborne lidar (Sallenger *et al.*, 2003). Elevation data derived from lidar normally have errors in the range of +/- 0.3 meters. Such data are not widely available but have been used in studies looking at inundation effects in specific localities (Bin *et al*., 2007; Csatho *et al*., 2001; Johnson *et al.*, 2006; Larsen *et al*., 2004; Lathrop and Love, 2007). Such data have been combined with high resolution bathymetry data to successfully model dynamic coastal environments (Feyen *et al*., 2005; Gesch and Wilson, 2001; Pietrafesa, *et al.*, 2007). The importance of higher quality geospatial information has been recognized by the National Research Council and others (NRC, 2004; Stockdon, 2007).

Table 1.1 Examples of studies that map/estimate the land vulnerable to inundation as sea level rises.

Study	Input Data	Vertical Precision[1]	Lowest SLR Estimated	Area Depicted	Method for Treating Uncertainty
Schneider and Chen, 1980	USGS Contours from printed topographic maps	5 to 40 ft (or worse)	4.57m	United States	None reported
Kana *et al.*, 1984	USGS Contours	5 ft	50cm	Charleston area	None reported
EPA, 1989	USGS Contours and wetlands	5 to 20-ft	50cm	U.S. sample of 48 4-quad sites	Sampling error, no model/data error
Najjar *et al.*, 2000	NED (30m)	3.74m	61cm	Delaware	None reported
Titus and Richman, 2001	1:250k USGS (1 degree NED)	10 to 20m	1m	US Atlantic and Gulf Coasts	None reported
Weiss and Overpeck, 2003	NED (30m)	2.44m	1m	United States	None reported
Cooper *et al.*, 2005	USGS NED (10m)	2.44m	61cm	NJ; case study Cape May Pt	None reported
Feyen *et al.*, 2005	6m generated from lidar	20 to 25 cm	Any SLR estimate (model)	Coastal NC	None reported
US DOT, 2007	USGS NED (10-30m res)	2.44m	6cm	DC, MD, VA, NC	None reported
Climate Impacts Group, 2007	NED (30m)	2.44m	11cm	Greater New York City Region	None reported
Titus and Wang,2008	Best available (lidar to USGS Contours)	Lidar (~20cm) to 20 ft	50cm	8 mid-Atlantic coastal states	Error assessment based RMSE of input

(1) For contours, elevation uncertainty is usually 1/2 contour interval (*i.e.*, 1/2 of value listed in this column).

Abbreviations:
NED: National Elevation Dataset. **SRTM**: Shuttle Radar Topography Mission **GTOPO30**: Global Digital Elevation Model, 30 arc seconds **Lidar**: Light Detection and Ranging **RMSE**: root mean square error. **LE**: Linear Error **USGS**: United States Geological Survey

1.2 DATA AND APPROACH

A range of elevation data sets, having large variations in vertical resolution and horizontal accuracy, are available to depict elevations for the mid-Atlantic region. In this report the best existing data is used to provide regional and state-wide depictions of the low-lying areas that may be susceptible to sea-level rise. It should be noted that over large areas, such as those depicted in this chapter, these maps do not accurately reflect the flooding or inundation that could occur at a precise location. Still the results of this analysis makes it possible to make general estimates of the dry land and wetland areas vulnerable to inundation with greater quantification than the other questions addressed by this report. Nevertheless, the resolution and accuracy of available data varies substantially. Like the other studies shown in Table 1.1, a set of new EPA studies used a “patchwork” of the best available elevation data, as shown in Figure 1.1 (Titus and Wang, 2008; Jones and Wang, 2008; Titus and Cacela, 2008). The maps presented here in Chapter 1 do not possess the resolution and accuracy required by localized DEM flooding models. Even so, this approach recognizes the drawbacks of the diverse set of inputs and uses NOAA tide station datums as a basis for vertical datum transformations, and provides uncertainty bounds and ranges in the output.

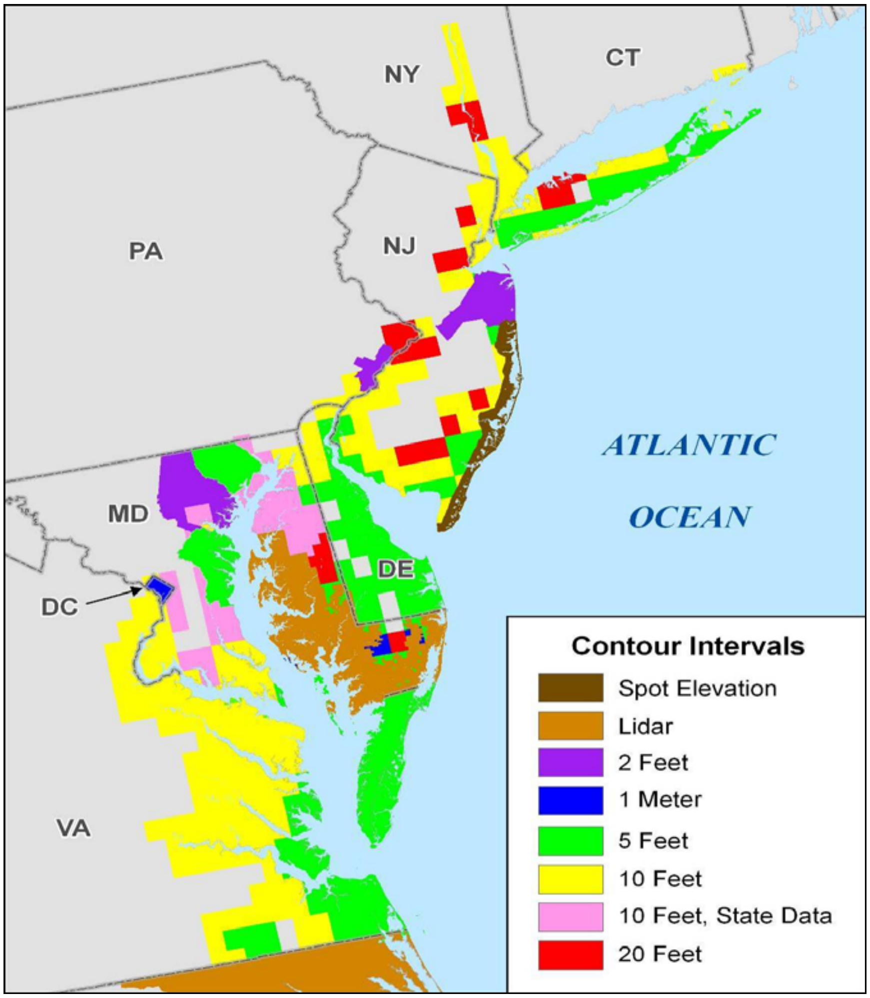


Figure 1.1 Variations in the precision of elevation data available in 2006. Rectangles generally signify USGS 1:24,000 data. The USGS maps had a 20-ft contour interval for the (pink) quads in Maryland where EPA used state data. Spot elevation data provided by the Corps of Engineers had approximately the same precision as 2-ft contours. Lidar was available for all of North Carolina and part of Maryland. Source: Titus and Wang (2008).

This report discusses elevations above “spring high water” rather than above present-day “sea level” or the National Geodetic Vertical Datum (NGVD29), which is the reference elevation for printed USGS maps. Spring high water is the average high tide during a full or new moon, and it approximates the boundary between tidal wetlands and dry land.

(Box 1.2). Thus, the land below spring high water is some form of tidal wetland (unless it is protected by a dike), and is flooded by the tides twice during a typical month.

Figure 1.2 shows the observed spring tide range at 768 locations reported by NOAA. Elevations relative to spring high water are one-half the tide range less than elevations relative to mean sea level. For example, along parts of the Delaware River, the spring tide range is generally 200 cm. Therefore, spring high water is about 100 cm above mean sea level, which is in turn approximately 30 cm above NGVD. Therefore, the USGS "5-ft" (152 cm) contour is only about 22 cm above spring high water at these locations.

Titus and Wang (2008) created coastal elevation maps showing elevations relative to spring high water. The analysis involved five steps:

1. *Obtain the best elevation data from usual sources of topographic map data, such as the USGS, as well as state and local governments and other federal agencies.* The accuracy of these data varies. (See Figure 1.2)

2. *Supplement the available topographic data with a "wetland supplemental contour" based on the upper boundary of regular tidal inundation. Use wetlands data to estimate the horizontal location of the wetland contour.* This step improves precision by providing an intermediate elevation between zero (NGVD) and the lowest topographic contour (*e.g.*, 5-ft NGVD).

3. *Use tidal data to estimate the elevation (relative to a reference elevation such as NGVD or NAVD), of spring high water, providing the vertical position of the wetland supplemental*

contour. Titus and Wang obtained estimates of the mean tide level and spring tide range at 152 and 768 locations, respectively. Figure 1.2 displays spring tide range.

4. *Interpolate elevations relative to the vertical datum for all land above spring high water using elevations obtained from the previous steps.* Titus and Wang used two different approaches for the summary tables and maps. For their summary tables, they assumed that elevations are uniformly distributed between contours, and interpolated. For the maps, they used Topogrid because it appeared to provide more reliable results. In areas with lidar, interpolation was not necessary.

5. *Use the information from step 3 to calculate elevations from NGVD to spring high water*.

Titus and Wang assessed the accuracy of both their specific data points and their summary statistics by comparing their elevation estimates with lidar from Maryland and North Carolina. The root mean square error at individual locations was approximately one-half the contour interval of the input data. They also found that the vertical error of the cumulative elevation distribution curve was generally less than one-quarter the contour interval of the input data, which implies that the systematic error for reasonably large areas could be up to one-quarter of a contour interval. Titus and Cacela (2008) estimated an uncertainty range for the area of land below particular elevations based on that assumption.

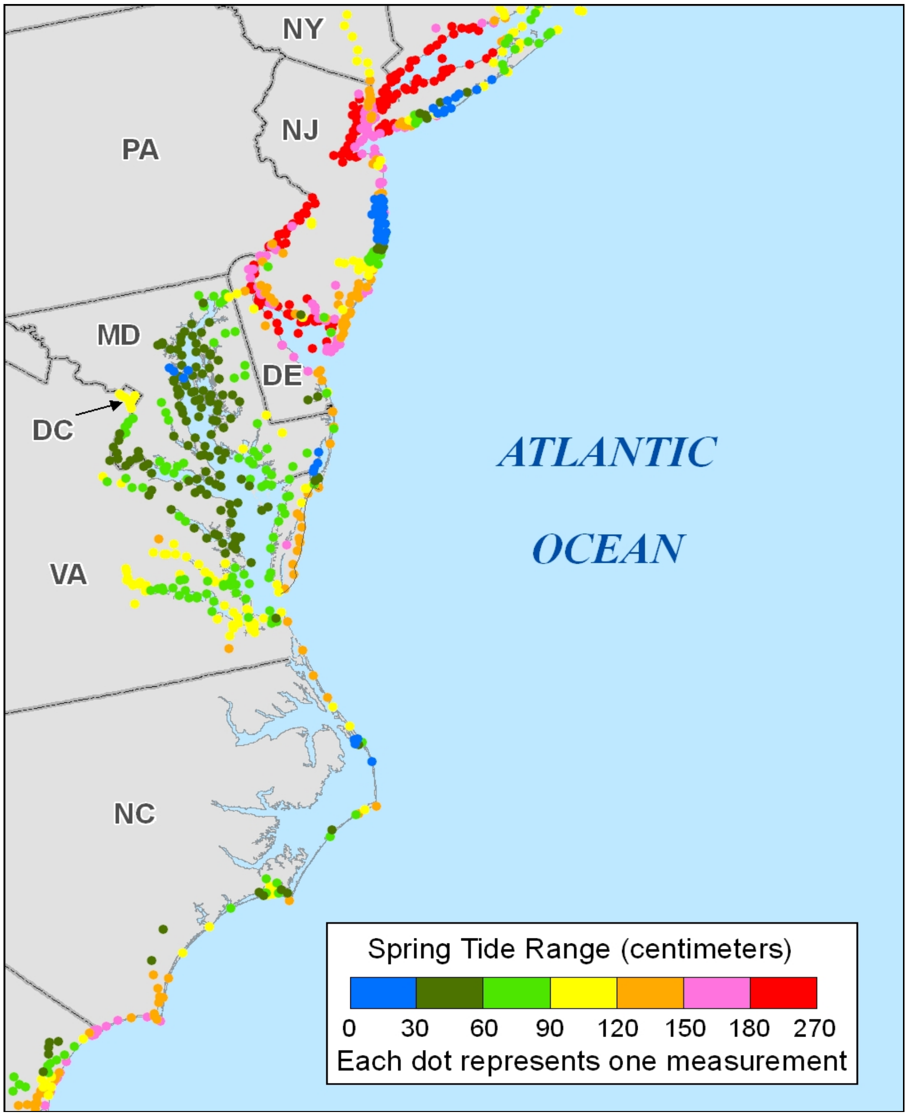
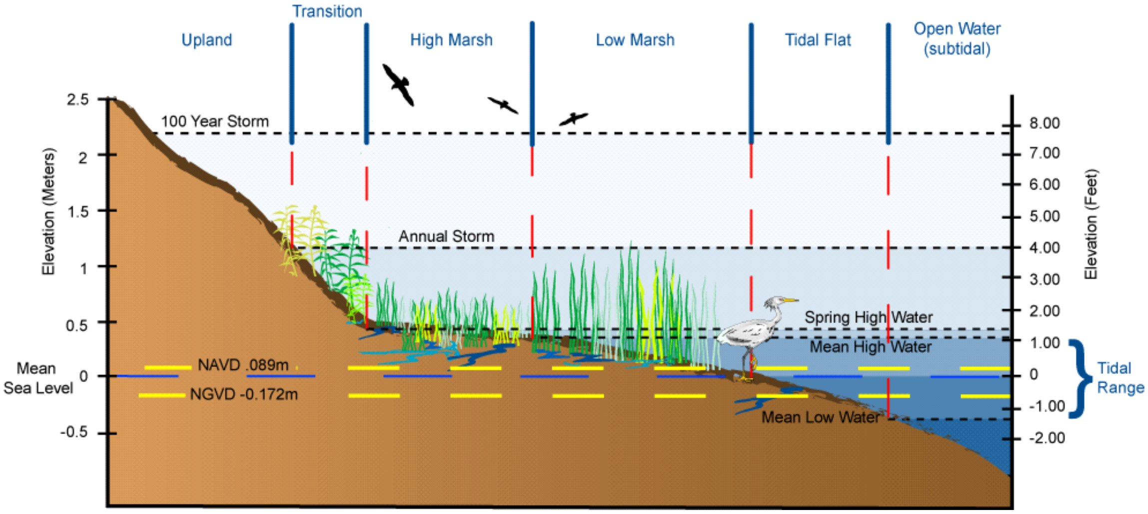


Figure 1.2 Observations of tide ranges used in this study. This figure depicts the 768 observations from NOAA's Tide Tables used to create a surface depicting spring tide range. When dots overlap, the dot with the lower tide range is shown on top. (Titus and Wang, 2008).

********* **BEGIN BOX 1.2: TIDES, SEA LEVEL, AND REFERENCE ELEVATIONS**

Tides are caused by the gravitational attraction of the moon and sun on the ocean water. Most places in the mid-Atlantic region have two high and low tides every day. The daily tide range varies over the course of the lunar month. *Mean high water* and *mean low water* are the average elevations of the daily high and low tides. During full and new moons, the gravitational pull of the moon and the sun are in alignment, which causes the tide range to be 15-25% greater than average. The average of the full and new moon high and low tides are known as *spring high water* and *spring low water*. In addition to the astronomic tides, water levels fluctuate due to winds, atmospheric pressure, ocean current, and--in inland areas—river flow, rainfall and evaporation. Daily tide ranges in the Mid-Atlantic are as great as 2.5 m in parts of the Delaware River and less than 5 cm in some of the sounds of North Carolina.

In coastal areas with tidal marshes, the high marsh is generally found between mean high water and spring high water, while low marsh is found from slightly below mean sea level up to spring high water. (See diagram.) In bays with small (*e.g.*, 10-20 cm) tide ranges, however, winds and seasonal runoff can cause water level fluctuations with a greater impact on tidal wetlands than the tides themselves. These areas are known as “*irregularly flooded*”. In some locations, such as upper Albemarle Sound in North Carolina, the astronomic tide range is essentially zero, and all wetlands are irregularly flooded. Freshwater wetlands in such areas are often classified as “nontidal wetlands” because there is no tide, but unlike most nontidal areas, the flooding—and risk of wetland loss—are still controlled by sea level. Wetlands that lie at sea level along an estuary with a very small tide range and have hydrology similar to nontidal wetlands are called *nanotidal wetlands*.



The term *sea level* refers to the average level of tidal waters, generally measured over a 19-year period. The 19-year cycle is necessary to smooth out variations in water levels caused by seasonal weather fluctuations and the 18.6-year cycle in the moon’s orbit.

Tide gauges measure the water level relative to the land, and thus include both changes in the elevation of the ocean surface and movements of the land. For clarity, scientists often use two different terms:

- *global sea-level rise* is the worldwide increase in the volume of the world’s oceans that occurs as a result of thermal expansion and melting ice caps and glaciers.

- *relative sea-level rise* refers to the total change in sea level relative to the elevation of the land, which includes both global sea level rise and land subsidence.

In this report, the term "sea-level rise" means "relative sea-level rise."
Land elevations are measured relative to either water levels or a fixed benchmark. Most topographic maps use one of two fixed reference elevations. USGS topographic maps measure elevations relative to the National Geodetic Vertical Datum of 1929 (NGVD29), which was approximately mean sea level in 1929 at 26 major coastal cities. Newer digital elevation maps and high-resolution data generally measure elevations relative to the North American Vertical Datum of 1988 (NAVD88) (Zilkoski *et al.*, 1992). This report measures elevations relative to spring high water (for the year 2000), which indicates how much the sea must rise before the land is inundated by the tides.

END BOX *******************

1.2 RESULTS

Figures 1.3 and 1.4 depict the locations of these lands using two different formats. Figure 1.3 shows land less than 3 meters above the tides, with dry land in 50-cm increments and nontidal wetlands depicted in two shades of purple. Figure 1.4 shows land less than 6 meters above the tides, in 1-meter elevation increments. This chapter displays the two separate formats for two reasons: First, Figure 1.3 displays nontidal wetlands because, for some purposes, it is more important to know that the land is already wet than the precise elevation. Second, information on which lands are between 3 and 6 meters above sea level can help identify lands that would be vulnerable to storm surge if the sea rises a meter or two. (For larger scale maps, see Appendices A-G).

Table 1.2 provides "best estimates"[2] from the Titus and Wang (2008) analysis of the amount of dry land, and nontidal wetlands close to sea level in each of the Mid-Atlantic states, using half-meter increments. For comparison, Table 1.2 also includes the area of tidal wetlands. Table 1.3 shows the corresponding uncertainty range from Titus and

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[2] By "best estimate" we mean a single estimate rather than an uncertainty range.

Cacela (2008), except that the table shows the total amount of land below a given elevation.

Given the poor resolution of the data, the chapter findings use the cumulative uncertainty range from Table 1.3; but the incremental results in Table 1.2 offer some insights. Most notably, the amount of dry land at various elevations is fairly similar within 4 meters above spring high water. More nontidal wetlands are within 1 meter of the tides than (for example) 3 to 4 meters—especially in North Carolina.

Table 1.2 Area of lands close to sea level in the Mid-Atlantic by state: (square kilometers) Source: Titus and Wang (2008).

		Meters above Spring High Water									
State		**0.5**	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**	**4.5**	**5.0**
		----------------Dry Land, by half meter elevation increment[1]----------------------------									
New York		82.4	81.5	85.9	86.4	78.5	70.6	67.5	61.4	57.8	51.7
New Jersey		127.2	148.0	150.2	125.5	110.5	108.4	104.5	100.5	98.8	95.0
Pennsylvania		12.6	11.1	15.0	13.4	11.3	11.3	9.8	9.2	9.3	9.1
Delaware		72.2	53.9	52.4	56.3	66.4	68.9	70.5	73.8	75.5	72.9
Maryland		185.3	265.1	240.7	265.1	226.3	243.8	246.1	231.2	202.9	195.4
DC		2.4	1.2	1.4	1.4	1.8	1.8	1.8	1.8	1.7	1.7
Virginia		172.1	176.8	223.0	236.9	253.4	332.1	346.2	337.9	275.0	253.0
North Carolina		741.9	626.1	581.7	637.0	632.6	572.0	618.4	715.5	566.5	412.2
Mid-Atlantic Region		1396.1	1363.7	1350.2	1422.1	1380.9	1409.0	1464.8	1531.3	1287.5	1090.9
	Tidal wetlands	---------Nontidal Wetlands, by half meter elevation increment--------------------------									
New York	149.1	5.0	4.8	3.4	3.2	2.8	2.0	1.9	1.9	1.9	1.8
New Jersey	980.4	99.5	72.6	70.9	64.4	43.2	41.0	39.8	36.0	35.5	35.0
Pennsylvania	6.1	1.9	1.5	1.7	1.6	1.1	1.0	1.0	1.0	0.8	0.3
Delaware	357.1	22.2	9.8	9.2	8.9	7.9	7.8	7.9	7.6	7.5	7.4
Maryland	1115.8	64.5	57.2	53.8	57.6	40.8	47.2	53.7	47.0	41.3	39.5
DC	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
Virginia	1618.9	73.1	75.0	70.4	68.6	72.6	74.3	73.7	74.1	66.5	64.1
North Carolina	1272.0	2372.3	718.5	394.4	320.8	295.7	259.4	233.5	238.1	218.9	234.4
Mid-Atlantic Region	5500.2	2638.5	939.5	603.8	525.1	464.0	432.7	411.5	405.7	372.5	382.6
		Cumulative (total) amount of land below a given elevation[2]									
Dry Land		**1396**	**2760**	**4110**	**5532**	**6913**	**8322**	**9787**	**11318**	**12606**	**13697**
Nontidal wetlands		**2638**	**3578**	**4182**	**4707**	**5171**	**5604**	**6015**	**6421**	**6793**	**7176**
All land	**5500**	**9535**	**11838**	**13792**	**15739**	**17584**	**19426**	**21302**	**23239**	**24899**	**26373**

(1) For example, New York has 81.5 square kilometers of dry land between 0.5 and 1.0 meters above spring high water.

(2) For example, the mid-Atlantic region has 2760 square kilometers of dry land less than 1 meter above spring high water.

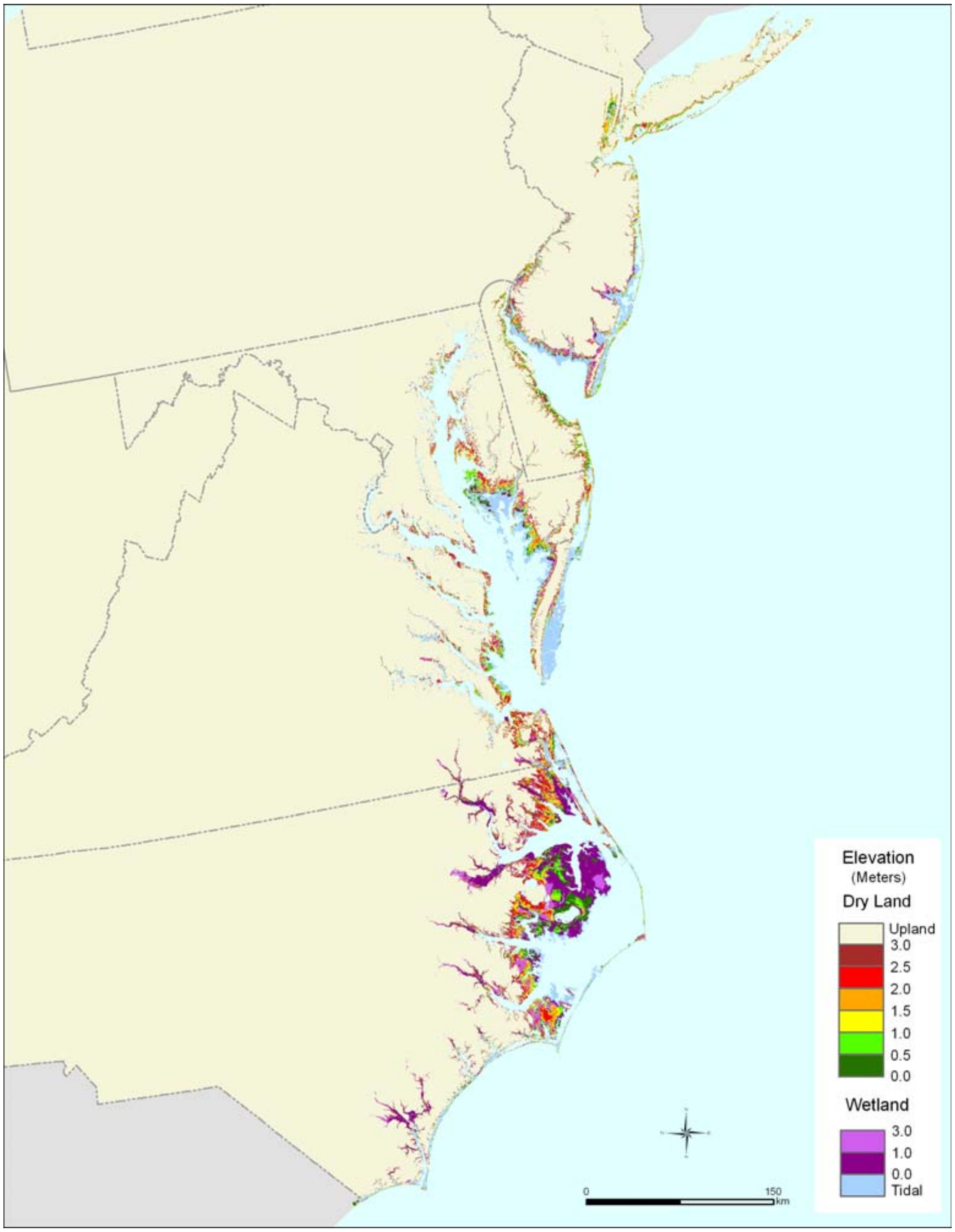

Figure 1.3 Dry land and nontidal wetlands within three meters above the tides in the mid-Atlantic region.

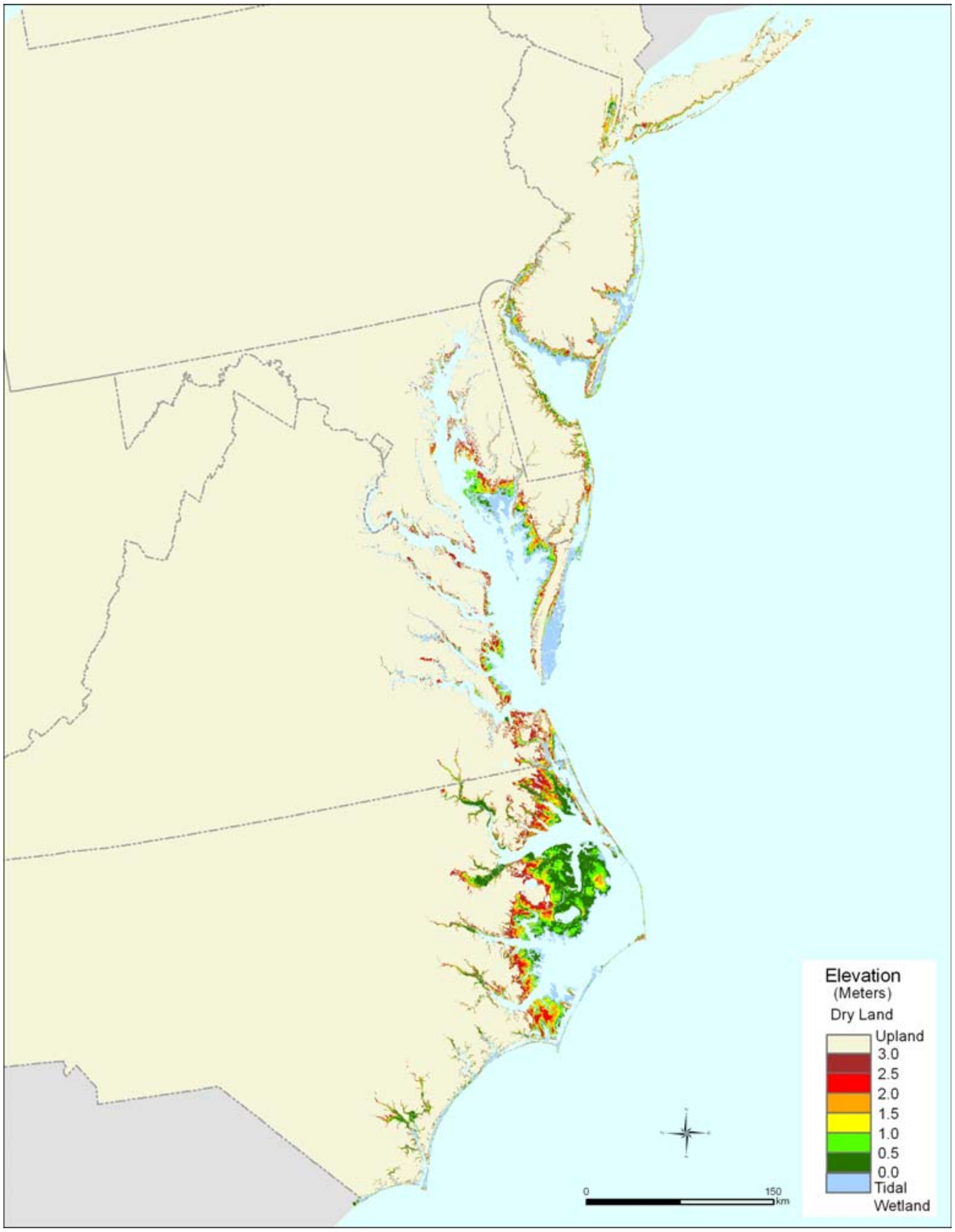

Figure 1.4 Land within six meters above the tides in the Mid-Atlantic.

These results show that the Mid-Atlantic has 5,500-7,500 km^2 of dry land and nontidal wetlands within one meter above the tides — an area the size of Delaware. Approximately half of this land is within 50 cm above the tides. Including tidal wetlands, the Mid-Atlantic has 18,000-20,700 km^2 of land within 3 m above the tides — an area the size of New Jersey.

Description. Most of this low-lying area includes the farms, forests, and residential back yards just inland of the tidal wetlands along most estuaries, as well as nontidal wetlands in particularly flat areas such as the lands along Pamlico and Albemarle Sounds in North Carolina and the lower portions of Chesapeake and Delaware Bays. The lowest developed lands include dry land that was created by filling tidal wetlands, the bay sides of barrier islands[3], and several small towns along Chesapeake Bay and the sounds of North Carolina[4].

The greatest concentration of low land is between Cape Lookout and the mouth of Chesapeake Bay (Figure 1.4). More than 5,000 km^2 of North Carolina is less than one meter above the tides, including the majority of three counties (Dare, Hyde, and Tyrrell). Almost half of the dry land close to sea level is in North Carolina. Figures 1.3 and 1.4 imply that North Carolina accounts for about 85 percent of the nontidal wetlands within one meter of spring high water — but less than 25 percent of the region’s tidal wetlands. That result, however, is partly an artifact of the fact that *nanotidal* freshwater wetlands

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[3] Long, narrow strips of sand forming islands that protect inland areas from ocean waves and storms (USGS).

[4] The dry sand beaches along the Atlantic Ocean and major bays, between the dunes and high water mark, is also low enough to be inundated if sea level rises 50-200 cm. But because these lands would generally erode before they become inundated by the tides, we discuss beaches in Chapter 2.

(areas with very small tides) are classified as *nontidal*. The astronomic tides of Albemarle Sound and its tributaries are only a few centimeters, but winds and other hydrological variations cause irregular flooding tens of centimeters above mean sea level. The elevation of this flooding will increase as the sea rises, just as high tides increase as the sea rises.

The second largest concentration of lands close to sea level is along the lower Eastern Shore of Maryland and adjacent Accomack County, Virginia. Many of the most vulnerable communities in this area are remnants of a time when fishing in Chesapeake Bay supported a large part of the Maryland and Virginia economies. Smith and Tangier Islands — both less than one meter above the tides — lack a bridge to the mainland and are still populated mainly by watermen. Other low-lying communities are inhabited by the descendants of residents of islands that have eroded or entirely converted to marsh. A few communities on the western side of the Bay are also very low lying, such as Poquoson and Gloucester County.

In both North Carolina and along Chesapeake Bay, the vulnerability to rising sea level is apparent to the naked eye. Water levels rise and fall with the tides in the small roadside ditches in Carteret (NC), Dorchester, and Somerset Counties. Hummocks surrounded by marsh are all that remain of some pine forests; and dead trees stand in the marsh elsewhere. Marsh grass grows in the front yards of many homes. In some locations, driveways through the marsh are all that remain. Salt-tolerant weeds sometimes break up an otherwise perfect row of corn where the intrusion did not occur in years past. Cypress trees, which only germinate on dry ground, stand in water that is nearly a meter deep.

The bay sides of some developed barrier islands in New Jersey and New York are already flooded during spring high tides. The coastal geological processes that create and sustain barrier islands tend to create very low land on the bay side. In New Jersey, tens of square kilometers along the low sides of developed barrier islands are within 50-100 cm above spring high water. The New Jersey shore was developed decades before the rest of the mid-Atlantic coast. The older development makes communities there more vulnerable, for two reasons. First, with sea level rising 3-4 mm/yr, communities developed 100 years ago are 30-40 cm (one foot) closer to sea level than when they were developed. Second, the dredge-and-fill approach to coastal development, which was commonplace in the mid-Atlantic until it was curtailed during the 1970s, created land barely above the elevation of the marsh.

Uncertainty. Comparing Map 1.1 with Table 1.3 shows that the uncertainty regarding the area of land within a given elevation above the tides is greatest in areas with poor topographic information, such as northern New Jersey, and least in areas where lidar is available, such as North Carolina and parts of Maryland. Given the need to interpolate in areas where high-quality data is unavailable, the uncertainty is more than twofold for the land within 50 cm above the tides, but only 30 percent for the land within 2 meters above the tides.

Titus and Cacela (2008) did not explicitly relate their uncertainty range to the probability lexicon used by this report. Instead, their analysis was based on standard deviations, which generally correspond to the likely range. Evaluated over the entire mid-Atlantic region, errors would normally be expected to offset. But Titus and Cacela had no information on the correlation of error across the region, and hence made the most cautious assumption possible by assuming that overestimates in one subregion are never offset by underestimates in another subregion. Therefore, the uncertainty range for regional totals likely represents a wider range of probability than the county-specific results.

Table 1.3a Uncertainty range of the cumulative area of dry land close to sea level, by subregion: Mid-Atlantic[1] (square kilometers)

	Meters above spring high water											
	0.5		1.0		2.0		3.0		4.0		5.0	
Sub-Region	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
L.I. Sound/ Peconic	**6**	**31**	**22**	**59**	**63**	**111**	**106**	**158**	**149**	**200**	**190**	**229**
S. Shore Long Island	**19**	**70**	**59**	**134**	**161**	**250**	**266**	**335**	**347**	**400**	**410**	**450**
NY Harbor/ Raritan Bay	**5**	**72**	**47**	**143**	**139**	**230**	**215**	**288**	**265**	**343**	**314**	**374**
New York	0	13	8	25	24	44	40	58	52	72	65	78
New Jersey	5	59	39	117	115	186	175	230	213	271	249	295
New Jersey Shore	**18**	**61**	**66**	**129**	**184**	**237**	**262**	**327**	**344**	**409**	**418**	**481**
Delaware Bay	**19**	**62**	**52**	**108**	**124**	**206**	**217**	**312**	**321**	**421**	**427**	**512**
New Jersey	3	19	15	36	39	73	70	114	109	154	146	182
Delaware	15	43	38	71	85	133	146	198	212	267	281	330
Delaware River	**17**	**80**	**56**	**146**	**152**	**262**	**249**	**368**	**342**	**467**	**430**	**549**
Atlantic Coast of Del-Mar-Va total	**27**	**87**	**81**	**148**	**200**	**275**	**318**	**390**	**425**	**495**	**529**	**599**
Delaware	11	32	28	53	64	95	104	139	149	187	196	234
Maryland	3	17	20	40	74	97	126	145	165	180	199	211
Virginia	13	37	33	55	62	82	87	106	111	129	134	154
Chesapeake Bay total	**102**	**466**	**441**	**906**	**1193**	**1827**	**1973**	**2859**	**2962**	**3818**	**3865**	**4633**
Delaware	1	2	1	3	4	7	9	14	15	24	26	36
Maryland	66	290	306	530	738	1007	1141	1451	1572	1865	1966	2213
District of Columbia	2	3	3	4	5	7	9	11	13	15	16	18
Virginia	34	172	131	369	445	805	815	1383	1362	1915	1857	2366
Virginia Beach Atlantic Coast	**7**	**27**	**25**	**56**	**78**	**142**	**158**	**219**	**235**	**288**	**293**	**310**
Pamlico Albemarle Sounds	**621**	**1028**	**1186**	**1519**	**2239**	**2601**	**3274**	**3629**	**4449**	**4789**	**5269**	**5441**
Atlantic Coast of North Carolina	**103**	**151**	**182**	**238**	**370**	**429**	**529**	**579**	**682**	**740**	**855**	**908**
Total NY to NC	**945**	**2136**	**2218**	**3585**	**4903**	**6569**	**7567**	**9463**	**10520**	**12370**	**13001**	**14486**

Table 1.3b Uncertainty range of the cumulative area of nontidal and tidal wetlands close to sea level, by subregion: Mid-Atlantic[1] (square kilometers)

		Meters above Spring High Water											
	Tidal wetlands	0.5		1.0		2.0		3.0		4.0		5.0	
Sub-Region		Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
L.I. Sound/ Peconic	36	1	2	2	4	4	7	7	9	9	11	11	13
S. Shore Long Island	104	1	4	4	7	8	10	11	12	12	13	14	15
NY Harbor/ Raritan Bay	68	0	3	2	6	6	9	9	11	10	13	12	16
New Jersey Shore	524	11	52	42	92	101	157	152	205	196	249	237	286
Delaware Bay	497	16	54	45	90	98	139	140	173	172	202	199	224
Delaware River	216	12	41	33	64	65	93	90	108	103	122	116	133
Atlantic Coast of Del-Mar-Va total	757	4	14	13	28	39	55	62	73	78	85	89	95
Chesapeake Bay total	1903	43	150	143	257	331	483	504	690	714	900	909	1119
Virginia Beach Atlantic Coast	124	6	21	20	37	42	57	61	73	76	88	89	96
Pamlico Albemarle Sounds	829	2083	2625	2772	3039	3401	3562	3852	3984	4235	4352	4592	4695
Atlantic Coast of North Carolina	443	197	255	275	315	393	429	495	525	583	616	680	710
Total NY to NC	**5500**	**2374**	**3221**	**3351**	**3940**	**4487**	**5001**	**5381**	**5864**	**6189**	**6652**	**6948**	**7401**

Table 1.3c Cumulative (total) amount of land below a given elevation

		Meters above Spring High Water											
	Tidal wetlands	0.5		1.0		2.0		3.0		4.0		5.0	
		Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Dry land		**945**	**2136**	**2218**	**3585**	**4903**	**6569**	**7567**	**9463**	**10520**	**12370**	**13001**	**14486**
Nontidal wetlands		**2374**	**3221**	**3351**	**3940**	**4487**	**5001**	**5381**	**5864**	**6189**	**6652**	**6948**	**7401**
All land	**5500**	**8819**	**10857**	**11069**	**13025**	**14890**	**17070**	**18448**	**20826**	**22208**	**24521**	**25448**	**27387**

Sources:
Titus, J.G. and Cacela, 2008.
(1) Low and high are an uncertainty range based on the contour interval and/or stated root mean square error (RMSE) of the input elevation data. Calculations assume that half of the RMSE is random error and half is systematic error.

1.3 IMPLICATIONS OF TOPOGRAPHY FOR TIDAL WETLANDS

In the chapters that follow, a fundamental concept is that land that is dry today may become intertidal and eventually submerged as sea level rises. Tables 1.2 and 1.3 show that the dry land within 50 cm above the tides is less than the area of tidal wetlands in most areas, with the exception of North Carolina. (Available data in North Carolina are poorly suited to this type of analysis). From New York to Virginia, the area of dry land within 1 meter above the tides is only about one-fourth the current area of tidal wetlands. North Carolina has approximately 3,000 km^2 of *wetlands* within 50 cm above the tides, but only 700 km^2 of *dry land* within 1 meter above the tides. Figure 1.5a shows county-by-county variability of the ratio of tidal wetlands to dry land within 1 meter above the tides[5].

Comparing the area of dry land within 1 meter above spring high water to the area of tidal wetlands, however, is only a rough approximation of the potential sustainability of tidal wetlands through landward migration. Tidal wetlands in some areas are within 25 cm below spring high water, while in other areas tidal wetlands may extend 1 to 1.5 meters below spring high water because the tide range may be 2 to 3 meters. Hence, the ratio depicted in Figure 1.5a has a denominator that is always the area of dry land within one meter above spring high water; but the numerator could be wetlands within 25 cm or 1.5 meters below spring high water. Figure 1.5b depicts the ratio of the area of tidal wetlands (*i.e.* wetlands within one-half the tide range below spring high water) to the area of dry land within one-half tide range above spring high water. (We exclude North Carolina because the small tide range would give us a meaninglessly large ratio.) This figure shows

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[5] Counties that are partly along the ocean and partly along Chesapeake Bay, Delaware Bay, or Long Island Sound are split.

the ratio of the average slope immediately above spring high water to the average slope between spring high water and the open water. Across the region depicted, excluding North Carolina, the current area of tidal wetlands in the Mid-Atlantic is more than six times the area of dry land available for wetland migration. (Table 1.4). That is, the area of land potentially available for inland wetland migration is approximately 15 percent the area of existing tidal wetlands.

Given the mid-Atlantic topography, it follows that the fate of tidal wetlands in the Mid-Atlantic is likely to depend more on their ability to keep pace with rising sea level through sedimentation and peat formation than on the availability of land for inland migration. Yet the potential for wetlands to keep pace with an accelerated rise in sea level is uncertain. For example, as we discuss in Chapter 3, the rate of sea-level rise at which wetlands can no longer keep pace varies by region. Thus a priority for additional research is to determine whether human activities are impairing—and how they might be able to enhance—the ability of wetlands to keep pace with rising sea level. (See Part VI).

Table 1.4 Potential for wetland migration: Area of tidal wetlands compared to area of land within one-half tide range above spring high water.

	Land within one-half tide range above spring high water (km^2)[1]		**Tidal wetlands (km^2)**	**Potential for wetland migration: Ratio[2] of tidal wetlands to:**	
State	**Dry land**	**Nontidal wetlands**		**Dry land**	**All land**
L.I. Sound and Peconic Estuary	34	**2**	**36**	1.06	1.01
South Shore Long Island	52	**1**	**104**	1.98	1.93
NY Harbor/Raritan Bay	**97**	**4**	**64**	0.65	0.63
New York	16	1	5	0.30	0.28
New Jersey	82	3	59	0.72	0.69
New Jersey Shore	**47**	**40**	**524**	11.12	6.02
Delaware Bay	**72**	**59**	**497**	6.88	3.78
New Jersey	22	41	261	12.10	4.17
Delaware	51	18	236	4.66	3.43
Delaware River	**98**	**45**	**215**	2.19	1.50
Delaware fresh	7	1	5	0.71	0.61
Delaware saline	16	3	69	4.26	3.59
New Jersey fresh	23	12	27	1.20	0.80
New Jersey saline	28	25	108	3.83	2.01
Pennsylvania	24	4	6	0.25	0.22
Atlantic Coast of Del-Mar-Va	**40**	**6**	**909**	22.46	19.76
Delaware	8	2	41	4.96	4.15
Maryland	1	0	105	76.07	68.09
Virginia	31	4	764	24.77	22.06
Chesapeake Bay	**166**	**57**	**1665**	10.05	7.47
Delaware	1	2	7	5.29	2.33
Maryland	72	26	1011	14.11	10.31
District of Columbia	2	0	0	0.20	0.19
Virginia	91	29	647	7.15	5.41
Virginia Beach — Atlantic Coast	**9**	**7**	**124**	13.17	7.47
Total: NY to VA	**617**	**221**	**4137**	**6.70**	**4.94**

1. Area of land potentially available for inland wetland migration.

2. The reciprocal of this ratio defines area of land potentially available for inland wetland migration, as a percentage of current wetlands. For example, the regionwide ratio of 6.48 implies that the area of land potentially available for inland wetland migration is 15 percent of the current wetland area.

SOURCE: Titus and Wang (2008); Jones and Wang (2008).

NOTE: Information presented here approximates the area that may be available for wetland migration or formation relative to existing wetland area and does not indicate the potential for loss or gain in total wetland area.

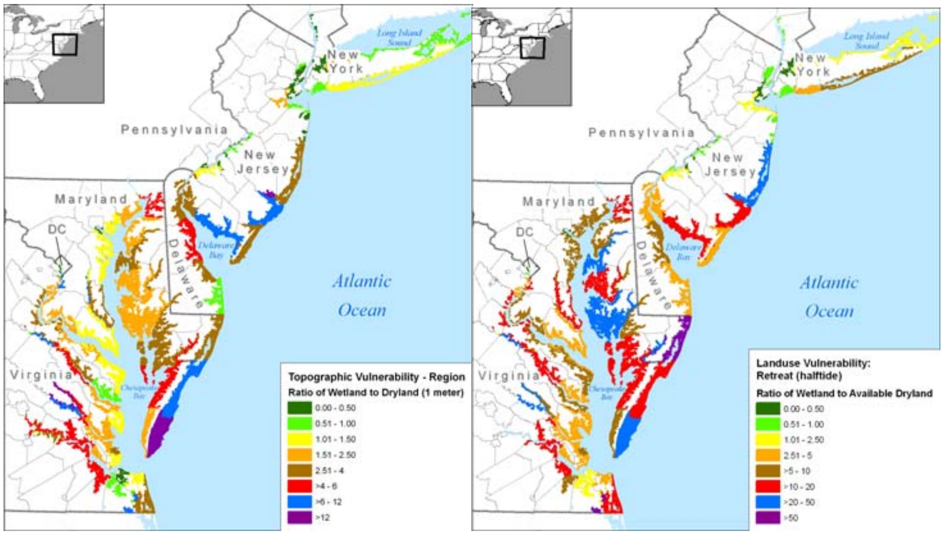

Figure 1.5 Dry land available for potential wetland migration or formation (New York to Virginia). a) County-by-county ratios of the area of tidal wetlands to the area of dry land within 1 meter above spring high water. The figure shades polygons from the tidal wetlands data set. Small polygons are exaggerated to ensure visibility, and b) County-by-county ratios of tidal wetlands to the area of dry land within one-half the tide range above spring high water.
NOTE: Information presented here approximates the area that may be available for wetland migration or formation relative to existing wetland area and does not indicate the potential for loss or gain in total wetland area.

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Chapter 2. Ocean Coasts

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KEY FINDINGS

- The majority of the mid-Atlantic region as well as the rest of the United States coastline consists of sandy shores whose landforms and characteristics of behavior are related to a variety of physical processes and factors. Along sandy coasts, it is **virtually certain** that erosion will dominate changes in shoreline position in response to sea-level rise and storms over the next century. Inundation from sea- level rise will be limited to the bedrock coasts such as those along portions of the New England and Pacific shores which are resistant to erosion, and to low-energy/low-relief coasts such as upper reaches of bays and estuaries.
- The potential for coastal change in the future is likely to increase and be more variable than has been observed in historic past. It is **very likely** that significant portions of the U.S. will undergo large changes to the coastal system if the higher sea-level rise scenarios occur, such as increased rates of erosion, landward migration of barrier islands, and possibly segmentation or disintegration.
- It is **very likely** that the rate of shoreline erosion will increase along the majority of the mid-Atlantic coast as sea level rises. This response will vary according the coastal landforms present at the shore and the local geologic and oceanographic conditions. Coasts containing headlands, spits, and barrier islands are generally

expected to erode. Especially for higher sea-level rise scenarios, it is **likely** that some barrier island coasts, such as low-lying and sand starved parts of Virginia and North Carolina, will cross a threshold and undergo morphological changes such as more rapid landward migration, segmentation, or even disintegration in extreme scenarios.

2.1 INTRODUCTION

The general morphology of the coast reflects a complex and dynamic interaction between the physical processes (*e.g.,* waves and tidal currents) that act on the coast, the availability of sediment transported by waves and tidal currents, and the local geology. Variations in these factors from one coastal region to the next are responsible for the different coastal landforms, such as barrier islands, that are observed along the coast today. Based on knowledge developed from studying the geologic record, the scope and general nature of the changes that can occur in response to sea-level rise are well established. On the other hand, constraining precisely how these changes occur in response to a specific rise in sea level has been elusive. Part of the complication arises due to the range of physical processes and factors influence that modify the coast and operate over a range of time scales (weeks-to-centuries-to-millennia). It is unclear how much these contribute to long-term changes that can be attributed to sea-level rise. Because of the complexity of the interaction between these factors it has been difficult to resolve a precise relationship between sea-level rise and shoreline change. Consequently, it has been difficult to reach a consensus among coastal scientists as to whether or not sea-level rise can be quantitatively related to observed shoreline changes.

Along many U.S. shores, shoreline changes are related to changes in the shape of the landscape at the water's edge (*e.g.*, the shape of the beach). Changes in beach morphology, and the resulting shoreline changes, do not occur directly as the result of sea-level rise but are in an almost continual state of change in response to waves and currents as well as the availability of sediment to the coastal system. This is especially true for shoreline changes over the past century, when increases in sea-level rise have been relatively small. During this time, large storms, variations in sediment supply to the coast, and human activity have had a more measurable influence on shoreline changes. Large storms can cause changes in shoreline position that persist for weeks to a decade or more (Morton *et al.*, 1994; Zhang *et al.*, 2004; List *et al.*, 2006; Riggs and Ames, 2007). Complex interactions with nearshore sand bodies and/or underlying geology (the geologic framework), the mechanics of which are not yet clearly understood, also influence the behavior of beach morphology over a range of time scales (Riggs *et al.*, 1995; Honeycutt and Krantz, 2003; Schuup *et al.*, 2006; Miselis and McNinch, 2006). In addition, human actions to control changes to the shore and coastal waterways have considerably altered the behavior of some portions of the coast (*e.g.*, Assateague Island (Dean and Perlin, 1977; Leatherman, 1984)).

It is even more difficult to develop quantitative predictions of how shorelines may change in the future. The most easily applied models incorporate relatively few processes and rely on assumptions that do not always apply to real-world settings (Thieler *et al.*, 2000; Cooper and Pilkey, 2004). These assumptions apply best to present conditions, but not necessarily to conditions that may exist in the future. Models that incorporate more factors require precise knowledge on a local scale, and it is therefore difficult to apply these models over larger coastal regions. Appendix H presents brief summaries of a few methods have been used to developed to predict and assess the potential for shoreline changes in response to sea-level rise.

Chapter 1 addresses the vulnerability of coastal lands to inundation as sea level rises. Recent and ongoing assessments of sea-level rise impacts have used a similar approach to identify lands vulnerable to inundation by specific sea-level rise scenarios (Najjar *et al.*, 2000; Titus and Richman, 2001; Rowley *et al.*, 2007). While this approach provides an estimate of the land areas that may be affected, it does not incorporate the processes (*e.g.*, barrier island migration) nor the environmental changes that may occur (*e.g.*, salt marsh deterioration) as sea level rises. Because of these complexities, inundation can be used as a first order approach to estimate land areas that could be affected by changing sea level. Because the majority of the nation's coasts, including the Mid-Atlantic, consist of sandy shores, inundation alone is unlikely to reflect the potential consequences of sea-level rise. Instead long-term, shoreline changes will involve both contributions from both inundation and erosion (Leatherman, 1990; Leatherman, 2001) as well as changes to other coastal environments such as wetlands.

Most portions of the open coast of the United States will be subject to significant changes and net erosion over the next century. The main reason for this assertion is that the majority of U.S. coastline consists of sandy beaches which are highly mobile and in a continual state of change. This chapter presents an overview and assessment of the important factors and processes that influence potential changes to the mid-Atlantic ocean coast which may occur due to sea-level rise expected by the end of the century.

2.2 ASSESSING THE POTENTIAL IMPACT OF SEA-LEVEL RISE ON THE OCEAN COASTS OF THE MID-ATLANTIC

Lacking a single agreed-upon method or scientific consensus view about shoreline changes in response to sea-level rise at a regional scale, a panel of coastal scientists was consulted to address the key question (Gutierrez *et al.*, 2007). Members of the panel were chosen based expertise in coastal studies, experience in the coastal research community, and involvement with coastal management in the mid-Atlantic region[6]. The panel discussed the changes that might be expected to occur to the ocean shores of the U.S. mid-Atlantic coast in response to predicted accelerations in sea-level rise over the next century, and considered the important geologic, oceanographic, and anthropogenic factors that contribute to shoreline changes in this region. The assessment presented here is based on the professional judgment of the panel. This qualitative assessment of potential changes that was developed based on an understanding of both field observations and quantitative information. In addition, the panel discussed and evaluated

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the challenges and uncertainties involved in using various predictive approaches some of which are described in Appendix H.

This assessment focuses on four sea-level rise scenarios consisting of the three defined in the Preface and the Context Chapter (See pages X) as well as an additional high scenario considering a 2 m rise over the next few hundred years. In all of the discussions, we are referring to relative sea level, the combination of global sea-level change and local change in land elevation. Using these scenarios, the assessment focused on:

- Identifying important factors and processes contributing to shoreline change over the next century;
- Identifying key geomorphic settings in the mid-Atlantic Bight;
- Defining potential responses of shorelines to sea-level rise; and
- Assessing the likelihood of these responses.

2.3 GEOLOGICAL CHARACTER OF THE MID-ATLANTIC COAST

The mid-Atlantic margin of the U.S. is a low-gradient coastal plain that has accumulated over millions of years in response to the gradual erosion of the Appalachian mountain chain. The resulting sedimentation has constructed a broad coastal plain and a continental shelf that extends up to 300 km seaward of the present coast (Colquhoun *et al.*, 1991). The current morphology of this coastal plain has resulted from the incision of rivers that drain the region and the construction of barrier islands along the mainland occurring between the river systems. Repeated ice ages, which have resulted in sea-level fluctuations up to 140 meters (Muhs *et al.*, 2004), caused these rivers to erode large valleys during periods of low sea level that then flooded and filled with sediments when sea levels rose. The northern extent of the mid-Atlantic region considered in this report, Long Island, New York, was also shaped by the deposition of glacial outwash plains and moraines that accumulated from the retreat of the Laurentide ice sheet which reached its maximum extent approximately 21,000 years ago. The gently sloping landscape that characterizes entire mid-Atlantic margin in combination with slow rates of sea-level rise over the past 5,000 years and abundant sand supply is also thought to have enabled the formation of the barrier islands that comprise the majority of the Atlantic coast (Walker and Coleman, 1987; Psuty and Ofiara, 2002).

Presently, the river systems along the mid-Atlantic coast generally discharge into large estuaries and bays, thereby delivering minor amounts of sediment to the open coast (Meade, 1972). As a result, the region is generally described as sediment-starved (Wright, 1995). The sediments that form the mainland beach and barrier beach environments are thought to be derived mainly from the wave-driven erosion of the mainland substrate and sediments from the seafloor of the continental shelf. Since the largest waves and associated currents occur during storms along the Atlantic coast, this margin of the United States is often referred to as a storm-dominated coast (Davis and Hayes, 1984).

The majority of the open coasts along the mid-Atlantic Bight are sandy shores that include the beach and barrier environments. Although barriers comprise 15 percent of the world coastline (Glaeser, 1978), they are the dominant shoreline type along the Atlantic coast. Along the portion of the mid-Atlantic Bight coast examined here, barriers line the majority of the open coast. Consequently scientific investigations exploring coastal geology of this portion of North America have focused on understanding barrier island systems (Fisher, 1962 and 1968; Pierce and Colquhoun, 1970; Kraft, 1971; Leatherman, 1979; Moslow and Heron, 1979; 1994; Swift, 1975; Nummedal, 1983; Oertel, 1985; Belknap and Kraft, 1985; Hine and Snyder, 1985; Davis, 1994).

2.4 IMPORTANT FACTORS FOR MID-ATLANTIC SHORELINE CHANGE

Several important factors influence the evolution of the mid-Atlantic coast in response to sea-level rise. Among these are: 1) the geologic framework, 2) physical processes, 3) the sediment supply, 4) and human activity. Each of these influences the development of the coastal landscape and influences the response of coastal landforms to changes in sea level.

2.4.1 Geologic Framework

An important factor influencing coastal morphology and behavior is the underlying geology of a setting, which is also referred to as the geological framework. On a large scale, an example of this is the contrast in the characteristics of the Pacific coast versus the Atlantic coast of the United States. The collision of tectonic plates along the Pacific margin has contributed to the development of a steep coast where cliffs line much of the shoreline (Inman and Nordstrom, 1971; Muhs *et al.*, 1987; Dingler and Clifton, 1994; Griggs and Patch, 2004; Hapke *et al.*, 2006; Hapke and Reid, 2007). While common, sandy barriers and beaches along the Pacific margin are confined to river mouths and low-lying coastal plains that stretch between rock outcrops and coastal headlands. On the other hand, the Gulf of Mexico and Atlantic coasts of the U.S. are situated on a passive margin where tectonic activity is minor (Walker and Coleman, 1987). As a result, these coasts are composed of wide coastal plains and wide continental shelves extending far offshore. The majority of these coasts are lined with barrier beaches and lagoons, large estuaries, isolated coastal capes, and mainland beaches that abut highs in the surrounding landscape.

From a smaller scale perspective focused on the mid-Atlantic Bight, the influence of the geological framework involves more subtle details of the regional geology. More specifically, the distribution, structure, and orientation of different rock and sediment units as well as the presence of features such as river and creek valleys eroded into these rock units provides a structural control on a coastal environment (*e.g.*, Kraft, 1971; Belknap and Kraft, 1985; Fletcher *et al.*, 1990; Riggs *et al.*, 1995; Schwab *et al.*, 2000; Honeycutt and Krantz, 2003). Specifically, the framework geology can control (1) the location of features, such as inlets, capes, or sand-ridges, (2) the erodibility of sediments, and (3) the type and abundance of sediment available to the littoral system. In the mid-Atlantic Bight, the position of tidal inlets, estuaries, and shallow water embayments can be related to the existence of river and creek valleys that were present in the landscape during periods of lower sea level in a number of cases (*e.g.*, Kraft, 1971; Belknap and Kraft, 1985; Fletcher *et al.*, 1990). Elevated regions of the landscape, which can often be identified by areas where the mainland abuts the ocean coast, form coastal headlands. The erosion of these features supplies sand to the nearshore system. Differences in sediment composition (sediment size or density), can sometimes be related to differences in shoreline retreat rates (*e.g.*, Honeycutt and Krantz, 2003). In addition, the distribution of underlying geological units (rock outcrops, hard-grounds or sedimentary strata) in shallow regions offshore of the coast can modify waves and currents and influencing patterns of sediment erosion, transport, and deposition on the adjacent shores (Riggs *et al.*, 1995). These complex interactions with nearshore sand bodies and/or underlying geology can also influence the behavior of beach morphology over a range of time scales (Riggs *et al.*, 1995; Honeycutt and Krantz, 2003; Schuup *et al.*, 2006; Miselis and McNinch, 2006).

2.4.2 Physical Processes

The physical processes acting on a coast are a principal factor shaping coastal landforms and changes in shoreline position. Waves, tidal currents, and winds continually erode, rework, winnow, redistribute, and shape the sediments that make up these landforms. Waves are generated by local winds or result from of far-away disturbances such as large storms out at sea. Waves typically approach the shore at an angle, resulting in the generation of longshore currents. These currents provide a mechanism for sand transport along the coast, referred to as littoral transport, longshore drift or longshore transport. Where there are changes in coastal orientation, the angle which waves approach the coast changes and can lead to local reversals in longshore sediment transport. These variations can result in the creation of abundances or deficits of longshore sediment transport and contribute to the seaward growth or landward retreat of the shoreline at a particular location (*e.g.*, Cape Lookout, NC (McNinch and Wells, 1999)).

Tidal currents can be strong, particularly near the mouths of bays and tidal inlets, serving as a mechanism that transports sediment from ocean shores to backbarrier wetlands, inland waterways on flood tides and vice versa on ebb tides. Aside from these settings, tidal currents are generally small along the mid-Atlantic Bight except near changes in shoreline orientation or sand banks. In these settings, the strong currents generated can significantly influence sediment transport pathways and the behavior of adjacent shores.

2.4.3 Sediment Supply

The availability of sediments to a coastal region also has important effects on coastal landforms and their behavior. Coastal sediments generally come from erosion of the coast and from erosion of the continental shelf and onshore transport. In general, an abundance of sediment along the coast can cause the coast to build seaward over the long term if the rate of supply exceeds the rate at which sediments are eroded and transported by nearshore currents. Conversely, the coast can retreat landward if the rate of erosion exceeds the rate at which sediment is supplied to a coastal region. Considering stretches of the shore approaching 50 km or less, the concept of sediment supply is often referred to as the sediment budget. This refers to the amount of sediment being gained or lost from a coastal setting such as a stretch of beach (Komar, 1996; List, 2005). The sediment budget is a critical determinant of how a specific shoreline setting will respond to changes in sea level. At the same time, it is difficult if not impossible to quantify with high confidence the sediment budget over time periods as long as a century or its precise role in influencing shoreline changes.

2.4.4 Human Impacts

The human impact on the coast is another important factor affecting shoreline changes, especially over the past century. A variety of erosion control practices and alterations of the coast have been undertaken over the last century along much of the mid-Atlantic region, particularly during the latter half of the 20th century. In many cases, shoreline engineering structures such as seawalls, revetments, groins and jetties have significantly altered sediment transport processes, often exacerbating erosion on a local scale (See Box 2.1, northern Assateague Island). At the same time, beach nourishment has been used on many beaches to temporarily mitigate erosion and provide storm protection by adding to the sediment budget. It is uncertain if these mitigation practices are sustainable for the long term and whether or how these shoreline protection measures might impede the ability of natural processes to respond to future sea-level rise, especially at higher rates. It is also uncertain whether beach nourishment will be continued into the future due to economic constraints and often limited supplies of suitable sand resources. Because of these uncertainties, this assessment focuses on assessing the vulnerability of the coastal system as it currently exists.

2.5 COASTAL LANDFORMS OF THE MID-ATLANTIC

For this assessment, the coastal landforms along the shores of the mid-Atlantic Bight can be classified using the criteria developed by Fisher (1962; 1982), Hayes (1979), and Davis and Hayes (1984). Four distinct geomorphic settings occur in the mid-Atlantic region, as shown in Figure 2.1 and described below.

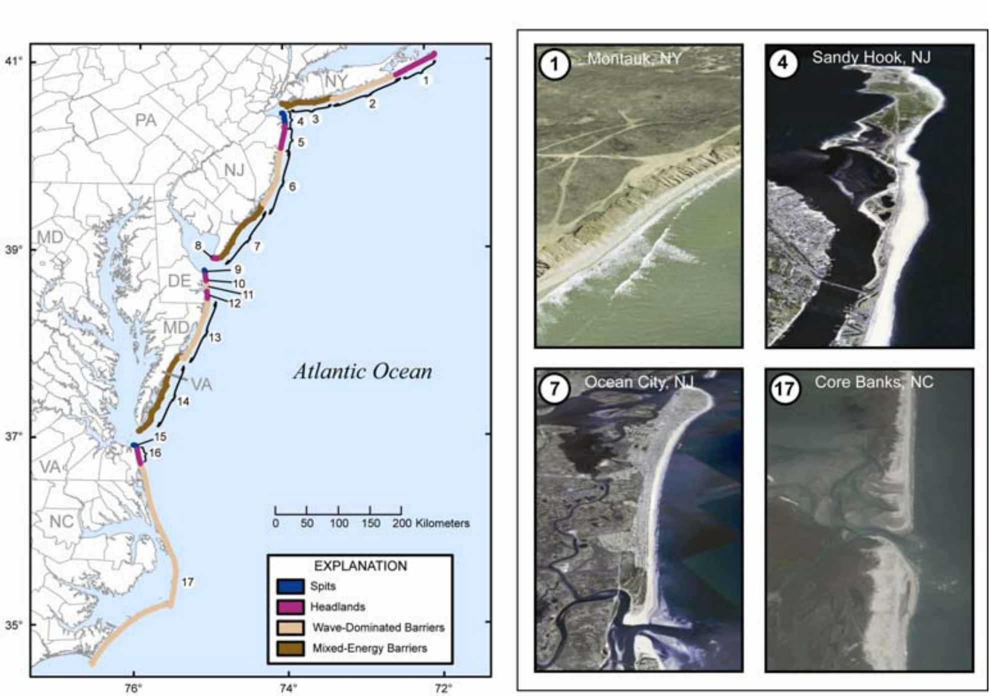


Figure 2.1 Map of the Mid-Atlantic coast of the U.S. showing the seventeen coastal compartments and their coastal geomorphic type**.** Numbers on the map specify specific coastal compartments and refer to the discussions in Sections 2.5 and 2.8. Numbers on the photographs refer to specific coastal compartments depicted on the map. Images from Google Earth. (Gutierrez *et. al.*, 2007).

2.5.1 Spits

The accumulation of sand from longshore transport has formed large spits that extend from adjacent headlands into the mouths of large coastal embayments (Figure 2.1, compartments 4, 9, and 15). Outstanding examples of these occur at the entrances of Raritan (Sandy Hook, NJ) and Delaware Bays (Cape Henlopen, DE). The evolution and existence of these spits results from the interaction between alongshore transport driven by incoming waves and the tidal flow through the large embayments. Morphologically these areas can evolve rapidly. For example, Cape Henlopen (Figure 2.1, compartment 9) has extended over 1.5 km to the north into the mouth of Delaware Bay since 1842 as the northern Delaware shoreline has retreated and sediment has been transported north by longshore currents (Kraft, 1971; Ramsey *et al.*, 2001).

2.5.2 Headlands

In the Mid-Atlantic, coastal headlands typically occur where elevated regions of the landscape intersect the coast. These regions are often drainage divides that separate creeks and rivers from one another in the landscape. The erosion of headlands provides a source of sediment that is incorporated into the longshore transport system that supplies and maintains adjacent beaches and barriers. Coastal headlands are present on Long Island, NY (See Figure 2.1), from Southampton to Montauk (compartment 1), in northern New Jersey from Monmouth to Point Pleasant (compartment 5; Oertel and Kraft, 1994), in southern New Jersey at Cape May (compartment 8), on Delaware north and south of Indian River and Rehoboth Bays (compartments 10 and 12; Kraft, 1971; Oertel and Kraft, 1994; Ramsey *et al.*, 2001), on the Virginia coast, from Cape Henry to Sandbridge (compartment 16).

2.5.3 Wave-Dominated Barrier Islands

Wave-dominated barrier islands occur as relatively long and thin stretches of sand fronting shallow estuaries, lagoons, or embayments and are bisected by widely-spaced tidal inlets (Figure 2.1, compartments 2, 6, 10, 13, and 17). These barriers are present in regions where wave energy is large relative to tidal energy, such as in the mid-Atlantic region (Hayes, 1979; Davis and Hayes, 1984). Limited tidal ranges result in flow through tidal inlets that is marginally sufficient to flush the sediments that accumulate from longshore sediment transport. In some cases this causes the inlet to migrate over time in response to a changing balance between tidal flow through the inlet and wave driven alongshore transport. Inlets on wave-dominated coasts often exhibit large flood-tidal deltas and small ebb-tidal deltas as tidal currents are often stronger during the flooding stage of the tide.

In addition, inlets on wave-dominated barriers are often temporary features. They open intermittently in response to storm-generated overwash and migrate laterally in the direction of net littoral drift. In many cases these inlets are prone to filling with sands from alongshore transport (*e.g.*, McBride, 1999).

Overwash produced by storms is common on wave-dominated barriers (*e.g.*, Morton and Sallenger, 2003; Riggs and Ames, 2007). Overwash erodes low-lying dunes into the island interior. Sediment deposition from overwash adds to the island's elevation. Washover fans that extend into the backbarrier waterways form substrates for backbarrier marshes and submerged aquatic vegetation.

The process of overwash is an important mechanism by which some types of barriers migrate landward and upward over time. This process of landward migration has been referred to as "roll-over" (Dillon, 1970; Godfrey and Godfrey, 1976; Fisher, 1982; Riggs and Ames, 2007). Over decades to centuries, the intermittent processes of overwash and inlet formation enable the barrier to migrate over and erode into back-barrier environments such as marshes as relative sea-level rise occurs over time. As this occurs, back-barrier environments such as marshes are eroded and buried by barrier beach and dune sands.

2.5.4 Mixed-Energy Barrier Islands

The other barrier island type present along the U.S. Atlantic coast, mixed-energy barrier islands, is shorter and wider than their wave-dominated counterparts (Hayes, 1979; Figure 2.1, compartments 3, 4, 7, and 14). The term “mixed-energy” refers to the fact that while waves are an important factor influencing the morphology of these systems, tidal currents are also significant and influence the barriers island morphology. Due to the influence of the tidal inlets, mixed energy barriers are punctuated by well-developed tidal inlets. Some authors have referred to the mixed-energy barriers as tide-dominated barriers along the Delmarva shoreline (*e.g.*, Oertel and Kraft, 1994).

The large sediment transport capacity of the tidal currents within the inlets of these systems maintains large ebb-tidal deltas seaward of the inlet mouth. The shoals that comprise ebb-tidal deltas cause incoming waves to refract around the large sand body that forms the delta so that local reversals of alongshore currents and sediment transport occur downdrift of the inlet. As a result, portions of the barrier downdrift of inlets become localized sediment sinks that are manifest as recurved sand ridges, giving the barrier islands a ‘drumstick’-like shape (Hayes 1979; Davis, 1994).

2.6 TWENTIETH CENTURY RATES OF SEA-LEVEL RISE

Over the last century, relative sea-level rise rates along the Atlantic coast of the U.S. have ranged between 1.8 mm/yr to as much as 4.4 mm/yr (Table 2.1; Zervas, 2001). The lowest rates (1.75-2 mm/yr) are close to the present global rate of 1.7 ± 0.5 mm/yr (Bindoff *et al.*, 2007) and occur along coastal New England and from Georgia to northern Florida. The highest rates have been observed in the mid-Atlantic region between northern New Jersey and southern Virginia. Subsidence of the land surface due to a range of factors contributes to the high rates of relative sea-level rise observed in this region. It is believed that the subsidence is attributable mainly to glacio-isostatic adjustments of the earth's crust in response to the melting of the Laurentide ice sheet, and to the compaction of sediments due to freshwater withdrawal from coastal aquifers (Gornitz and Lebedeff, 1987; Emery and Aubrey, 1991; Kearney and Stevenson, 1991; Douglas, 2001; Peltier, 2001).

With the anticipated acceleration in the rate of global sea-level rise (*e.g.*, IPCC report, Bindoff *et al.*, 2007), local rates of relative sea-level rise will also accelerate. Recently, the Fourth Assessment Report (FAR) of the Intergovernmental Panel on Climate Change (IPCC) has predicted that sea level will rise by 10-59 cm over the next century (Bindoff *et al.*, 2007), which is a somewhat smaller rise and range than indicated in the Third Assessment Report (TAR, IPCC, 2001; estimate 11-88 cm) (Church *et al.*, 2001), but has a higher confidence (90%) than the TAR. Since rates of relative sea-level rise in the Mid-Atlantic exceed the global rate for the 20th century, it can be expected that sea-level rise in this region will exceed these projections.

Table 2.1 Rates of relative sea-level rise for selected long-term tide gauges on the East Coast of the United States (Zervas, 2001).

Station	Rate of Sea-level rise (mm/yr)	Latitude	Longitude	Time Span of Record
Eastport, ME	2.12 ± 0.13	44.9033	-66.9850	1929-1999
Portland, ME	1.91 ± 0.09	43.6567	-70.2467	1912-1999
Seavey Island, ME	1.75 ± 0.17	43.0833	-69.2500	1926-1999
Boston, MA	2.65 ± 0.1	42.3550	-71.0517	1921-1999
Woods Hole, MA	2.59 ± 0.12	41.5233	-70.2222	1932-1999
Providence, RI	1.88 ± 0.17	41.8067	-71.4017	1938-1999
Newport, RI	2.57 ± 0.11	41.5050	-71.3267	1930-1999
New London, CT	2.13 ± 0.15	41.3550	-72.0867	1938-1999
Montauk, NY	2.58 ± 0.19	41.0733	-71.935	1947-1999
Willets Point, NY	2.41 ± 0.15	40.8000	-72.2167	1931-1999
The Battery, NY	2.77 ± 0.05	40.7000	-74.0150	1905-1999
Sandy Hook, NJ	3.88 ± 0.15	40.4667	-73.9833	1932-1999
Atlantic City, NJ	3.98 ± 0.11	39.355	-74.4183	1922-1999
Philidelphia, PA	2.75 ± 0.12	39.9335	-75.1417	1900-1999
Lewes, DE	3.16 ± 0.16	38.7817	-75.1200	1919-1999
Baltimore, MD	3.12 ± 0.08	39.2667	-76.5783	1902-1999
Annapolis, MD	3.53 ± 0.13	38.9833	-76.4800	1928-1999
Solomons Island, MD	3.29 ± 0.17	38.3167	-76.4517	1937-1999
Washington D.C.	3.13 ± 0.21	38.8733	-77.0217	1931-1999
Hampton Roads, VA	4.42 ± 0.16	36.9467	-76.3300	1927-1999
Portsmouth, VA	3.76 ± 0.23	36.8167	-75.7000	1935-1999
Wilmington, NC	2.22 ± 0.25	34.2267	-77.9533	1935-1999
Charleston, SC	3.28 ± 0.14	32.7817	-79.9250	1921-1999
Fort Pulaski, GA	3.05 ± 0.2	32.3330	-80.9017	1935-1999
Fernandina Beach, FLA	2.04 ± 0.12	30.6717	-81.4650	1897-1999
Mayport, FLA	2.43 ± 0.18	30.3967	-81.4300	1928-1999
Miami, FLA	2.39 ± 0.22	25.7667	-79.8667	1931-1999
Key West, FLA	2.27 ± 0.09	24.5533	-81.8083	1913-1999

2.7 POTENTIAL RESPONSES TO FUTURE SEA-LEVEL RISE

Based on our understanding of the four landforms discussed in the previous section, three potential responses could occur along the mid-Atlantic coast in response to sea-level rise over the next century.

2.7.1 Bluff and Upland Erosion

Shorelines along headland regions of the coast will retreat landward with rising sea level. As sea level rises over time, uplands will be eroded and the sediments incorporated into the beach and dune systems along these shores. Along coastal headlands, bluff and upland erosion will persist under all four of the sea-level rise scenarios considered in this report. A possible management reaction to bluff erosion is shore armoring. This may reduce bluff erosion in the short term but could increase erosion of the adjacent coast by reducing sediment supplies to the littoral system.

2.7.2 Overwash, Inlet Processes, and Barrier Island Morphologic Changes

For barrier islands, three main processes are agents of change as sea level rises. First, storm overwash may occur more frequently. This is especially critical if the sand available to the barrier is limited and insufficient to allow the barrier to maintain its width and/or build vertically over time in response to rising water levels. If sediment supplies or the timing of the barrier recovery are insufficient, storm surges coupled with breaking waves will affect increasingly higher elevations of the barrier systems as mean sea level increases, possibly causing more extensive erosion and overwash. In addition, the potential for higher waves and storm surge can be linked to recent assertions that hurricanes have become more powerful over the last century in response to global warming (Emanuel, 2005; Webster *et al.*, 2005). Some have argued that there is insufficient evidence to support this finding (Landsea *et al.*, 2006), but others have confirmed the increase in hurricane strength region in the western North Atlantic (Kossin *et al.*, 2007) and the link to greenhouse warming (Holland and Webster, 2007). Recently, analyses of long-term wave data from Atlantic coast ocean buoys indicates that summer-time wave heights have increased since the mid-1970s and are related to Atlantic hurricane activity (Komar and Allan, 2007). At the same time, scientists acknowledge that it is not yet possible to predict future increases in hurricane intensity nor frequency with certainty due to a range of complexities. Some attempts to model future scenarios indicate that some meteorological factors such as wind shear could strengthen limiting tropical cyclone activity (Vecchi and Soden, 2007). Details regarding current and future trends are reviewed in detail in SAP 3.3.

Second, tidal inlet formation and migration will contribute to important changes in the future shoreline position. Storm surges coupled with high waves can cause not only barrier island overwash but also breach the barriers and create new inlets. In some cases, breaches can be large enough to form inlets that persist for some time until the inlet channels fill with sediments accumulated from longshore transport. Geological investigations along the shores of the mid-Atlantic Bight have found numerous deposits indicating former inlet positions (Moslow and Heron, 1979; Everts *et al.*, 1983; Leatherman, 1985; for North Carolina and Fire Island, New York, respectively). Some classic examples of mid-Atlantic Bight inlets that were formed by the storm surges and breaches from the 1933 hurricane are: Shackleford inlet (NC); Ocean City inlet (MD); Indian River inlet (DE); and Moriches inlet (NY). Most recently, tidal inlets formed in the North Carolina Outer Banks in response to Hurricane Isabel (in 2003) and on Nauset Beach, on Cape Cod, in response to an April 2007 storm. While episodic inlet formation and migration are natural processes and can occur independently of long-term sea-level rise, a long-term increase in sea level coupled with limited sediment supply and increases in storm frequency and/or intensity could increase the likelihood for future inlet breaching.

Third, the combined effect of rising sea level and stronger storms could accelerate barrier island shoreline changes. These will involve both changes to the seaward facing and landward facing shores of some barrier islands. Assessments of shoreline change on barrier islands indicate that that barriers have thinned in some areas over the last century (Leatherman, 1979; Jarrett, 1983; Everts *et al.*, 1983; Penland *et al.*, 2005). Evidence of barrier migration has been less apparent, but is documented at Core Banks, NC (Riggs and Ames, 2007), Louisiana and southern Virginia.

2.7.3 Threshold Behavior

Barrier islands are dynamic environments that are sensitive to a range of factors. Some evidence suggests that changes in some or all of these factors can lead to conditions where a barrier system becomes less stable and crosses a geomorphic threshold. In this situation, the potential for significant changes to the barrier island is high. These changes can involve landward migration or changes to the barrier island dimensions itself (reduction in size, increased presence of tidal inlets). It is difficult to precisely define an unstable barrier but indications of instability can be:

- Rapid landward migration of the barrier

- Decrease in barrier width and height possibly from a loss of beach and dune sand volume
- Increased frequency of overwash during storms
- Increased frequency of barrier breaching and inlet formation
- Segmentation of the barrier.

Given the unstable state of some barrier islands under current rates of sea-level rise and climate trends, it is very likely that conditions will worsen under accelerated sea-level rise rates. The unfavorable conditions for barrier maintenance could result in significant changes to barrier islands as witnessed in coastal Louisiana (See also, Box 2.1; McBride *et al.*, 1995; McBride and Byrnes, 1997; Penland *et al.*, 2005; Day *et al.*, 2007; Sallenger *et al.*, 2007). Here the Chandeleur Islands appear to be disintegrating as the result of a combination of 1) limited sediment supply by longshore or cross-shore transport, 2) accelerated rates of sea-level rise, and 3) permanent sand removal from the barrier system by storms such as Hurricanes Camille, Georges and Katrina. In addition, recent studies from the North Carolina Outer Banks indicate that there have been at least two periods during the past several thousand years where fully open-ocean conditions have occurred in Albemarle and Pamlico Sounds, which are estuaries fronted by barrier islands at the present time (Culver *et al.*, 2007). These findings have led marine scientists to suggest that portions of the North Carolina barrier island system may have segmented or become less continuous than present for periods of a few hundred years, and later reformed. Given future increases in sea level and/or storm activity, the potential for a threshold crossing exists. Portions of these barrier islands could once again become segmented or disintegrate.

Changes in sea level coupled with changes in the hydrodynamic climate and sediment supply in the broader coastal environment contribute to the development of unstable behavior. The threshold behavior of unstable barriers could result in: a) barrier segmentation b) barrier disintegration, or, c) landward migration and roll-over. If the barrier were to disintegrate, portions of the ocean shoreline could migrate or back-step toward and/or merge with the mainland.

The parts of the mid-Atlantic coast most vulnerable to threshold behavior can be estimated based on their physical dimensions. During storms, large portions of low-elevation, narrow barriers can be inundated under high waves and storm surge. Narrow, low-elevation barrier islands are most susceptible to storm overwash, which can lead to landward migration, and the formation of new tidal inlets. The northern portion of Assateague Island, MD is an example of a barrier that is extremely vulnerable to even modest storms because of its narrow width and low elevation (*e.g*., Leatherman, 1979; see also Box 2.1 and included figures).

The future evolution of low-elevation, narrow barriers could depend in part on the ability of salt marshes in back-barrier lagoons and estuaries to keep pace with sea-level rise (FitzGerald *et al.*, 2003; FitzGerald *et al.*, 2006; Reed *et al.*, 2007). It has been suggested that a reduction of salt marsh in back-barrier regions could change the hydraulics of backbarrier systems, altering local sediment budgets and leading to a reduction in sandy materials available to sustain barrier systems (FitzGerald *et al.*, 2003; 2006).

Box 2.1 Evidence for threshold crossing of coastal barrier landforms

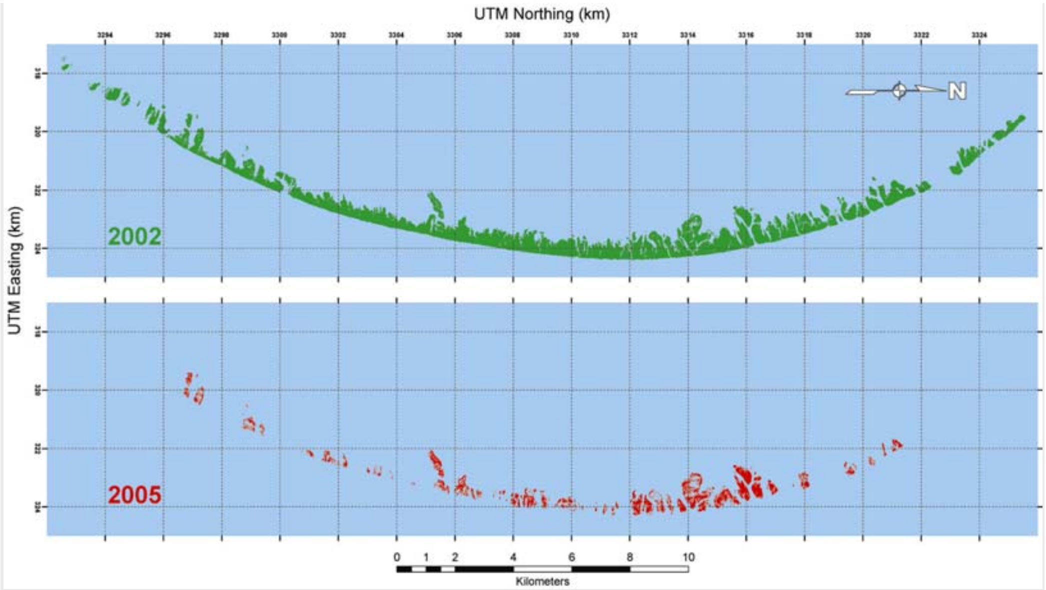
It has been generally thought by coastal scientists that barrier islands change and evolve in subtle and somewhat predictable ways over time in response to storms, changing sediment supply, and sea-level rise. Recent field observations, however, suggest that some barrier islands can reach a "threshold" condition where they become unstable and disintegrate. Two sites where barrier island disintegration is occurring and may occur are **a)** along the 72 km long Chandeleur Islands in Louisiana, east of the Mississippi River delta, due to impacts of Hurricane Katrina in September 2005, and **b)** the northern 10 km of Assateague Island National Seashore, Maryland due to 70 years of sediment starvation caused by the construction of jetties to maintain Ocean City inlet.

Chandeleur Islands, Louisiana

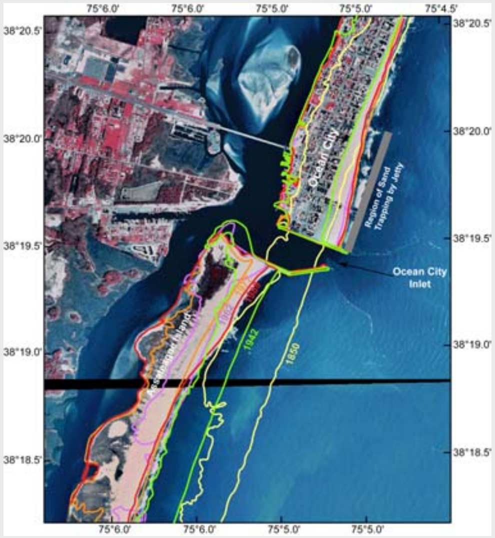
In the Chandeleur Islands, the high storm surge (~ 4 m) and waves associated with Hurricane Katrina in 2005 completely submerged the islands and eroded about 85 percent of the sand from the beaches and dunes (Sallenger *et al.*, 2007). Box Figure 2.1a (UTM Northing) shows the configuration of the barriers in 2002, and in 2005 after Katrina's passage. Follow-up USGS aerial surveys indicate that erosion has continued. Natural island rebuilding has been minimal. When the Chandeleur Islands were last mapped in the late 1980s and erosion rates were calculated from the 1850s, it was calculated that the Chandeleurs would last approximately 250 to 300 years (Williams *et al.*, 1992). The results from post-Katrina studies suggest that some threshold has been crossed such that conditions have changed and natural processes may not contribute to the rebuilding of the barrier in the future.

Assateague Island National Seashore, Maryland

An example of one shoreline setting where human activity has increased the vulnerability of the shore to sea-level rise, is Assateague Island, Maryland. Prior to a hurricane in 1933, Assateague Island was a continuous, straight barrier connected to Fenwick Island (Dolan *et al.*, 1980). An inlet that formed during the storm separated the island into two sections at the southern end of Ocean City, Maryland. Subsequent construction of two stone jetties to maintain the inlet for navigation interrupted the longshore transport of sand to the south. Since then, the jetties have trapped sand building the Ocean City shores seaward by 250 m by the mid-1970s (Dean and Perlin, 1977). In addition, the development of sand shoals (ebb tidal deltas) around the inlet mouth has sequestered large volumes of sand from the longshore transport system (Dean and Perlin, 1977; FitzGerald, 1988). South of the inlet, the opposite has occurred. The sand starvation on the northern portion of Assateague Island has cause the shore to migrate almost 700 m landward and transformed the barrier into a low-relief, overwash-dominated barrier (Leatherman, 1979; 1984). This extreme change in barrier island sediment supply has caused a previously stable segment of the barrier island to migrate. To mitigate the effects of the jetties, beach nourishment is undertaken periodically by the U.S. Army Corps of Engineers and National Park Service as shown in Box Figure 2.1c, to elevate the barrier using sand dredged from the tidal deltas and offshore. Current, plans call for periodic sand renourishment of Assateague to prevent further deterioration. The long-term sustainability of such an approach to maintain Assateague Island is unknown.



Box Figure 2.1a Maps showing the extent of the Chandeluer Islands in A) 2002, three years before Hurricane Katrina and in B) 2005, after Hurricane Katrina (B). Land area above Mean High water. Source: USGS



Box Figure 2.1b Aerial Photo of northern Assateague Island and Ocean City, MD with historical shorelines showing former barrier positions. Note that in 1850, a single barrier island occupied this stretch of coast. Ocean City was opened during a 1933 storm. Shorelines acquired from the State of Maryland Geological Survey. Photo source: NPS.

Box Figure 2.1c North oblique photographs of northern Assateague Island in 1998 after a severe winter storm. The left photo of Assateague Island barrier shows clear evidence of overwash. The right 2006 photo shows a more robust barrier that had been augmented by recent beach nourishment. The white circles in the photos specify identical locations on the barrier. The offset between Fenwick Island (north) and Assateague Island due to Ocean City inlet and jetties can be seen at the top of the photo. Sources: a) Unknown, b) Jane Thomas, IAN Photo and Video Library.

2.8 POTENTIAL CHANGES TO THE MID-ATLANTIC OCEAN COAST DUE TO SEA-LEVEL RISE

In this section, the responses to the four sea-level rise scenarios considered in this chapter are described according to coastal landform types (Figure 2.2). As defined in the Preface and Context Chapter the first three sea-level rise scenarios (Scenarios 1-3) are: 1) a continuation of the 20th century rate, 2) the 20th century rate plus 2 mm/yr, and 3) the 20th century rate plus 7 mm/yr. The last scenario, Scenario 4, specifies a 2-m rise over the next few hundred years. The coastal scientists that contributed to this assessment recognized that there are a few caveats to this approach. These are:

- This is a regional scale assessment and there are local exceptions to these classifications and potential outcomes,
- Given that some portions of the mid-Atlantic coast are heavily influenced by development and erosion mitigation practices, it could not be assumed that these would be continued into the future given uncertainties regarding the decision-making process that occurs when these practices are pursued, but
- At the same time, there were locations where some members of the panel felt that erosion mitigation would be implemented regardless of cost.

To express the likelihood of a given outcome for a particular sea-level rise scenario, the terminology advocated by ongoing CCSP assessments was used (CCSP, 2006; See the Preface of this Report). This terminology is used to quantify and communicate the degree of likelihood of a given outcome specified by the assessment. This represents the degree of confidence that the contributing scientists believe that a specific outcome will be achieved. These terms should not be construed to represent a quantitative relationship between a specific sea-level rise scenario and a specific dimension of coastal change, or rate at which a specific process operates on a coastal geomorphic compartment. The potential coastal responses to the sea-level rise scenarios are described below according to the coastal landforms defined in Section 2.5.

2.8.1 Spits (Compartments 4, 9, 15)

For sea-level rise Scenarios 1-3, it is **virtually certain** that the coastal spits in the mid-Atlantic Bight will be subject to increased storm overwash, erosion, deposition over the next century. It is **virtually certain** that some of these coastal spits will continue to grow though the accumulation of sediments from longshore transport as the erosion of updrift coastal compartments occurs. For Scenario 4, it is **likely** that threshold behavior could occur for this type of coastal landform (rapid landward and/or alongshore migration).

2.8.2 Headlands (Compartments 1, 5, 8, 10, 12, 16)

Over the next century, it is **virtually certain** that these headlands will be subject to increased erosion for all four sea-level rise scenarios. It is **very likely** that shoreline and upland (bluff) erosion will accelerate in response to projected increases in sea level.

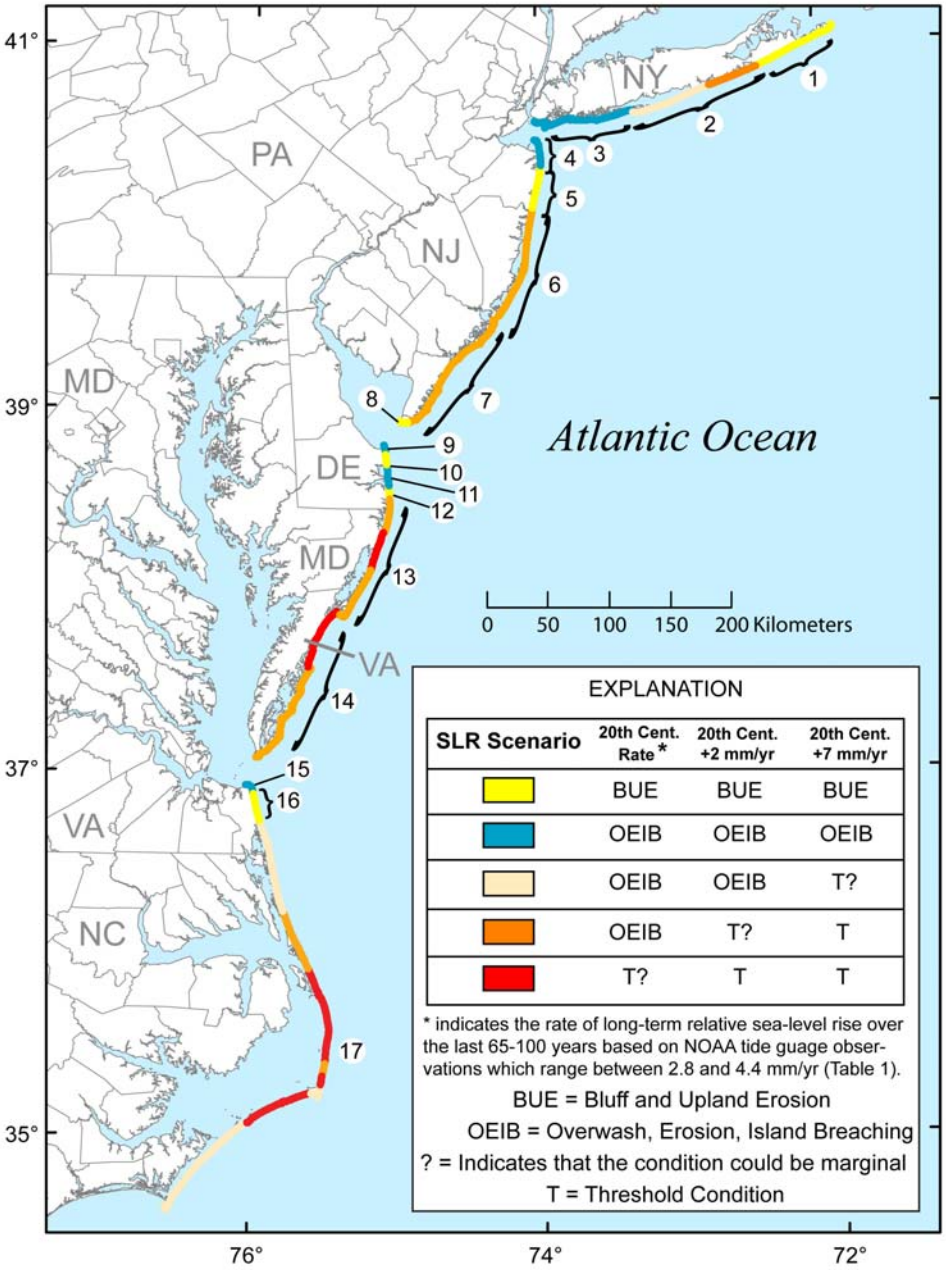
2.8.3 Wave-Dominated Barrier Islands (Compartments 2, 6, 11, 13, 17)

Potential sea-level rise impacts on wave-dominated barriers in the Mid-Atlantic vary spatially and depend on the sea-level rise scenario (Figure 2.2). For Scenario 1, it is **virtually certain** that the majority of the wave-dominated barrier islands in the mid-Atlantic Bight will continue to experience morphological changes through erosion, overwash, and inlet formation as they have over the last several centuries. The northern portion of Assateague Island (compartment 13) is an exception. Here the shoreline exhibits high rates of erosion and large portions of this barrier are submerged during moderate storms. At times in the past, large storms have breached and segmented portions of northern Assateague Island (Morton *et al.*, 2003). Due to this behavior, it is possible that these portions of the coast are already 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 this island. Periodic nourishment and sand bypassing at Ocean City Inlet may reduce erosion on

Compartment 13, but the long-term sustainability of this practice is uncertain. Portions of the North Carolina Outer Banks (Figure 2.2) may similarly be nearing a geomorphic threshold.

For Scenario 2, it is **virtually certain** that the majority of the wave-dominated barrier islands in the mid-Atlantic Bight will continue to experience morphological changes through overwash, erosion, and inlet formation as they have over the last several centuries. It is also **about as likely as not** that a geomorphic threshold could be reached in a few locations, resulting in rapid morphological changes in these barrier systems. Along the shores of northern Assateague Island (compartment 13) and a substantial portion of compartment 17 it is **very likely** that the barrier islands could exhibit threshold behavior (barrier segmentation). For 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.*, 2007). It is **about as likely as not** that the loss of back-barrier marshes could lead to changes in hydrodynamic conditions between tidal inlets and back-barrier lagoons affecting the evolution of barrier islands (*e.g.*, FitzGerald *et al.*, 2003; 2006).

For Scenario 3, it is **very likely** that the potential for threshold behavior will increase. It is **virtually certain** that a 2 m sea-level rise will lead to threshold behavior (segmentation or disintegration) for this landform type.



SLR Scenario	20th Cent. Rate*	20th Cent. +2 mm/yr	20th Cent. +7 mm/yr
🟨	BUE	BUE	BUE
🟦	OEIB	OEIB	OEIB
▨	OEIB	OEIB	T?
🟧	OEIB	T?	T
🟥	T?	T	T

* indicates the rate of long-term relative sea-level rise over the last 65-100 years based on NOAA tide guage observations which range between 2.8 and 4.4 mm/yr (Table 1).

BUE = Bluff and Upland Erosion

OEIB = Overwash, Erosion, Island Breaching

? = Indicates that the condition could be marginal

T = Threshold Condition

Figure 2.2 Map showing the potential sea-level rise responses for each coastal compartment. Colored portions of the coastline indicates the potential response for a given sea-level rise scenario according to the inset table. Numbers designate coastal compartments shown in Figure 2.1 (Gutierrez *et. al.*, 2007).

2.8.4 Mixed-Energy Barrier Islands (Compartments 3, 7, 14)

The response of mixed-energy barrier islands will vary among coastal compartments. For Scenarios 1 and 2, the mixed-energy barrier islands along the Mid-Atlantic will be subject to processes much as have occurred over the last century such as storm overwash and shoreline erosion. Given the degree to which these barriers have been developed, it is difficult to determine the likelihood of future inlet breaches, or whether such breaches would be allowed to persist. In addition, changes to the back-barrier shores are uncertain due to the extent of development.

For the higher sea-level rise scenarios (Scenarios 3 and 4), it is **about as likely as not** that these barriers could reach a geomorphic threshold. This threshold is dependent on the availability of sand from the longshore transport system to supply the barrier. It is **virtually certain** that a 2 m sea-level rise will have severe consequences along the shores of this compartment, including one or more of the extreme responses described above. For Scenario 4, the ability of wetlands to maintain their elevation through accretion at higher rates of sea-level rise may be reduced (Reed *et al.*, 2007). It is **about as likely as not** that the loss of back-barrier marshes could lead to changes in the hydrodynamic conditions between tidal inlets and back-barrier lagoons, affecting the evolution of barrier islands (FitzGerald *et al.*, 2003; 2006).

It is **about as likely as not** that four of the barrier islands along the Virginia coast (Wallops Island, Assawoman Island, Metompkin Island, and Cedar Island) are presently at a geomorphic threshold. Thus, it is **very likely** that further sea-level rise will contribute to significant changes resulting in the segmentation, disintegration and/or more rapid landward migration of these barrier islands.

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Chapter 3. Coastal Wetland Sustainability

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KEY FINDINGS

- It is **virtually certain** that tidal wetlands already experiencing submergence by sea-level rise and associated high rates of loss (*e.g.*, Mississippi River Delta in Louisiana, Blackwater River marshes in Maryland) will continue to lose area under the influence of future accelerated rates of sea-level rise and changes in other climate and environmental drivers.
- It is **very unlikely** that there will be a net increase in tidal wetland area on a national scale over the next 100 years, given current wetland loss rates and the relatively minor accounts of new tidal wetland development (*e.g.*, Atchafalaya Delta in Louisiana),
- Current model projections of wetland vulnerability on regional and national scales are uncertain because of the coarse level of resolution of landscape scale models. In contrast, site-specific model projections are quite good where local information has been acquired on factors that control local accretionary processes in specific wetland settings. However, we have low confidence that site-specific model simulations can

be successfully scaled up to provide realistic projections at regional or national scales.

- A regional assessment based on an expert opinion approach projects with a moderate level of confidence that those wetlands keeping pace with 20th century rates of sea-level rise (Scenario 1) would survive under Scenario 2 only under optimal hydrology and sediment supply conditions, and would not survive under Scenario 3. Exceptions may be found locally where sediment supplies are abundant, such as those that accompany storm overwash events.
- The regional assessment revealed a wide variability in wetland responses to sea-level rise, both within and among subregions and for a variety of wetland settings. This underscores both the influence of local processes on wetland elevation and the difficulty of scaling down regional/national scale projections of wetland sustainability to the local scale in the absence of local accretionary data. Thus regional or national scale assessments should not be used to develop local management plans where local accretionary dynamics may override regional controls on wetland vertical development.
- Several key uncertainties need to be addressed to improve confidence in projecting wetland vulnerability to sea-level rise. These include a better understanding of maximum rates at which wetland vertical accretion can be sustained; interactions and feedbacks among wetland elevation, flooding, and soil organic matter accretion; broad scale, spatial variability in accretionary dynamics; land use change effects (freshwater runoff, sediment supply, barriers to wetland migration) on tidal wetland

accretionary processes; and local and regional sediment supplies, particularly fine-grain cohesive sediments needed for wetland formation.

Given the expected increase in the rate of sea-level rise in the next century, effective management of the highly valuable coastal wetland habitats and resources in the United States will be enhanced by an in-depth assessment of the effects of accelerated sea-level rise on wetland vertical development (*i.e.*, vertical accretion), the horizontal processes of shoreline erosion and landward migration affecting wetland area, and the expected changes in species composition of plant and animal communities. This chapter assesses future changes in the vertical buildup of coastal wetland surfaces and wetland sustainability during the next century under the three sea-level rise scenarios described in the Context chapter. Many factors must be considered in such an assessment, including the interactive effects of sea-level rise and other environmental drivers (*e.g.*, changes in sediment supplies and storms), local processes controlling wetland vertical and horizontal development and the interaction of these processes with the array of environmental drivers, geomorphic setting, and limited opportunities for landward migration (*e.g.*, human development on the coast, or a steep slope) (Figures 3.1 and 3.2). Consequently, there is no simple, direct answer to this chapter's key question, particularly on national and regional scales, because of the various combinations of local drivers and processes controlling wetland elevation across the many tidal wetland settings found in North America, and the lack of available data on the critical drivers and local processes across these larger landscape scales. The ability of wetlands to keep pace with sea-level rise can be more confidently addressed at the scale of individual wetlands where data are available on the critical drivers and local processes. Scaling up from the local to the national perspective, however, is difficult, and is rarely done, because of data constraints and spatial and temporal interactions that become influential at larger scales. Better estimates of coastal wetland sustainability during future sea-level rise, and the factors influencing future sustainability, are needed to inform coastal management decision making. This chapter gives an overview of the factors influencing wetland sustainability (*e.g.*, environmental drivers, accretionary processes, and geomorphic settings), our understanding of current and future wetland sustainability, including a regional case study analysis of the Mid-Atlantic coast of the United States, and information needed to improve our projections of future wetland sustainability at national, regional, and local scales.

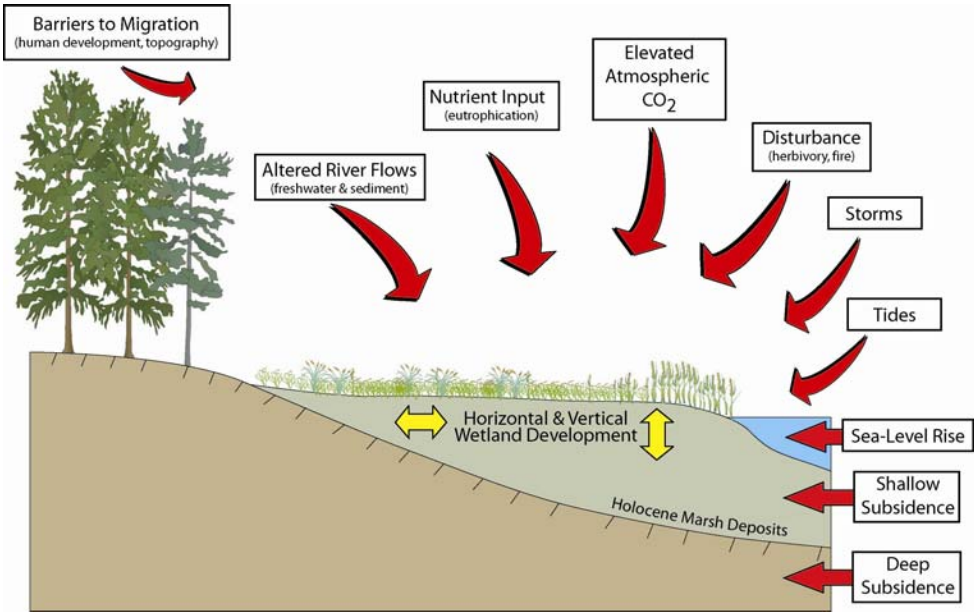


Figure 3.1 Climate and environmental drivers influencing vertical and horizontal wetland development.

3.1 WETLAND ACCRETIONARY DRIVERS AND PROCESSES

Coastal managers would like to know if marsh elevation change will keep pace with future, accelerated sea-level rise. It is well established that marsh surface elevation changes in response to sea-level rise. Tidal wetland surfaces are frequently considered to be in an equilibrium relationship with local mean sea level (*e.g.*, Pethick, 1981; Allen, 1990), although recent modeling research suggests marshes are not at equilibrium with relatively high frequency sea-level oscillations (Kirwan and Murray, 2006). The response of tidal wetlands to future sea-level rise will be influenced not only by local site characteristics (*e.g.*, slope and soil erodibility influences on sediment flux) but also by changes in drivers of vertical accretion, some of which are themselves influenced by climate change (Figure 3.1). Wetland accretionary dynamics are sensitive to changes in a suite of climate-related drivers, including the rate of sea-level rise, alterations in river and sediment discharge, increased frequency and intensity of hurricanes, and increased atmospheric temperatures and carbon dioxide concentrations. Accretion is also affected by local environmental drivers such as shallow (local) and deep (regional) subsidence, disturbance, and human coastal development that can form a barrier to landward marsh migration (Figure 3.1). Even if landward migration is blocked by natural or human barriers, a marsh could survive in place given an adequate accumulation of mineral sediment and soil organic matter to counteract sea-level rise (Cahoon *et al.*, 2000) and to offset shore erosion. The relative roles of these drivers of wetland vertical development vary with geomorphic setting.

3.1.1 Wetland Accretionary Dynamics

Projecting future wetland sustainability is made more difficult by the complex interaction of processes by which wetlands build vertically (Box 3.1, Figure 3.2) and which vary across geomorphic settings. This suite of processes controls the rates of mineral sediment deposition and accumulation of plant organic matter in the soil, and ultimately wetland elevation change. A description of the geomorphic settings is presented in the Part I Overview and a list of accretionary processes in Box 3.1. Net mineral sedimentation represents the balance between sediment import and export, which is influenced by sediment supply and grain size distribution, and varies among geomorphic settings and tidal and wave energy regimes. The delivery of sediments to the wetland surface occurs during flooding, which controls both the opportunity for deposition and the availability of sediment (Reed, 1989). Sediment may be derived from within an estuary by remobilization, and from fluvial and oceanic sources. Mechanisms of sediment remobilization and delivery include storms, tides, and, in higher latitudes, ice rafting. The formation of organic-rich wetland soils is an important contributor to wetland elevation, particularly in environments with low mineral sediment supplies. Organic matter accumulation represents the balance between plant production (especially production of roots and rhizomes) and decomposition/export of plant organic matter (Figure 3.2). Roots and rhizomes contribute mass, volume, and structure to the sediments. Figure 3.2 displays the relationship among environmental drivers, minerogenic and organogenic soil development processes, and wetland elevation. The dominant accretionary processes vary with geomorphic setting (Table 3.1).

Table 3.1 Wetland geomorphic settings and dominant accretionary processes in the continental United States.

Geomorphic Setting	**Description**	**Sub-settings**	**Dominant processes**	**Example Site**	**Dominant vegetation**
1. Open Coast	Areas sheltered from waves and currents due to coastal topography or bathymetry		Storm sedimentation Peat accumulation	Appalachee Bay, FL	smooth cordgrass ***(Spartina alterniflora)*** black needlerush ***(Juncus roemerianus)*** spike grass *(Distichlis spicata)* salt hay *(Spartina patens)* glasswort *(Salicornia* spp.) saltwort *(Batis maritima)*
2. Back Barrier Lagoon Marsh (BB)	Occupies fill within transgressive back barrier lagoons	Backbarrier Active flood tide delta Lagoonal fill	Storm sedimentation (including barrier overwash) Peat accumulation Oceanic inputs via inlets	Great South Bay, NY; Chincoteague Bay, MD, VA	smooth cordgrass *(Spartina alterniflora)* black needlerush ***(Juncus roemerianus)*** spike grass *(Distichlis spicata)* salt hay *(Spartina patens)* glasswort *(Salicornia* spp.) saltwort *(Batis maritima)*
3. Estuarine Embayment	Shallow coastal embayments with some river discharge, frequently drowned river valleys			Chesapeake Bay, MD, VA; Delaware Bay, NJ, PA, DE,	
a. Saline Fringe Marsh (SF)	Transgressive marshes bordering uplands at the lower end of estuaries (can also be found in back barrier lagoons)		Storm sedimentation Peat accumulation	Peconic Bay, NY; Western Pamlico Sound, NC	smooth cordgrass *(Spartina alterniflora)* black needlerush ***(Juncus roemerianus)*** spike grass *(Distichlis spicata)* salt hay *(Spartina patens)* glasswort *(Salicornia* spp.) saltwort *(Batis maritima)*
b. Stream Channel Wetlands	Occupy estuarine/alluvial channels rather than open coast			Dennis Creek, NJ; Lower Nanticoke River, MD	
Estuarine	Located in	Meander	Alluvial and tidal inputs	Lower James	smooth cordgrass

Geomorphic Setting	Description	Sub-settings	Dominant processes	Example Site	Dominant vegetation
Brackish Marshes (ES)	vicinity of turbidity maxima zone	Fringing Island	Peat accumulation	River, VA; Lower Nanticoke River, MD; Neuse River Estuary, NC	*(Spartina alterniflora)* salt hay *(Spartina patens)* spike grass *(Distichlis spicata)* black grass *(Juncus gerardi)* black needlerush *(Juncus roemerianus)* sedges *(Scirpus olneyi)* cattails *(Typha spp.)* big cordgrass *(Spartina cynosuroides)* pickerelweed *(Pontederis cordata)*
Tidal Fresh Marsh (FM)	Located above turbidity maxima zone; develop in drowned river valleys as filled with sediment		Alluvial and tidal inputs Peat accumulation	Upper Nanticoke River, MD; Anacostia River, DC	arrow arum *(Peltandra virginica)* pickerelweed *(Pontederis cordata)* arrowhead *(Sagitarria spp.)* bur-marigold *(Bidens laevis)* halberdleaf tearthumb *(Polygonum arifolium)* scarlet rose-mallow *(Hibiscus coccineus)* wild-rice *(Zizannia aquatica)* cattails *(Typha spp.)* giant cut grass *(Zizaniopsis miliacea)* big cordgrass *(Spartina cynosuroides)*
Tidal Fresh Forests (FF)	Develop in riparian zone along rivers and backwater areas beyond direct influence of seawater	Deepwater Swamps (permanently flooded) Bottomland Hardwood Forests (seasonally flooded)	Alluvial input Peat accumulation	Upper Raritan Bay, NJ; Upper Hudson River, NY	bald cypress *(Taxodium distichum)* blackgum *(Nyssa sylvatica)* oak *(Quercus* spp.) green ash *(Fraxinus*

Geomorphic Setting	Description	Sub-settings	Dominant processes	Example Site	Dominant vegetation
					pennsylvanica) (var. *lanceolata*)
Nontidal Brackish Marsh	Transgressive marshes bordering uplands in estuaries with restricted tidal signal		Alluvial input Peat accumulation	Pamlico Sound, NC	black needlerush *(Juncus roemerianus)* smooth cordgrass *(Spartina alterniflora)* spike grass *(Distichlis spicata)* salt hay *(Spartina patens)* big cordgrass *(Spartina cynosuroides)*
Nontidal Forests	Develop in riparian zone along rivers and backwater areas beyond direct influence of seawater in estuaries with restricted tidal signal	Bottomland Hardwood Forests (seasonally flooded)	Alluvial input Peat accumulation	Roanoke River, NC; Albemarle Sound, NC	bald cypress *(Taxodium distichum)* blackgum *(Nyssa sylvatica)* oak *(Quercus* spp.)
4. Delta	Develop on riverine sediments in shallow open water during active deposition; reworked by marine processes after abandonment		Alluvial input Peat accumulation Compaction/Subsidence Storm sedimentation Marine Processes	Mississippi Delta, LA	smooth cordgrass *(Spartina alterniflora)* black needlerush *(Juncus roemerianus)* spike grass *(Distichlis spicata)* salt hay *(Spartina patens)* glasswort *(Salicornia* spp.) saltwort *(Batis maritima)* maidencane *(Panicum haemitomon)* arrowhead *(Sagitarria spp.)*

3.1.2 Influence of Climate Change on Accretionary Drivers and Processes

Projections of wetland sustainability are further complicated by the fact that sea-level rise is not the only climate-related factor influencing wetland accretionary dynamics and sustainability. The influence of sea-level rise and other climate-related environmental drivers on mineral sediment delivery systems is complex. For example, the balance of forces between river discharge and the tides controls the physical processes of water circulation and mixing, which in turn determines the fate of sediment within an estuary. Where river discharge dominates, highly stratified estuaries may develop, and where tidal motion dominates, well-mixed estuaries tend to develop (Dyer, 1995). Many mid-Atlantic estuaries are partially mixed systems because of the combination of river discharge and tides. River discharge is affected by interannual and seasonal changes in precipitation and evapotranspiration patterns and intensity that can be influenced by alterations in land use and control over river flows by impoundments, dams, and impervious surfaces. Sea-level rise can further change the balance between river discharge and tides by its effect on tidal range (Dyer, 1995). An increase in tidal range would increase tidal velocities and consequently tidal mixing and sediment transport, as well as extending landward the reach of the tide. In addition, sea-level rise can affect the degree of tidal asymmetry in an estuary (*i.e.*, ebb versus flood dominance). In flood dominant estuaries, marine sediments are more likely to be imported to the estuary. But an increase in sea level without a change in tidal range may cause a shift toward ebb dominance, thereby reducing the input of marine sediments that might otherwise be deposited on intertidal flats and marshes (Dyer, 1995). Estuaries with relatively small intertidal areas and small tidal amplitudes would be particularly vulnerable in this regard.

The degree of influence of sea-level rise on wetland flooding, sedimentation–erosion, and salinity is directly linked with the influence of altered river flows and storm impacts (Figure 3.2). Changes in freshwater inputs to the coast can affect coastal wetland community structure and function (Sklar and Browder, 1998) through fluctuations in the salt balance up and down the estuary. Particularly affected by increases in salinity are low-salinity and freshwater wetlands. In addition, the location of the turbidity maximum (the zone in the estuary where suspended sediment concentrations are higher than in either the river or sea) varies directly with river discharge. And the size of the turbidity maximum zone increases with increasing tidal ranges (Dyer, 1995). Heavy rains (freshwater) and tidal surges (salty water) from storms can exacerbate or alleviate (at least temporarily) salinity and inundation effects of altered freshwater input and sea-level rise in all wetland types. The direction of elevation change depends on the storm characteristics, wetland type, and local conditions at the area of storm landfall (Cahoon, 2006). Predicted increases in the magnitude of coastal storms from higher sea surface temperatures (Webster *et al.*, 2005) will likely increase storm-induced wetland sedimentation in the mid-Atlantic region. Increased storm intensity could increase resuspension of nearshore sediments and the storm-related import of oceanic sediments into tidal marshes.

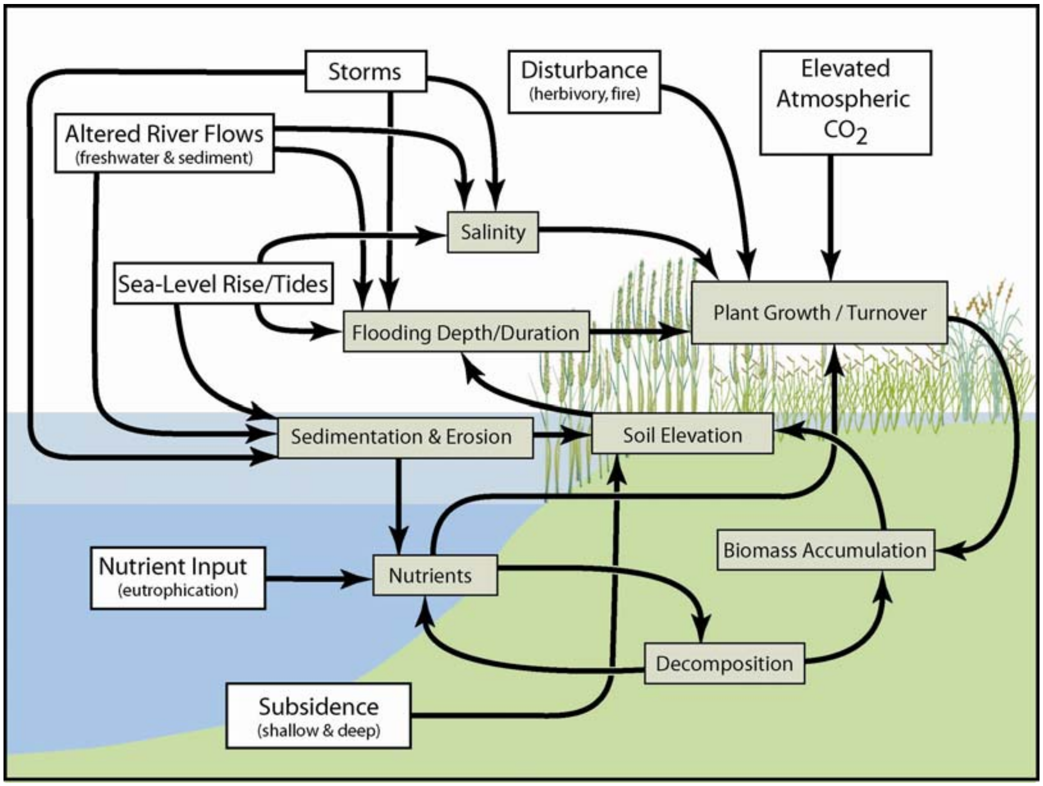


Figure 3.2 A conceptual diagram showing how environmental drivers and accretionary processes influence vertical wetland development.

3.2 WETLAND VULNERABILITY TO 20th CENTURY SEA-LEVEL RISE

A recent global-scale evaluation of 49 salt marsh accretion and elevation trends, including sites from the Atlantic, Gulf of Mexico, and Pacific coasts of the United States, provides insights into the mechanisms and variability of wetland responses to 20th century trends of local sea-level rise (Cahoon *et al.,* 2006). Globally, average surface accretion rates were greater than and positively related to local relative sea-level rise, suggesting that the marsh surface level was being maintained by surface accretion within the tidal range as sea level rose. In contrast, average rates of rise in elevation were not significantly related to sea-level rise and were significantly less than average surface accretion rates (indicating shallow soil subsidence occurs at many sites), although elevation change at many sites was greater than local sea-level rise (Cahoon *et al.*, 2006). Hence understanding elevation change, and not just surface accretion, is important when determining wetland sustainability. Secondly, accretionary dynamics differed strongly among geomorphic settings, with deltas and embayments exhibiting high accretion and high shallow subsidence compared to backbarrier and estuarine settings (Figure 12.6 in Cahoon *et al.*, 2006). Thirdly, strong regional differences in accretionary dynamics were observed for the North American salt marshes evaluated, with northeastern U. S. marshes exhibiting high rates of both accretion and elevation change, southeastern Atlantic and Gulf of Mexico salt marshes exhibiting high rates of accretion and low rates of elevation change, and Pacific salt marshes exhibiting low rates of both accretion and elevation change (Figure 12.7 in Cahoon *et al.*, 2006). Those marshes with low elevation change rates are likely vulnerable to current and future sea-level rise, except those marshes in areas of coastal uplift such as the Pacific Northwest coast of the U. S.

3.2.1 Sudden Marsh Dieback

An increasing number of reports (http://wetlands.neers.org/, www.inlandbays.org, www.brownmarsh.net, www.lacoast.gov/watermarks/2004-04/3crms/index.htm) of widespread "sudden marsh dieback" and "brown marsh dieback" from Maine to Louisiana, along with published studies documenting losses of marshes dominated by *Spartina alterniflora* (as well as other halophytes), suggest that a wide variety of marshes may be approaching or have actually gone beyond their "tipping point" where they can continue to accrete enough inorganic material to survive (Delaune *et al.*, 1983; Stevenson *et al.,* 1985; Kearney *et al.,* 1988; Mendelssohn & Mckee, 1988; Kearney *et al.,* 1994; Hartig *et al.,* 2002; McKee *et al.,* 2004; Turner *et al.,* 2004). Sudden dieback was documented over 40 years ago by marsh ecologists (Goodman & Williams, 1961). However, it is not known whether all recently identified events are in fact the same phenomenon and caused by the same factors. There likely are biotic factors, in addition to physical factors, that lead to sudden marsh dieback, including fungal diseases and overgrazing by animals such as waterfowl, nutria, and snails. Interacting factors may cause marshes to decline even more rapidly than we would predict from one driver such as sea-level rise. Details about the onset of sudden dieback have been elusive because most studies are done after the fact (Ogburn & Alber, 2006). Thus more research is needed to understand sudden marsh dieback. The apparent increased frequency of this phenomenon over the last several years certainly suggests an additional risk factor for marsh survival over the next century (Stevenson & Kearney, in press).

3.3 PREDICTING FUTURE WETLAND SUSTAINABILITY

Projections of future wetland sustainability on regional to national scales are constrained by the limitations of the two modeling approaches used to evaluate the relationship between future sea-level rise and coastal wetland elevation: landscape scale models and site-specific models. Large scale landscape models, such as the SLAMM model (Park *et al.*, 1989), simulate general trends at large spatial scales, but typically at a very coarse resolution. These landscape models do not mechanistically simulate the processes controlling wetland elevation, and thus do not account for low frequency events (*e.g.*, storms and floods) and elevation feedback effects on inundation and sedimentation. Nor are these models suitable for site-specific research and management problems because scaling down of results to the local level is not feasible. Thus, although landscape models can simulate wetland sustainability on broad spatial scales, their coarse resolution limits their accuracy and usefulness to the local manager.

On the other hand, process oriented site-specific models (*e.g.*, Morris *et al.*, 2002; Rybczyk and Cahoon, 2002) are more mechanistic than landscape models and are used to simulate responses for a specific site with unique conditions and settings. These site-specific models can account for accretion events that occur over long return frequencies (*e.g.*, hurricanes and major river floods), and the effects of elevation feedback on inundation and sedimentation that influence accretionary processes over timeframes of a century, making it possible to predict long-term sustainability of an individual wetland in a particular geomorphic setting. But, like the landscape models, site-specific models also have a scaling problem. Scaling up results from the individual wetland to long-term predictions at larger or even national spatial scales is problematic because accretionary and process data are not available across these larger-scale landscapes for calibrating and verifying models. Thus, although site-specific models provide high resolution simulations for a local site, future coastal wetland response to sea-level rise over large areas can be predicted with only low confidence at present.

Recently, two different modeling approaches have been used to provide regional or national scale assessments of wetland response to climate change. In a bottom-up approach, detailed site specific models were parameterized with long-term data to generalize landscape-level trends with moderate confidence for inland wetland sites in the Prairie Pothole Region (Carroll *et al.*, 2005; Voldseth *et al.*, 2007; Johnson *et al.*, 2005). The utility of this approach for coastal wetlands should be evaluated. Alternatively, a top down approach was used to assess coastal wetland vulnerability at regional to global scales from three broad environmental forcing factors: 1) ratio of relative sea-level rise to tidal range, 2) sediment supply, and 3) lateral accommodation space (*i.e.*, barriers to wetland migration) (McFadden *et al.*, 2007). This Wetland Change Model remains to be validated, however, and faces similar challenges when downscaling as do the previously described bottom-up models when scaling up.

Given the limitations of current predictive modeling approaches, what can we say and with what confidence can we generalize about future wetland sustainability at the national scale?

- It is **virtually certain** that tidal wetlands already experiencing submergence by sea-level rise and associated high rates of loss (*e.g.*, Mississippi River Delta in Louisiana, Blackwater River marshes in Maryland) will continue to lose area under the influence of future accelerated rates of sea-level rise and changes in other climate and environmental drivers.
- It is **very unlikely** that there will be a net increase in tidal wetland area on a national scale over the next 100 years, given current wetland loss rates and the relatively minor accounts of new tidal wetland development (*e.g.*, Atchafalaya Delta in Louisiana),

- Current model projections of wetland vulnerability on regional and national scales are uncertain because of the coarse level of resolution of landscape scale models. In contrast, site-specific model projections are quite good where local information has been acquired on factors that control local accretionary processes in specific wetland settings. However, we have low confidence that site-specific model simulations can be successfully scaled up to provide realistic projections at regional or national scales.

What information is needed to improve our confidence about projections of future coastal wetland sustainability on regional and national scales?

- *Models and validation data*. To scale up site-specific model outputs to a national scale with high confidence, we need detailed data on the various local drivers and processes controlling wetland elevation across all the tidal geomorphic settings of North America. Obtaining and evaluating the necessary data would be an enormous and expensive task, but not a totally impractical one. It would require substantial contributions from and coordination with various organizations, both private and government, to develop a large, query able database. Until such a database becomes a reality, current modeling approaches need to improve or adapt such that they can be applied across a broad spatial scale with better confidence. For example, evaluating the utility of applying the multi-tiered modeling approach used in the Prairie Pothole Region to coastal wetland systems and validating the Wetland Change Model for North American coastal wetlands would be important first steps. Our ability to predict coastal wetland sustainability with a higher level of confidence will improve as we gain understanding of the specific ecological and geological processes controlling accretion and their interactions on local and regional scales.

- *Expert opinion*. Although models driven by empirical data would be preferable, given the modeling limitations described, an expert opinion (*i.e.*, subjective) approach could be used today to develop spatially explicit landscape-scale predictions of coastal wetland responses to future sea-level rise with a low to moderate level of confidence. This approach requires convening a group of scientists with expert knowledge of coastal wetland geomorphic processes. The group’s conclusions would be based on an understanding of the processes driving marsh survival during sea-level rise and how the magnitude and nature of these processes might change because of the effects of climate change and other factors. Because of the enormous complexity of these issues at the national scale, the expert opinion approach would be applied with greater confidence at the regional scale. Two case studies are presented below; one using the expert opinion approach applied to the mid-Atlantic region from New York to Virginia, the second a description of North Carolina wetlands from the Albemarle–Pamlico Region and an evaluation of their potential response to sea-level rise, based on a review of the literature. Wetlands of North Carolina were not included in the expert opinion mid-Atlantic regional analysis because of the unique physical setting (*i.e.*, nontidal hydrologic regime) of the Albemarle–Pamlico Region.

3.3.1 Case Study: Mid-Atlantic Regional Assessment, New York to Virginia

A panel of scientists with diverse and expert knowledge of wetland accretionary processes was convened to develop spatially explicit landscape scale predictions of coastal wetland response to the three scenarios of sea-level rise assessed in this report (see Context Chapter) for the mid-Atlantic region from New York to Virginia. The results of this effort (Reed *et al.*, 2007) inform the assessment of coastal elevations and sea-level rise. The approach used by the scientific panel is described in Box 3.1.

BOX 3.1 EXPERT PANEL APPROACH

To ensure a systematic approach across the different settings of the mid-Atlantic region, (Roman *et al.*, 2000), the panel agreed upon the following procedures. See Reed *et al.* (2007) for a detailed explanation of the procedures.

To assist in distinguishing between the different process regimes controlling wetland accretion, the panel identified a series of geomorphic settings and subsettings for the mid-Atlantic region (backbarrier lagoon and estuarine embayment, which includes saline fringe marsh and three types of stream channel wetlands: estuarine brackish marsh, tidal fresh marsh, and fresh forest) (Table 3.1, Box Figure 3.1, Part I Overview). The panel also identified nine processes that influence the ability of wetlands to keep pace with sea-level rise: storm sedimentation (sediment laden runoff, sediment resuspension, barrier overwash), tidal fluxes of sediment, riverine sediment input, oceanic sediment input, ice rafting, peat accumulation, nutrient input, groundwater (freshwater) input, and herbivory. The panel further recognized that accretionary processes differ among settings and that these processes will change in magnitude and direction with future climate change. The influence of erosional processes was not taken into consideration.

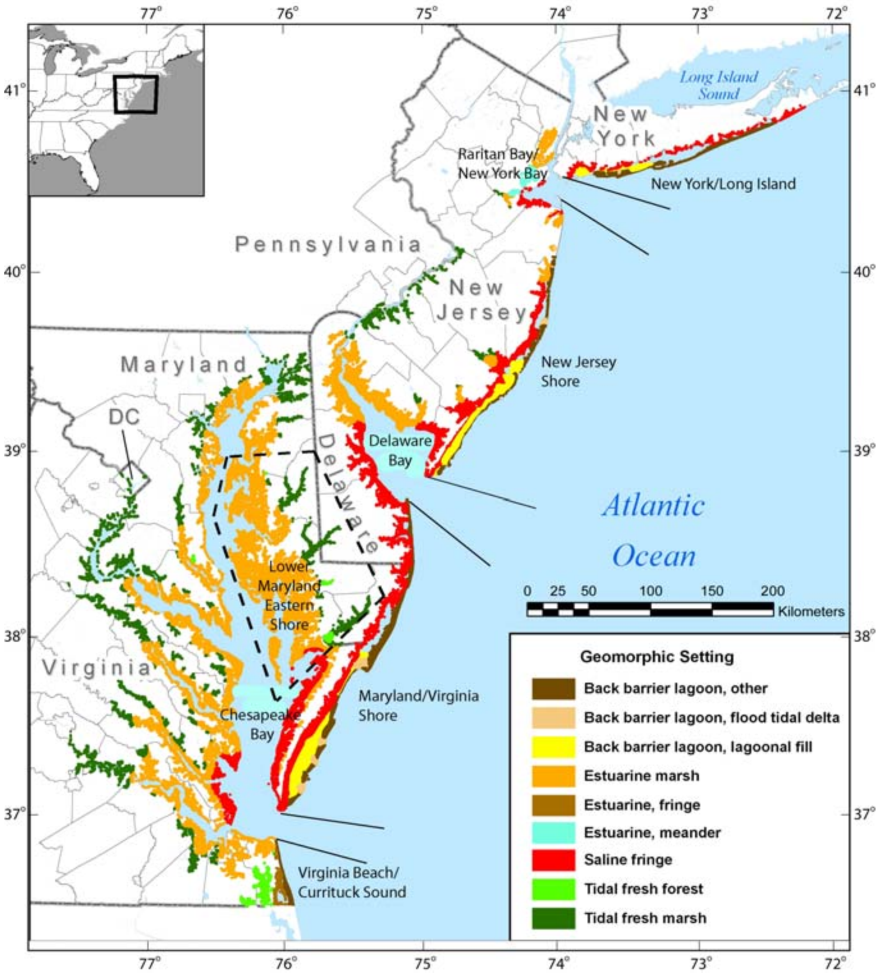
For example, the magnitude of coastal storms will increase as sea-surface temperatures increase (Webster *et al.*, 2005), likely resulting in an increase in storm sedimentation and oceanic sediment inputs. And the importance of peat accumulation is expected to increase in response to sea-level rise, up to a threshold rate. However, if salinities also increase in freshwater systems, elevation gains from increased peat accumulation could be offset by increased decomposition from sulfate reduction. Enhanced microbial breakdown of organic-rich soils is likely to be most important in formerly fresh and brackish environments where the availability of sulfate, and not organic matter, generally limits sulfate-reduction rates (Goldhaber and Kaplan, 1974). Increases in air and soil temperatures will diminish the importance of ice effects. Changes in precipitation and human land-use patterns will alter fluvial sediment inputs.

The panel reviewed the published wetland accretion literature (88 accretion rates from Long Island to Virginia), and then divided the mid-Atlantic region into a series of subregions based on similarity of accretionary process regime and current sea-level rise rates determined from tide gauge data (Box Figure 3.1). Geomorphic settings were delineated on 1:250,000 scale maps (Box Figure 3.1). After considering all information, the expert panel determined the fate of the wetlands for the three sea-level rise scenarios (Figure 3.3) by consensus opinion. The wetlands were classified as keeping pace, marginal, or loss (Reed *et al.*, 2007):

Keeping pace — Wetlands will not be submerged by rising sea levels and will be able to maintain their relative elevation.

Marginal — Wetlands will be able to maintain their elevation only under optimal conditions. Depending on the dominant accretionary processes, this could include inputs of sediments from storms or floods, or the maintenance of hydrologic conditions conducive for optimal plant growth. Given the complexity and inherent variability of climatic and other factors influencing wetland accretion, the panel cannot predict the fate of these wetlands. Under the best of circumstances they are expected to survive.

Loss — Wetlands will be subject to increased flooding beyond that normally tolerated by the vegetative communities, leading to deterioration and conversion to open water habitat.



Box Figure 3.1 Geomorphic settings of mid-Atlantic tidal wetlands (data source: Reed *et al.*, 2007; map source: Titus *et al*., 2008).

Wetlands identified as marginal or loss will not become so uniformly; the rate and spatial distribution of change will vary within and among similarly designated areas. Wetland response to sea-level rise over the next century will vary spatially and temporally depending on the rate of sea-level rise, current wetland condition (*e.g.*, elevation relative to sea level), and local process controls. In addition, changes in flooding and salinity patterns may result in a change of dominant species (*i.e.*, high marsh species replaced by low marsh species), which could affect wetland sediment trapping and organic matter accumulation rates. A wetland is considered marginal when it becomes severely degraded (> 50 % of vegetated area is converted to open water) but still supports ecosystem functions associated with that wetland type. A wetland is considered lost when its function shifts primarily to that of shallow open water habitat.

There are notable caveats to the expert panel approach, interpretations, and application of findings. First, regional scale assessments are intended to provide a landscape scale projection of wetland vulnerability to sea-level rise (*e.g.*, likely trends, areas of major vulnerability) and not to replace assessments based on local process data. Local exceptions to the panel's regional scale assessment exist in the published literature. Second, the panel's projections of backbarrier wetland sustainability assume that protective barrier islands remain stable. Should barrier islands collapse, the lagoonal marshes would be exposed to an increased wave energy environment and erosive processes, with massive marsh loss very likely over a relatively short period of time. (In such a case, vulnerability to marsh loss would be only one of a host of environmental problems.) Third, the regional projections of wetland sustainability assume that the health of marsh vegetation is not adversely affected by local outbreaks of disease or other biotic factors (*e.g.*, sudden marsh dieback). Fourth, the panel considered the effects of a rate acceleration of 2 mm/y and 7 mm/y, but not rates in between. There are few estimates of the maximum rate at which marsh vertical accretion can occur (Bricker-Urso *et al.*, 1989; Morris *et al.*, 2002) and no studies addressing the thresholds for organic matter accumulation in the marshes considered by the panel. Determining wetland sustainability at sea-level rise rates between Scenarios 2 and 3 requires greater understanding of the variations in the maximum accretion rate regionally and among vegetative communities (Reed *et al.*, 2007). Lastly, the panel recognized the serious limitations of scaling down their projections from the regional to local level and would place a low level of confidence on such projections in the absence of local accretionary and process data.

Thus findings from this regional scale approach should not be used for local planning activities where local effects may over-ride regional controls.

Findings. The panel developed a model for predicting wetland response to sea-level rise that was better constrained by available studies of accretion and accretionary processes in some areas of the mid-Atlantic region (*e.g.*, Lower Maryland Eastern Shore) than in other areas (*e.g.*, Virginia Beach/Currituck Sound). Given these inherent data and knowledge constraints, the authors classified the confidence level for all findings in Reed *et al.* (2007) as likely (*i.e.*, > 0.66 < 0.90).

Figure 3.3 and Table 3.2 present the panel's consensus findings on wetland vulnerability of the mid-Atlantic region. The panel determined that a majority of tidal wetlands settings in the mid-Atlantic region (with some local exceptions) is likely keeping pace with Scenario 1 (Table 3.2, and areas depicted in brown, beige, yellow, and green in Figure 3.3) through either mineral sediment deposition, organic matter accumulation, or both. However, extensive areas of estuarine marsh in Delaware Bay and Chesapeake Bay are marginal (areas depicted in red in Figure 3.3), with some areas currently being lost (areas depicted in blue in Figure 3.3). It is virtually certain that estuarine marshes currently being lost will not be rebuilt or replaced by natural processes. Human manipulation of hydrologic and sedimentary processes and the elimination of barriers to onshore wetland migration would be required to restore and sustain these degrading marsh systems. The removal of barriers to onshore migration invariably would result in land use changes that have other societal consequences.

Under accelerated rates of sea-level rise, the panel agreed that wetland survival would very likely depend on optimal hydrology and sediment supply conditions. Wetlands primarily dependent on mineral sediment accumulation for maintaining elevation would be very unlikely to survive Scenario 3; a 7 mm/y increase in the rate of sea-level rise (*i.e.*, ≥ 10 mm/y rate of sea-level rise when combined with the 20th century rate). Exceptions may occur locally where sediment inputs from inlets, overwash events or rivers are substantial (*e.g.*, backbarrier lagoon and lagoonal fill marshes depicted in green on western Long Island, Figure 3.3).

Wetland responses to sea-level rise are typically complex. A close comparison of Text Box Figure 3.1 and Figure 3.3 reveals that marshes from all geomorphic settings, except estuarine meander (which occurs in only one subregion), responded differently to sea-level rise within and/or among subregions, underscoring the variability in the influence of local processes and drivers. Given the variety of marsh responses to sea-level rise among and within subregions (Table 3.1), assessing the likelihood of survival for each wetland setting is best done by subregion.

Table 3.2 The range of wetland responses to three sea level rise (slr) scenarios (20th Century rate, 20th Century rate + 2 mm/yr, and 20th Century rate + 7 mm/y) within and among geomorphic settings and subregions of the Mid-Atlantic Region from New York to Virginia

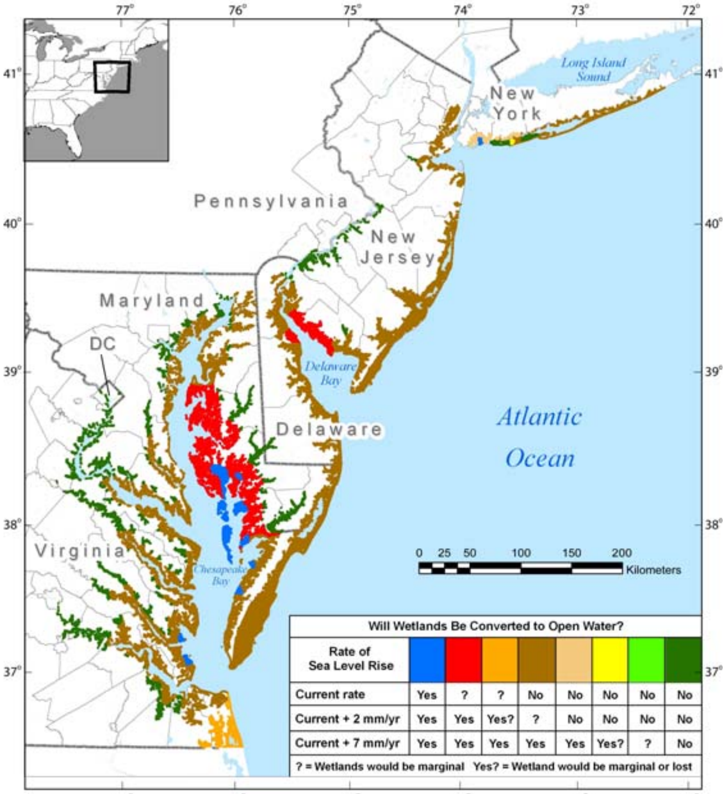
Geomorphic Setting	Region																							
	Long Island, NY			Raritan Bay, NY			New Jersey			Delaware Bay			Maryland - Virginia			Chesapeake Bay			Lower Maryland Eastern Shore			Virginia Beach – Currituck Sound		
	slr	+2	+7	slr	+2	+7	slr	+2	+7	slr	+2	+7	slr	+2	+7	slr	+2	+7	slr	+2	+7	slr	+2	+7
Back barrier lagoon, other	K	K,M	K,L				K	M	L				K	M	L							M	M-L	L
Back barrier lagoon, flood tide delta	K	K	M				K	M	L				K	M	L									
Back barrier lagoon, lagoonal fill	K,L	M,L	L				K	M	L				K	M	L									
Estuarine marsh				K	M	L	K	M	L	K,M	M,L	L				K,M, L	M-L	L	L,M	L	L	K	M	L
Estuarine fringe				K	M	L	K	M	L													M	M-L	L
Estuarine meander				K	M	L	K	M	L															
Saline fringe	K	K,L	M	K	M	L	K	M	L	K	M	L	K,L	M,L	L									
Tidal fresh forest																			K	K	K	M	M-L	
Tidal fresh marsh				K	K	K	K	M	L	K	K	K				K	K	K	K	K	K	K	K	K

K = keeping pace, M = marginal, L = loss; multiple letters under a single slr scenario (e.g., K,M or K,M,L) indicate more than one response for that geomorphic setting; M-L indicates that the wetland would be either marginal or lost.

The panel determined that tidal fresh marshes and forests in the upper reaches of rivers are likely to be sustainable (*i.e.*, less vulnerable to future sea-level rise than most other wetland types) (Table 3.1), because they have access to reliable and often abundant sources of mineral sediments. Even so, their sediments typically have 20 – 50 percent organic matter content indicating that large quantities of plant organic matter are also available. Assuming that salinities do not increase, a condition that may reduce soil organic matter accumulation rates, and current mineral sediment supplies are maintained, the panel considered it likely that tidal fresh marshes and forests would survive under Scenario 3. For example, some managed tidal fresh marshes positioned low in the tidal range in the high sediment-load Delaware River estuary exhibited rapid vertical accretion (> 1 cm per year) through the accumulation of both mineral and plant matter when normal tidal exchange was restored (Orson *et al.*, 1992). Exceptions to this finding are noted for the New Jersey shore where tidal fresh marsh is considered marginal under Scenario 2 and lost under Scenario 3, and for Virginia Beach-Currituck Sound where fresh forest is marginal under Scenario 1,, marginal or lost under Scenario 2, and lost under Scenario 3.

Marshes from backbarrier other, backbarrier lagoonal fill, estuarine marsh, and saline fringe settings responded differently to sea-level rise within at least one subregion as well as among subregions (Table 3.1). For example, backbarrier lagoonal fill marshes on Long Island, NY were classified as either keeping pace or lost at the current rate of sea-level rise. Those surviving under Scenario 1 were classified as either marginal (brown) or keeping up (beige and green) under Scenario 2 (Figure 3.3). Under Scneario 3,, only the lagoonal fill marshes depicted in green in Figure 3.3 are expected to survive.

The management implications of these findings are important on several levels. The expert panel approach provides a regional assessment of future wetland resource conditions, defines likely trends in wetland change, and identifies areas of major vulnerability. But the wide variability of wetland responses to sea-level rise within and among subregions for a variety of wetland settings underscores not only the influence of local processes on wetland elevation but also the difficulty of scaling down predictions of wetland sustainability from the regional to the local scale in the absence of local accretionary data. Most importantly for managers, regional scale assessments such as this one should not be used to develop local management plans because local accretionary effects may override regional controls on wetland vertical development (McFadden *et al.*, 2007). Instead, local managers are encouraged to acquire data on the factors influencing the sustainability of their local wetland site, including environmental stressors, accretionary processes, and geomorphic settings, as a basis for developing local management plans.



Will Wetlands Be Converted to Open Water?								
Rate of Sea Level Rise	🟦	🟥	🟧	🟫	🟧	🟨	🟩	🟩
Current rate	Yes	?	?	No	No	No	No	No
Current + 2 mm/yr	Yes	Yes	Yes?	?	No	No	No	No
Current + 7 mm/yr	Yes	Yes	Yes	Yes	Yes	Yes?	?	No

? = Wetlands would be marginal Yes? = Wetland would be marginal or lost

Figure 3.3 Wetland survival in response to three sea-level rise scenarios (data source: Reed *et al.,* 2007; map source: Titus *et al.,* 2008).

3.3.2 Case Study: Albemarle–Pamlico Sound Wetlands and Sea-Level Rise

The Albemarle–Pamlico (A–P) region of North Carolina is distinct in the manner and the extent to which rising sea level is expected to affect coastal wetlands. Wetlands of the region influenced by sea level are among the most extensive on the east coast of the U.S. because of large regions less than 3 m above sea level and flatness of the underlying surface. Further, the wetlands lack astronomic tides as a source of estuarine water to wetland surfaces in most of the A-P region. Instead, wind-generated water level fluctuations in the sounds and precipitation are the principal sources of water. This “irregular flooding” is the hallmark of the hydrology of these wetlands. Both forested wetlands and marshes can be found; variations in salinity of floodwater determine ecosystem type. This is in striking contrast to most other fringe wetlands on the east coast.

3.3.2.1 Distribution of Wetland Types

Principal flows to Albemarle Sound are from the Chowan and Roanoke Rivers, and to Pamlico Sound from the Tar and Neuse Rivers. Hardwood forests occupy the floodplains of these major rivers. Only the lower reaches of these rivers are affected by rising sea level. Deposition of riverine sediments in the estuaries approximates the rate of rising sea level (2-3 mm/yr) (Benninger and Wells, 1993). These sediments generally do not reach coastal marshes in part because they are deposited in subtidal areas and in part because astronomic tides are lacking to carry them to wetland surfaces. Storms, which generate high water levels (especially ‘northeasters’ and tropical storms), deposit sediments on shoreline storm levees and potentially onto marshes and wetland forests. Blackwater streams that drain pocosins (peaty, evergreen shrub and forested wetlands), as well as other tributaries that drain the coastal plain, are a minor supply of suspended sediment to the estuaries.

Most wetlands in the A-P region were formed upon Pleistocene sediments deposited during multiple high stands of sea level. Inter-stream divides, typified by the Albemarle-Pamlico Peninsula, are flat and poorly drained, resulting in extensive developments of pocosin swamp forest habitats. The original accumulation of peat was not due to rising sea level but to poor drainage and climatic controls. Basal peat ages of even the deepest deposits correspond to the last glacial period when sea level was over 100 m below its current position. Rising sea level has now intercepted some of these peatlands, particularly those at lower elevations on the extreme eastern end of the A-P peninsula (Riggs, in review). As a result, scarped peat shorelines are extensive with large volumes of peat occurring below sea level (Riggs and Ames, 2003).

Large areas of nontidal marshes and forested wetlands in this area are exposed to the influence of sea level. They can be classified as fringe wetlands because they occur along the periphery of estuaries that flood them irregularly. Salinity, however, is the major control that determines the dominant vegetation type. In the fresh to oligohaline Albemarle Sound region, forested and shrub-scrub wetlands dominate. As the shoreline erodes into the forested wetlands, bald cypress trees become stranded in the permanently flooded zone and finally die and fall down. This creates a zone of complex habitat structure of fallen trees and relic cypress knees in shallow water. Landward, a storm levee of coarse sand borders the swamp forest in areas exposed to waves (Riggs and Ames, 2003).

Trees are killed by exposure to extended periods of salinity above 10 ppt (approximately 1/4-1/3 sea water), and most trees and shrubs have restricted growth and reproduction at much lower salinities (Conner *et al.*, 1997). In brackish water areas, marshes consisting of halophytes replace forested wetlands. Marshes are largely absent from the shore of Albemarle Sound and mouths of the Tar and Neuse Rivers where salinities are too low to affect vegetation. In Pamlico Sound, however, large areas consist of brackish marshes with few tidal creeks. Small tributaries of the Neuse and Pamlico River estuaries grade from brackish marsh at estuary mouths to forested wetlands in oligohaline regions further upstream (Brinson *et al.*, 1985).

3.3.2.2 Future Sea-Level Rise Scenarios

Three scenarios were used to frame projections of the effects of rising sea level over the next few decades in the non-tidal coastal wetlands of North Carolina. The first is a non-drowning scenario that assumes rising sea level will maintain its 20th century, constant rate, of 2-4 mm/yr (Scenario 1). Predictions in this case can be inferred from wetland response to sea-level changes in the recent past (Spaur and Snyder, 1999). Accelerated rates of sea-level rise (Scenarios 2 and 3), however, may lead to a drowning scenario. This is more realistic if IPCC predictions and other climate change models prove to be correct (Church and White, 2006), and the Scenario 1 rates double or triple. An additional scenario possible in North Carolina whereby some of the barrier islands begin to collapse, as documented by Riggs and Ames (2003), is more daunting because it anticipates a state change from non-tidal to tidal regime. The underlying effects of these three scenarios and effects on coastal wetlands are summarized in Table 3.3.

Table 3.3 Comparison of three scenarios of rising sea level and their effects on coastal processes.

Scenario	Vertical accretion of wetland surface	Shoreline erosion rate	Sediment supply
Non-drowning: historical exposure of wetlands (past hundreds to several thousand yrs) is predictive of future behavior. Vertical accretion will keep pace with rising sea level (~2-4 mm/yr)	Keeps pace with rising sea level	Recent historical patterns are maintained	Low due to a lack of sources; vertical accretion mostly biogenic
Drowning: vertical accretion rates cannot accelerate to match rates of rising sea level; barrier islands remain intact	Wetlands undergo collapse and marshes break up from within	Rapid acceleration when erosion reaches collapsed regions	Local increases of organic and inorganic suspended sediments as wetlands erode
Barrier islands breached: change to tidal regime throughout Pamlico Sound	Biogenic accretion replaced by inorganic sediment supply	Rapid erosion where high tides overtop wetland shorelines	Major increase in sediments and their redistribution; tidal creeks develop along antecedent drainages mostly in former upland regions

Under the non-drowning scenario, vertical accretion would keep pace with rising sea level as it has for millennia. Current rates (Cahoon, 2003) and those based on basal peats suggest that vertical accretion roughly matches the rate of rising sea level (Riggs, in review; Riggs *et al.*, 2000; Erlich, 1980; Whitehead and Oakes, 1979). Sources of inorganic sediment to supplement vertical marsh accretion are negligible due to both the large distance between the mouths of piedmont-draining Neuse, Tar, Roanoke and Chowan Rivers and the absence of both tidal currents and creeks to transport sediments to marsh surfaces.

Under the drowning scenario, the uncertainty of the effects of accelerated rates lies in the untested capacity of marshes and swamp forests to biogenically accrete organic matter at sea-level rise rates more rapid than experienced currently. It has been well established that brackish marshes of the Mississippi Delta cannot survive when subjected to relative rates of sea-level rise of 10 mm/y (Day *et al.*, 2005), well over twice the rate currently experienced in Albemarle and Pamlico Sounds. As is the case for the Mississippi Delta

(Reed *et al.,* 2006), external sources of mineral sediments would be required to supplement or replace the process of organic accumulation that now dominates wetlands of the A-P region. Where abundant supplies of sediment are available and tidal currents strong enough to transport them, as in North Inlet, South Carolina, Morris *et al.* (2002) reported that the high salt marsh (dwarf *Spartina*) could withstand a 12 mm/yr rate. In contrast to fringe wetlands, swamp forest wetlands along the piedmont-draining rivers above the freshwater/seawater interface are likely to sustain themselves under drowning scenario conditions. This is due to the general abundance of mineral sediments during flood stage. This applies to regions within the floodplain but not at river mouths where shoreline recession occurs in response to more localized drowning.

Pocosin peatlands and swamp forest at higher elevations of the coastal plain will continue to grow vertically since they are both independent of sea-level rise. Under the drowning scenario, however, sea-level influenced wetlands of the lower coastal plain would convert to aquatic ecosystems, and the large, low, and flat pocosin areas identified by Poulter (2005) would transform to aquatic habitat. In areas of pocosin peatland, shrub and forest vegetation first would be killed by brackish water. It is unlikely that pocosins would undergo a transition to marsh due to two factors: (1) the pocosin root mat would collapse due to plant mortality and decomposition causing a rapid subsidence of several centimeters, resulting in a transition to ponds rather than marshes and (2) brackish water may accelerate decomposition of peat due to availability of sulfate to drive anaerobic decomposition. With the simultaneous death of woody vegetation and elimination of potential marsh plant establishment, organic-rich soils would be exposed directly to decomposition, erosion, suspension, and transport without the stabilizing properties of vegetation.

Under the “collapsed barrier island” scenario, the A-P regions would undergo a change from non-tidal estuary to one dominated by astronomic tides due to the collapse of some portions of the barrier islands. A transition of this magnitude is difficult to predict in detail. However, Poulter (2005), using the ADCIRC-2DDI model of Leuttich *et al.* (1992), estimated that conversion from a non-tidal to tidal estuary might flood hundreds of square kilometers. The effect was largely due to an increase in tidal amplitude that produced the flooding rather than a mean rise in sea level itself. While the mechanisms of change are speculative, it is doubtful that an intermediate stage of marsh colonization would occur on former pocosin and swamp forest areas because of the abruptness of change. Collapse of the barrier islands in this scenario would be so severe due to the sediment-poor condition of many barrier segments that attempts to maintain and/or repair them would be extremely difficult, or even futile (Riggs, in review).

The conversion of Pamlico Sound to a tidal system would likely re-establish tidal channels where ancestral streams are located, as projected by Riggs and Ames (2003). The remobilization of sediments could then supply existing marshes with inorganic sediments. It is more likely, however, that marshes would become established landward on newly inundated mineral soils of uplands. Such a state change has not been observed elsewhere, and computer models are seldom robust enough to encompass such extreme hydrodynamic transitions.

3.4 DATA NEEDS

A few key uncertainties must be addressed to increase confidence in our predictions of wetland vulnerability to sea-level rise. First, determining the fate of coastal wetlands over a range of accelerated sea-level rise rates requires more information on variations in the maximum accretion rate regionally and among vegetative communities. To date, few studies have specifically addressed the maximum rates at which marsh vertical accretion can occur, particularly the thresholds for organic accumulation. Second, although the interactions among changes in wetland elevation, sea level, and wetland flooding patterns are becoming better understood, the interaction of these feedback controls on flooding with changes in other accretion drivers, such as nutrient supply, sulfate respiration, and soil organic matter accumulation is less well understood. Third, scaling up from numerical model predictions of local wetland responses to sea-level rise to long-term projections at regional or national scales is severely constrained by a lack of available accretionary and process data at these larger landscape scales. Newly emerging numerical models used to predict wetland response to sea-level rise need to be applied across the range of wetland settings. Fourth, we need to better understand the role of changing land use on tidal wetland processes, including space available for wetlands to migrate landward and alteration in the amount and timing of freshwater runoff and sediment supply. Last, sediment supply is a critical factor influencing wetland vulnerability, but the amount of sediments available for wetland formation and development is often poorly understood. Coastal sediment budgets typically evaluate coarse-grain sediments needed for beach and barrier development, and fine-grain cohesive sediments needed for wetland formation and development are typically not evaluated. Improving our understanding of each of these factors is critical for predicting the fate of tidal marshes.

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Chapter 4. Vulnerable Species

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KEY FINDINGS

- The quality, quantity, and spatial distribution of coastal habitats will change as a result of shoreline erosion, salinity changes, and wetland loss. Species that rely on these habitats include both terrestrial and aquatic plants and animals. Depending on local conditions, habitat may be lost or migrate inland in response to sea-level rise. A key uncertainty and determinant of habitat and species loss is whether or not coastal landforms and present-day habitats will have space to migrate inland.
- Loss of tidal marshes would seriously threaten coastal ecosystems, causing fish and birds to move or produce less offspring. Many estuarine beaches may also be lost, threatening species such as the terrapin and horseshoe crab.
- Numerous bird species depend on tidal marshes for forage or nesting, including several marsh specialists: rails, the least bittern, Forster's tern, willets, seaside sparrows, and laughing gulls. Endangered beetles, horseshoe crabs, the red knot shorebird, and diamondback terrapins rely on sandy beach areas. Tidal marshes and submerged aquatic vegetation are important spawning, nursery, and shelter areas for fish and shellfish, including commercially important species like the blue crab.

- Loss of bay islands already undergoing submersion will reduce available nesting for bird species that prefer island sites. Tidal freshwater swamp forests are considered globally uncommon to rare, and are at risk from sea-level rise among other threats. Seagrass beds may suffer from reduced sunlight for photosynthesis if water deepens over them or turbidity from sediment increases. Tidal flats, a rich source of invertebrate food for shorebirds, may be inundated, though new areas may be created as other shoreline habitats are submerged.

INTRODUCTION

Coastal ecosystems consist of a variety of environments, including tidal marshes, marsh and bay islands, tidal forests, seagrass beds, tidal flats, beaches, and cliffs, which provide important ecological and human use services, including habitat for endangered and threatened species. These ecosystem services, described in detail within this chapter, include not only those processes that support the ecosystem itself such as nutrient cycling, but also the human benefits derived from those processes, including fish production, water purification, water storage and delivery, and the provision of recreational opportunities that help promote human well-being. The high value that humans place on these services has been demonstrated in a number of studies, particularly of coastal wetlands (NRC, 2005).

The services provided by coastal ecosystems could be affected in a number of ways by sea-level rise and coastal engineering projects designed to protect coastal properties from erosion and inundation. As seas rise, coastal habitats are subject to inundation, storm surges, saltwater intrusion, and erosion. The placement of hard structures along the shoreline may reduce sediment inputs from upland sources and increase erosion rates in front of the structures (USGS, 2003). If less sediment is available, marshes that are seaward of such structures may have difficulty maintaining appropriate elevations in the face of rising seas. Wetlands that are unable to either accrete sufficient substrate or migrate inland as sea level rises will gradually convert to open water, eliminating critical habitat for many coastal species. On the other hand, even where migration is possible, landward migration of wetlands may occur at the expense of other habitats (NRC, 2007). Shallow water and shoreline habitats are also affected by shoreline responses. Table 1 in Chapter 5 provides a preliminary overview of the expected environmental effects of human responses to sea-level rise.

Habitat changes in response to sea-level rise and related processes may include structural changes (such as shifts in vegetation zones or loss of vegetated area) and functional changes (such as altered nutrient cycling). In turn, degraded ecosystem processes and habitat fragmentation and loss may not only alter species distributions and relative abundances, but may ultimately reduce local populations of the species that depend on coastal habitats for feeding, nesting, spawning, nursery areas, protection from predators, and other activities that affect growth, survival, and reproductive success.

Habitat interactions are extremely complex. Each habitat supports adjacent systems - for example, the denitrifying effects of wetlands aids adjacent submerged vegetation beds by reducing algal growth; the presence of nearshore oyster or mussel beds reduces wave energy which decreases erosion of marsh edges. This chapter presents simplifications of these interactions in order to identify primary effects of both increased rates of sea-level rise and likely shore protections. In particular, sea-level rise is just one factor among many affecting coastal areas: sediment input, nutrient runoff, fisheries management, and other factors all contribute to the ecological condition of the various habitats discussed in this section. Under natural conditions, habitats are also continually shifting; the focus of this chapter is the effect that shoreline management will have on the ability for those shifts to occur (*e.g.*, for marshes or barrier islands to migrate, for marsh to convert to tidal flat or vice versa) and any interruption to the natural shift. Scenarios are primarily presented broadly as habitat vulnerability rather then species vulnerability, since species generally have some versatility in their habitat usage, either by geography or by habitat type, and specific species data are limited.

Although these potential ecological effects are understood in general terms, few studies have sought to demonstrate or quantify how sea-level rise and shoreline hardening in combination may affect the ecosystem services provided by coastal habitats, and in particular the abundance and distribution of animal species. While some studies have looked at impacts of either sea-level rise (*e.g.*, Erwin *et al.*, 2006b; Galbraith *et al.*, 2002) or shore protections (*e.g.*, Seitz *et al.*, 2006), there is minimal literature available on the combined affects of rising seas and shore protections. Nonetheless, it is possible in some cases to identify species most likely to be affected based on knowledge of species-habitat associations. Therefore, in this chapter we draw upon the ecological literature to describe the primary coastal habitats and species that are vulnerable to sea-level rise and shoreline protection activities, and highlight those species that are a particular concern. In Appendices A-G of this report, we discuss in greater detail specific local habitats and animal populations that are at risk.

4.1 TIDAL MARSHES

In addition to their dependence on tidal influence, tidal marshes are defined primarily in terms of their salinity, and include salt, brackish, and freshwater wetlands immediately landward of the shoreline. Because of their direct connection to the ocean, tidal salt marshes are the most vulnerable of coastal habitats to rising seas.

Salt marshes are among the most productive systems in the world because of the extraordinarily high amount of above- and below-ground plant matter that they produce. In turn, this large reservoir of primary production supports a wide variety of invertebrates, fish, birds, and other animals that make up the estuarine food web (Teal, 1986). Insects and other small invertebrates feed on the organic material of the marsh and provide food for larger organisms, including crabs, shrimp, and small fishes, which in turn provide food for larger consumers such as birds and estuarine fishes that move into the marsh to forage.

Although much marsh primary production is used within the marsh itself, some is exported to adjacent estuaries and marine waters. It is estimated that about 40% of the aboveground primary production is exported (Teal, 1986). In addition, some of the secondary production of marsh resident fishes, particularly mummichog, and of juveniles, such as blue crab, is exported out of the marsh to support both nearshore estuarine food webs as well as fisheries in coastal areas (Boesch and Turner, 1984; Knieb, 1997; Kneib, 2000; Deegan *et al.*, 2000; Beck *et al.*, 2003; Dittel *et al.*, 2006; Stevens *et al.*, 2006)[7]. As studies of flood pulses have shown, the extent of the benefits provided by wetlands may be greater in regularly flooded tidal wetlands than in irregularly flooded areas (Bayley, 1991; Zedler and Calloway, 1999).

Figure 4.1 Marsh and tidal creek, Mathews County, VA.

Tidal creeks and channels (Figure 4.1) frequently cut through low marsh areas, draining the marsh surface and serving as routes for nutrient-rich plant detritus to be flushed out into deeper water as tides recede and for small fish, shrimps, and crabs to move into the marsh during high tides (Lippson and Lippson, 2006). In addition to mummichog, fish species found in tidal creeks at low tide include Atlantic silverside, striped killifish, and sheepshead minnow (Rountree and Able, 1992). Waterbirds such as great blue herons and

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[7] See Glossary for a list of corresponding scientific names.

egrets are attracted to marshes to feed on the abundant small fish, snails, shrimps, clams, and crabs found in tidal creeks and marsh ponds.

As discussed in Chapter 3, tidal marshes can keep pace with sea-level rise through vertical accretion (*i.e.*, soil build up through sediment deposition and organic matter accumulation) or inland migration as long as a dependable sediment supply exists and inland movement is not impeded by shoreline structures (Figure 4.2) or by geology (*e.g.* sloped areas between geologic terraces, as found around Chesapeake Bay) (Ward *et al.*, 1998). In areas where neither sufficient accretion nor migration can occur, increased tidal flooding may stress marsh plants through water logging and changes in soil chemistry, leading to a change in plant species composition and vegetation zones. If marsh plants become too stressed and die, the marsh will eventually convert to open water or tidal flat (Callaway *et al.*, 1996)[8].

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[8] The Plum Tree Island National Wildlife Refuge is an example of a marsh deteriorating through lack of sediment input and migration capacity, due to development on its landward side. Extensive mudflats front the marsh. See Appendix F for additional details.

Figure 4.2 Fringing marsh and bulkhead, Monmouth County, New Jersey.

Sea-level rise is also increasing salinity upstream in some rivers, leading to shifts in vegetation composition and the conversion of some tidal freshwater marshes into brackish marshes (Maryland DNR, 2005). At the same time, brackish marshes can deteriorate as a result of ponding and smothering of marsh plants by beach wrack (aquatic plants that are carried on shore during high tide and are left behind when tides recede) as salinity increases and storms accentuate marsh fragmentation[9]. While this process may allow colonization by lower marsh species, that outcome is not certain (Stevenson and Kearney, 1996). Low brackish marshes can change dynamically in area and composition as sea level rises. If they are lost, forage fish and invertebrates of the low marsh, such as fiddler crabs, grass shrimp, and ribbed mussels, will no longer be available to predators. Though more ponding may provide some additional foraging areas as marshes

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[9] Along the Patuxent River, Maryland, refuge managers have noted marsh deterioration and ponding with sea level rise. See Appendix F for additional details.

deteriorate, the associated increase in salinity due to evaporative loss can also inhibit the growth of marsh plants (Maryland DNR, 2005).

Brackish marshes support many of the same wildlife species as salt marshes, with some notable exceptions. Bald eagles forage in brackish marshes and nest in nearby wooded areas. Because there are few resident mammalian predators, small herbivores such as meadow vole thrive in these marshes. Fish species common in the brackish waters of the Mid-Atlantic include striped bass and white perch, which move in and out of brackish waters year-round. Anadromous fish found in the Mid-Atlantic include herring and shad, while marine transients such as Atlantic menhaden and drum species are present in summer and fall (White, 1989).

Freshwater tidal marshes are characteristic of the upper reaches of estuarine tributaries. In general, the plant species composition of freshwater marshes depends on the degree of flooding, with some species germinating well when completely submerged, while others are relatively intolerant of flooding (Mitsch and Gosselink, 2000). Freshwater tidal marshes have been shown to possess higher plant diversity than other tidal marsh types (Perry and Atkinson, 1997). The vegetative species composition of the higher elevation freshwater marsh typically includes abundances of jewelweed, (*Impatiens capensis*), green arrow arum (*Peltandra virginica*), knotweed, tearthumb and smartweed species (*Polygonum* spp.), river bulrush (*Schoenoplectus fluviatilis*), and narrowleaf cattail (*Typha angustifolia*). The low freshwater marsh includes common threesquare (*Scirpus pungens*), tidalmarsh amaranth (*Amaranthus cannabinus*), and wild rice (*Zizania* *aquatica*) among others, depending on location, and salinity (NatureServe, accessed 2008).

Tidal freshwater marshes provide shelter, forage, and spawning habitat for numerous fish species, primarily cyprinids (minnows, shiners, carp), centrarchids (sunfish, crappie, bass), and ictalurids (catfish). In addition, some estuarine fish and shellfish species complete their life cycles in freshwater marshes. Freshwater tidal marshes are also important for a wide range of bird species. Some ecologists suggest that freshwater tidal marshes support the greatest diversity of bird species of any marsh type. The avifauna of these marshes includes waterfowl; wading birds; rails and shorebirds; birds of prey; gulls, terns, kingfishers, and crows; arboreal birds; and ground and shrub species. Perching birds such as red-winged blackbirds are common in stands of cattail. Tidal freshwater marshes support additional species that are rare in saline and brackish environments, such as frogs, turtles, and snakes (White, 1989).

Effects of marsh inundation on fish and shellfish species are likely to be complex. In the short term, inundation may make the marsh surface more accessible, increasing production. However, benefits will decrease as submergence decreases total marsh habitat (Rozas and Reed, 1993). For example, deterioration and mobilization of marsh peat sediments increases the immediate biological oxygen demand and may deplete oxygen in marsh creeks and channels below levels needed to sustain fish. In these oxygen-deficient conditions, mummichogs and other killifish may be among the few species able to persist (Stevenson *et al.*, 2002). Inadequate tidal flow can result in hypersaline conditions, leading to die-off of marsh vegetation, and loss of the network of tidal creeks characteristic of natural marshes. Fish production is known to be significantly lower in marshes that lack a high drainage density (Kneib, 1997).

In areas where marshes are reduced, remnant marshes may provide lower quality habitat, fewer nesting sites, and greater predation risk for a number of bird species that are marsh specialists and are also important components of marsh food webs, including the clapper rail, black rail, least bittern, Forster's tern, willet, and laughing gull (Figure 4.3) (Erwin *et al.*, 2006b). The majority of the Atlantic Coast breeding populations of Forster's tern and laughing gull are considered to be at risk because of loss of lagoonal marsh habitat due to sea-level rise (Erwin *et al.*, 2006b). In a Virginia study, scientists found that the minimum marsh size to support significant marsh bird communities was 4.1-6.7 ha (Watts, 1993). Some species may require even larger marsh sizes; minimum marsh size for successful communities of the saltmarsh sharp-tailed sparrow and the seaside sparrow, both on the Partners in Flight WatchList, are estimated at 10 ha and 67 ha, respectively (Benoit and Askins, 2002).

Figure 4.3 Marsh drowning and hummock in Blackwater Wildlife Refuge, Maryland.

4.2 MARSH AND BAY ISLANDS

Marsh and bay islands are found throughout the mid-Atlantic study region, and are particularly vulnerable to sea-level rise. Islands are common features of salt marshes, and some estuaries and back barrier bays have islands formed by deposits of dredge spoil. Many islands are a mix of habitat types, with vegetated and unvegetated wetlands in combination with upland areas[10]. These isolated areas provide nesting sites for various bird species, particularly colonial nesting waterbirds, where they are protected from terrestrial predators such as red fox. Gull-billed terns, common terns, black skimmers, and American oystercatchers all nest on marsh islands (Rounds *et al.*, 2004; Eyler *et al.*, 1999).

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[10] Thompson's Island in Rehoboth Bay, Delaware, is a good example of a mature forested upland with substantial marsh and beach area. The island hosts a large population of migratory birds. See Strange, E., D. Wilson, and C. Bason. 2006. Maryland and Delaware Coastal Bays: Supporting Document for CCSP 4.1, Question 8.

Many islands along the Mid-Atlantic, and particularly in Chesapeake Bay, have already been lost or severely reduced as a result of erosion and flooding related to sea-level rise. Field studies indicate that the loss of wetland islands poses a serious, near-term threat for island-nesting bird species, and in some areas, diamond-back terrapins. Mainland marshes are often not a good substitute, because of predators[11].

Figure 4.4 Cypress along Roanoke River, North Carolina.

4.3 TIDAL FRESHWATER SWAMP FORESTS

Limited primarily by their requirements for low salinity water in a tidal regime, tidal swamp forests occur primarily in upper regions of tidal tributaries in Virginia, Maryland, Delaware, New Jersey, and New York (NatureServe, 2006). The low-lying shorelines of North Carolina also contain large stands of forested wetlands, including cypress and pocosins (Figure 4.4). Also in the mid-Atlantic coastal plains (*e.g.*, around Barnegat Bay, NJ) are Atlantic white cedar swamps, found in areas where a saturated layer of peat overlays a sandy substrate (NatureServe, 2006).

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[11] *e.g.*, see general discussion in McGowan , 2005.

Tidal freshwater swamp forests face a variety of threats, including sea-level rise, and are currently considered globally uncommon to rare. The responses of these forests to sea-level rise may include retreat at the open-water boundary, drowning in place, or expansion inland. One study noted that, “Crown dieback and tree mortality are visible and nearly ubiquitous phenomena in these communities and are generally attributed to sea-level rise and an upstream shift in the salinity gradient in estuarine rivers” (Fleming *et al.*, 2006). Figure 4.5 presents an example of inundation and tree mortality. Ecologists in Virginia have observed that where tree death is present, the topography is limiting inland migration of the hardwood swamp and the underbrush is being invaded by marsh plants[12].

Figure 4.5 Inundation and tree mortality in tidal freshwater swamp at Swan’s Point, Lower Potomac River.

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[12] Gary Fleming, Vegetation Ecologist. Virginia Department of Conservation and Recreation, Division of Natural Heritage, written communication to Christina Bosch, Industrial Economics, September 11, 2006.

4.4 SEA-LEVEL FENS

Sea-level fens are a rare type of coastal wetland with a mix of freshwater tidal and northern bog vegetation and unique assemblage of vegetation including carnivorous plants such as sundew and bladderworts (Fleming *et al.*, 2006; VNHR, 2006). The eastern mud turtle and the smallest northeastern dragonfly (*Nanothemis bella*) are among the animal species found in sea-level fens. Fens may occur in areas where soils are acidic and a natural seep from a nearby slope provides nutrient-poor groundwater (VNHR, 2006). It is not clear what effect sea-level rise may have on these wetlands. Fens do not tolerate nutrient-rich ocean waters, and therefore if a fen is at an elevation where it can become inundated by rising seas it may not persist[13]. On the other hand, sea-level rise could cause the natural seep (groundwater discharge) to migrate upslope and increase in volume at some locations, which would benefit fens[14].

4.5 SUBMERGED AQUATIC VEGETATION

Submerged aquatic vegetation (SAV) is distributed throughout the mid-Atlantic region, dominated by eelgrass in the higher-salinity areas and a large number of brackish and freshwater species elsewhere (*e.g.*, widgeon grass, sea lettuce) (Hurley, 1990). SAV plays a key role in estuarine ecology, helping to regulate the oxygen content of nearshore waters, trapping sediments and nutrients, stabilizing bottom sediments, and reducing wave energy (Short and Neckles, 1999). SAV also provides food and shelter for a variety of fish and shellfish and the species that prey on them. Organisms that forage in SAV

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[13] Chris Bason, Delaware Inland Bays Program, written communication to EPA, May 14, 2007.

[14] Barry Truitt,Chief Conservation Scientist, The Nature Conservancy, Virginia Coast Reserve, written communication to EPA, July 25, 2007.

beds feed on the plants themselves, the detritus and the epiphytes on plant leaves, and the small organisms found within the SAV bed[15]. The commercially valuable blue crab hides in eelgrass during its molting periods, when it is otherwise vulnerable to predation. In Chesapeake Bay, summering sea turtles frequent eelgrass beds. The federally listed endangered Kemp's Ridley sea turtle forages in eelgrass beds and flats, feeding on blue crabs in particular (Chesapeake Bay Program [sea turtles], 2007). Various waterbirds feed on SAV, including brant, canvasback, and American black duck (Perry and Deller, 1996).

Forage for piscivorous birds and fish is also provided by residents of nearby marshes that move in and out of SAV beds with the tides, including mummichog, Atlantic silverside, naked goby, northern pipefish, fourspine stickleback, and threespine stickleback. Juveniles of many commercially and recreationally important estuarine and marine fishes (such as menhaden, herring, shad, spot, croaker, weakfish, red drum, striped bass, and white perch) and smaller adult fish (such as bay and striped anchovies) use SAV beds as nurseries (Chesapeake Bay Program [SAV], 2007; Wyda *et al.*, 2002.). Adults of estuarine and marine species such as sea trout, bluefish, perch, and drum search for prey in SAV beds.

Effects of sea-level rise on SAV beds are uncertain because most changes in SAV occur on a significantly shorter timescale than can be attributed to sea-level rise[16]. However,

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[15] See various sources, including Stockhausen**,** 2003 for blue crabs and Wyda, 2002 for fish.

[16] For example, nutrient pollution from various sources is a common problem for SAV beds (USFWS, undated).

Short and Neckles (1999) estimate that a 50 cm increase in water depth as a result of sea-level rise could reduce the available light in coastal areas by 50%, resulting in a 30-40% reduction in seagrass growth in current bed areas (Short and Neckles, 1999).

Although plants in some portion of a SAV bed may decline as a result of such factors, landward edges may migrate inland depending on shore slope and substrate suitability. SAV growth is significantly better in areas where erosion provides sandy substrate, rather than fine-grained or high organic matter substrates (Stevenson *et al.*, 2002).

Sea-level rise effects on the tidal range could also impact SAV, although the effect may be detrimental or beneficial. In areas where the tidal range increases, plants at the lower edge of the bed will receive less light at high tide, increasing plant stress (Koch and Beer, 1996). In areas where the tidal range decreases, the decrease in intertidal exposure at low tide on the upper edge of the bed will reduce plant stress (Short and Neckles, 1999).

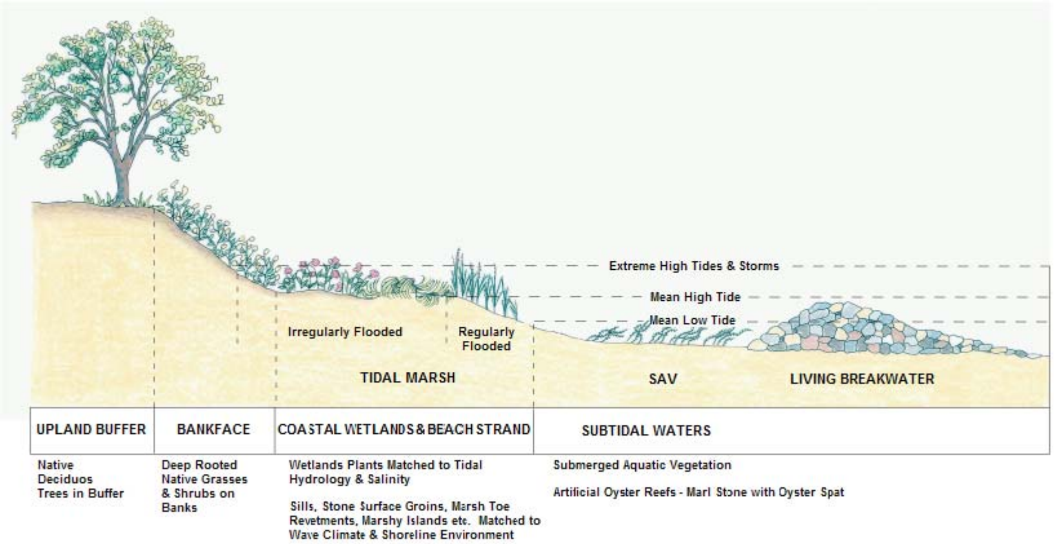
Shoreline construction and armoring will impede shoreward movement of SAV beds (Short and Neckles, 1999). First, hard structures tend to affect the immediate geomorphology as well as any adjacent seagrass habitats. Particularly during storm events, wave reflection off of revetments can increase water depth and magnify the inland reach of waves on downcoast beaches (Plant and Griggs, 1992; USGS, 2003; Small and Carman, 2005). Second, as sea level rises in armored areas, the nearshore area deepens and light attenuation increases, restricting and finally eliminating seagrass growth. Finally, high nutrient levels in the water are a limiting factor. Sediment trapping behind breakwaters, which increases the organic content, may limit eelgrass success. Low-profile armoring, including stone sills and other "living shorelines" projects, may be beneficial to SAV growth (NRC, 2007). Projects to protect wetlands and restore adjacent SAV beds are taking place and represent a potential protection against SAV loss (*e.g.*, U.S. Army Corps of Engineers restoration for Smith Island in Chesapeake Bay) (USACE, 2004).

Loss of SAV affects numerous animals that depend on the vegetation beds for protection and food. By one estimate, a 50% reduction in SAV results in a roughly 25% reduction in striped bass production (Kahn and Kemp, 1985). For diving and dabbling ducks, a decrease in SAV in their diets since the 1960s has been noted (Perry and Deller, 1996). The decreased SAV in Chesapeake Bay is cited as a major factor in the substantial reduction in wintering waterfowl (Perry and Deller, 1996).

Box 4.1 Shore Protection Alternatives: Living Shorelines

Shore erosion and methods for its control are a major concern in estuarine and marine ecosystems. However, awareness has grown in recent years of the negative impacts that many traditional shoreline protection methods have, including loss of wetlands and their buffering capacities, impacts on nearshore biota, and ability to withstand storm events. Along all but the highest-energy shorelines (due to fetch or boat traffic), non-structural approaches are being considered, or hybrid-type projects that combine a marsh fringe with groins, sills, or breakwaters. The cost per foot for these projects is also significantly less than for bulkheads or stone reinforcements.

These projects typically combine marsh replanting (generally *Spartina patens* and *Spartina alterniflora*) and stabilization through sill, groins, or breakwaters. A survey of projects on the eastern and western sides of Chesapeake Bay (including Wye Island, Epping Forest near Annapolis, and the Jefferson Patterson Park and Museum on the Patuxent) found that the sill structures or breakwaters were most successful in attenuating wave energy and allowing the development of a stable marsh environment.



Box Figure 4.1 Depiction of Living Shoreline Treatments from the Jefferson Patterson Park and Museum, Patuxent River.

Sources: Jefferson Patterson Park and Museum, wetlands restoration firm Environmental Concern (www.wetland.org), "Shore Erosion Control: The Natural Approach" from the Maryland Department of Natural Resources, Burke *et al.*, 2005.

End of text box****************

4.6 TIDAL FLATS

Tidal flats are composed of mud or sand and provide habitat for a rich abundance of invertebrates. Tidal flats are critical foraging areas for numerous birds, including wading birds, migrating shorebirds, and dabbling ducks.

In areas with low accretion rates, marsh will revert to unvegetated flats and eventually open water as seas rise (Brinson *et al.*, 1995). For example, in New York's Jamaica Bay, several hundred acres of low saltmarsh have converted to open shoals[17]. Modeling by Galbraith *et al.* (2002) predicted that under a two degree Celsius global warming scenario, sea-level rise could inundate significant areas of intertidal flats in some regions

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[17] See Appendix B for additional details.

(Galbraith *et al.*, 2002). In some cases where tidal range increases with increased rates of sea-level rise; however, there may be a net increase in the acreage of tidal flats (Field *et al.*, 1991).

In areas where sediments accumulate in shallow waters and shoreline protection prevents landward migration of salt marshes, flats may become vegetated as low marsh encroaches waterward. This will accelerate sediment deposition at the waterward edge of the vegetated area and increase low marsh at the expense of tidal flats (Redfield, 1972). If sediment inputs are not sufficient, tidal flats will convert to subtidal habitats, which may or may not be vegetated depending on substrate composition.

Loss of tidal flats would eliminate a rich invertebrate food source for migrating birds, including insects and small crabs and other shellfish. As tidal flat area declines, increased crowding in remaining areas could lead to exclusion and reductions in local shorebird populations (Galbraith *et al.*, 2002). At the same time, ponds within marshes may become more important foraging sites for the birds if flats are inundated by sea-level rise (Erwin *et al.*, 2004).

Figure 4.6 Estuarine beach and bulkhead along Arthur Kills.

4.7 ESTUARINE BEACHES

Throughout most of the mid-Atlantic region and its tributaries, estuarine beaches front the base of low bluffs and high cliffs as well as bulkheads and revetments (see Figure 4.6) (Jackson *et al.*, 2002). Estuarine beaches can also occur in front of marshes and on the mainland side of barrier islands.

Figure 4.7 Dinner time along Peconic Estuary Beach, Long Island, NY.

The most abundant beach organisms are microscopic invertebrates that live between sand grains, feeding on bacteria and single-celled protozoa. It is estimated that over two billion of these organisms are in a single square meter of sand (Bertness, 1999). They play a critical role in beach food webs as a link between bacteria and larger consumers such as sand diggers, fleas, crabs and other macroinvertebrates burrow in sediments or hide under rocks. Various rare and endangered beetles also live on sandy shores. Diamondback terrapin and horseshoe crabs bury their eggs in beach sands. In turn, shorebirds such as the piping plover, American oystercatcher, and sandpipers feed on these resources (USFWS, 1988). The insects and crustaceans found in deposits of wrack on estuarine beaches are also an important source of forage for birds (Figure 4.7) (Dugan *et al.*, 2003). As sea levels rise, the fate of estuarine beaches depends on their ability to migrate and the availability of sediment to replenish eroded sands (Figure 4.8) (Jackson *et al.*, 2002). Estuarine beaches continually erode, but under natural conditions the landward and waterward boundaries usually retreat by about the same distance. Shoreline protection structures may prevent migration, effectively squeezing beaches between development and the water. Armoring that traps sand in one area can limit or eliminate longshore transport, and, as a result, diminish the constant replenishment of sand necessary for beach retention in nearby locations. Areas with bulkheads frequently have artificially elevated land areas because not all structures are built in a straight line. In armored areas between headlands, the beach will likely become steeper and the sediments coarser (Jackson *et al.*, 2002). Waterward of the bulkheaded headlands, the foreshore habitat will be lost, frequently even without sea-level rise. For areas between these headlands that are not armored, sediment input may be reduced and inundation may occur with rising sea level. In areas with sufficient sediment input relative to sea-level rise (*e.g.*, upper tributaries and upper Chesapeake Bay) beaches may remain in place in front of armoring.

Figure 4.8 Beach with beach wrack and marsh in New Jersey.

In many developed areas, estuarine beaches may be maintained with beach nourishment if there are sufficient sources. However, the ecological effects of beach nourishment remain uncertain. Beach nourishment will allow retention in areas with a sediment deficit, but may reduce habitat value through effects on sediment characteristics and beach slope (Peterson and Bishop, 2005).

Beach loss will cause declines in local populations of rare beetles found in Calvert County, Maryland. While the Northeastern beach tiger beetle is able to migrate in response to changing conditions, suitable beach habitat must be available nearby (USFWS, 1994).

At present, the degree to which horseshoe crab populations will decline as beaches are lost remains unclear. Early research results indicate that horseshoe crabs may lay eggs in intertidal habitats other than estuarine beaches, such as sandbars and the sandy banks of tidal creeks (Loveland and Botton, 2007). Nonetheless, these habitats may only provide a temporary refuge for horseshoe crabs if they are inundated as well.

Where horseshoe crabs decline because of loss of suitable habitat for egg deposition, there can be significant implications for migrating shorebirds, particularly the red knot, a candidate for protection under the federal Endangered Species Act, which feeds almost exclusively on horseshoe crab eggs during stopovers in the Delaware Estuary (Karpanty *et al.*, 2006). In addition, using high-precision elevation data from nest sites, researchers are beginning to examine the effects that sea-level rise will have on oystercatchers and other shore birds (Rounds, 2002). To the extent that estuarine and riverine beaches, particularly on islands, survive better than barrier islands, shorebirds may be able to migrate to these shores (McGowan *et al.*, 2005).

4.8 CLIFFS

Unvegetated cliffs and the sandy beaches sometimes present at their bases are constantly reworked by wave action, providing a dynamic habitat for cliff beetles and birds. Little vegetation exists on the cliff face due to constant erosion, and the eroding sediment augments nearby beaches. Cliffs are present on Chesapeake Bay's western shore and tributaries and its northern tributaries (see Figure 4.9), as well as in Hempstead Harbor on Long Island's North Shore.

Figure 4.9 Crystal Beach, along the Elk River, Maryland.

If the cliff base is armored to protect against rising seas, erosion rates may decrease, eliminating the unvegetated cliff faces that are sustained by continuous erosion and provide habitat for species such as the Puritan tiger beetle and bank swallow. Naturally eroding cliffs are "severely threatened by shoreline erosion control practices" according to the Maryland DNR's Wildlife Diversity Conservation Plan (Maryland DNR, 2005). Shoreline protections may also subject adjacent cliff areas to wave undercutting and higher recession rates (Wilcock *et al.*, 1998). Development and shoreline stabilization structures that interfere with natural erosional processes are cited as threats to bank-nesting birds as well as two species of tiger beetles (federally listed as threatened) at Maryland's Calvert Cliffs (USFWS, 1993; USFWS, 1994; CCB, 1996).

4.9 SUMMARY

Based on the information currently available, it is possible to identify particular taxa and even some individual species that appear to be at greatest risk if coastal habitats are degraded or lost in response to sea-level rise and shoreline hardening:

- Degradation and loss of tidal wetlands will affect fish and shellfish production in both the marshes themselves and adjacent estuaries.
- Bird species that are marsh specialists, including the clapper rail, black rail, least bittern, Forster’s tern, willet, and laughing gull, are particularly at risk. At present, the majority of the Atlantic Coast breeding populations of Forster’s tern and laughing gull are considered to be at risk from loss of lagoonal marshes.
- Increased turbidity in nearshore areas and increased water depths may reduce light penetration to seagrass beds, reducing photosynthesis and therefore the growth and survival of seagrasses. Degradation and loss of seagrass beds will affect the numerous organisms that feed, carry on reproductive activities, and seek shelter in seagrass beds.
- Diamondback terrapin are at risk of losing both marsh habitat that supports growth and adjoining beaches where eggs are buried.
- Many marsh islands along the Mid-Atlantic, and particularly in Chesapeake Bay, have already been lost or severely reduced as a result of erosion and flooding related to sea-level rise. Loss of such islands poses a serious, near-term threat for island-nesting bird species such as gull-billed terns, common terns, black skimmers, and American oystercatchers.

- Tidal freshwater swamp forests are at risk from sea-level rise and a variety of other threats, and are now considered globally uncommon to rare.
- Shoreline stabilization structures interfere with natural erosional processes that maintain unvegetated cliff faces that provide habitat for bank-nesting birds and tiger beetles.
- Loss of tidal flats could lead to increased crowding of foraging birds in remaining areas, resulting in exclusion of many individuals; if alternate foraging areas are unavailable, starvation of excluded individuals may result, ultimately leading to reductions in local bird populations.
- Loss of estuarine beaches could cause declines in local populations of rare tiger beetles.
- Where horseshoe crabs decline because of loss of suitable beach substrate for egg deposition, there could be significant implications for migrating shorebirds, particularly the red knot, a candidate for protection under the federal Endangered Species Act. Red knot feed almost exclusively on horseshoe crab eggs during stopovers in the Delaware Estuary.

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