U.S. Climate Change Science Program

Synthesis and Assessment Product 4.1

Coastal Sensitivity to Sea Level Rise: A Focus on the Mid-Atlantic Region

Lead Agency:
Environmental Protection Agency

Contributing Agencies:
National Oceanic and Atmospheric Administration
U.S. Geological Survey
Department of Transportation

NOTE TO REVIEWERS: Only minimal copy editing (primarily formatting) has been done. Extensive copy editing will take place prior to layout for publication.

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Preface

The U.S. Climate Change Science Program (CCSP) was launched in February 2002 as a collaborative interagency program, under a new cabinet-level organization designed to improve the government-wide management of climate science and climate-related technology development. The mission of the CCSP is to "facilitate the creation and application of knowledge of the Earth's global environment through research, observations, decision support, and communication." As part of this mission, this report is one of twenty-one synthesis and assessment products (SAPs) identified in the *Strategic Plan for the U.S. Climate Change Science Program* (CCSP, 2003). The SAPs are intended to support informed discussion and decisions by policymakers, resource managers, stakeholders, the media, and the general public. The products help meet the requirements of the Global Change Research Act of 1990, which directs agencies to "produce information readily usable by policymakers attempting to formulate effective strategies for preventing, mitigating, and adapting to the effects of global change" and to undertake periodic scientific assessments. This SAP (4.1) on *Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region* provides a detailed assessment of the effects of sea-level rise on coastal environments and presents some of the challenges that will need to be addressed to adapt to sea-level rise while protecting environmental resources and sustaining economic growth.

A large and expanding proportion of the U.S. population and associated urban development is located along the coasts of the United States and is increasingly affected by the natural processes associated with coastal change from storms and sea-level rise. Recent international assessments of climate change and related impacts indicate that the rate of sea-level rise is increasing in association with a warming ocean and melting ice caps and glaciers. Future sea-level rise is expected to increase at rates exceeding those observed over the last century, and the rise could be exponential rather than linear as it has been (Bindoff *et al.*, 2007; Meehl *et al.*, 2007). Rising sea levels will potentially affect large portions of the U.S. coast, presenting challenges to those residing at and using the coast, as well as to the sustainability of critical coastal habitats and ecosystems.

P.1 SCOPE AND APPROACH OF THIS REPORT

The focus of this report is to review and identify the potential impacts of future sea-level rise based on the state of our present scientific understanding. To do so, this report evaluates several aspects of sea-level rise impacts to the natural environment and also examines the impact to human development. In addition, the report addresses the interplay between sea-level rise impacts and human adaptation measures, and assesses the role of the existing coastal management infrastructure in identifying and responding to potential challenges.

The report focuses on the mid-Atlantic coast of the United States which consists of the region between Montauk, New York and Cape Lookout, North Carolina. While other regions in the U.S. such as the Gulf coast are potentially as or more vulnerable to sea-level rise, the Mid-Atlantic is also a region where high population density and extensive coastal development could be at risk. In addition, there is substantial scientific research on the mid-Atlantic coast, as well as recent studies of this region by EPA and NOAA, as listed in the *Strategic Plan for the U.S. Climate Change Science Program* (CCSP, 2003).

The development of this report was guided by ten prospectus questions, focusing on different aspects of future sea-level rise and the impact to the coastal environment. The first four prospectus questions focus on evaluating the impact to and vulnerability of the natural environment. Specifically, these questions are:

1. Which lands are currently at an elevation that could lead them to be inundated without shore protection measures? (Chapter 1)
2. How does sea-level rise change the coastline? Among those lands with sufficient elevation to avoid inundation, which land could potentially erode in the next century? Which lands could be transformed by related coastal processes? (Chapter 2)
3. What is a plausible range for the ability of wetlands to vertically accrete, and how does this range depend on whether shores are developed and protected, if at all? That is: will sea-level rise cause the area of wetlands to increase or decrease? (Chapter 3)
4. Which lands have been set aside for conservation uses so that wetlands will have the opportunity to migrate inland; which lands have been designated for uses requiring shore protection; and which lands could realistically be available for either wetland migration or coastal development requiring shore protection? (Chapter 5)

The remaining prospectus questions focused on the societal impacts expected with future sea-level rise. These questions are:

5. What are the potential impacts of sea-level rise on coastal floodplains? What issues would FEMA, coastal floodplain managers, and coastal communities face as sea level rises? (Chapter 8)
6. What are the population, infrastructure, economic activity, and value of property within the area potentially inundated by rising sea level given alternative levels of shore protection? (Chapter 6)
7. How does sea-level rise affect the public's access to, and use of, the shore? (Chapter 7)
8. Which species depend on habitat that may be lost due to sea-level rise given various levels of shore protection and other response options? (Chapter 4)
9. Which decisions and activities (if any) have outcomes sufficiently sensitive to sea-level rise so as to justify doing things differently, depending on how much the sea is expected to rise? (Chapter 9)
10. What adaptation options are being considered by specific organizations that manage land or regulate land use for environmental purposes? What other adaptation options are being considered by federal, state or local governments? What are the specific implications of each option? What are the institutional barriers to preparing for sea-level rise? (Chapters 10 and 11)

The first four questions are addressed for the entire mid-Atlantic study area, whereas our answers to most of the latter questions are focused on sub-regions, based on site-specific examples, direct observations, stakeholder input, or case studies. During the preparation of this report, three regional stakeholder meetings were held between the author team and representatives from local, county, and state agencies, other federal agencies and non-governmental organizations. Many of the prospectus questions were discussed in detail with the audience and the feedback was incorporated into the report.

Many of the findings expressed in this report are expressed using common expressions of likelihood as in the most recent Intergovernmental Panel on Climate Change (IPCC) Assessment. These likelihood determinations were established by the report authors and modeled after other CCSP SAPs (*e.g*. Karl *et al*., 2006) (Figure P1). These determinations are based on the judgment of authors and the published uncertainties in literature cited.

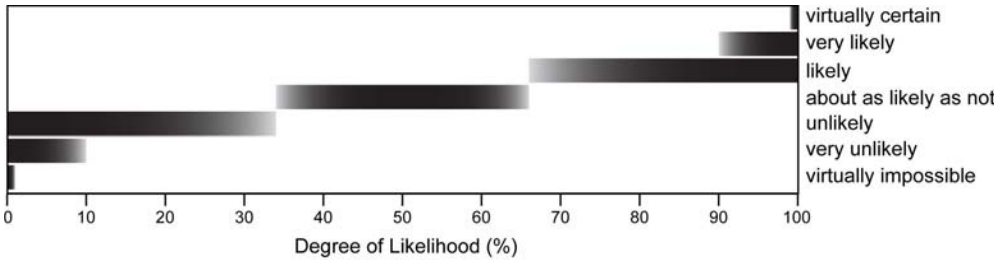

Figure P.1 The likelihood terms and related probabilities that were used for this report.

In some cases, specific chapters may incorporate more quantitative assessment of uncertainty related to a specific analysis conducted to address a specific question in the report.

P.2 FUTURE SEA LEVEL SCENARIOS ADDRESSED IN THIS REPORT

In this report, the term “sea level” refers to mean sea level or the average level of tidal waters, generally measured over a 20-year period (See Glossary). These measurements generally indicate the water level relative to the land, and thus incorporate changes in the elevation of the land as well as absolute changes in sea level (*e.g.*, relative sea level). 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 due to a range of factors with the most significant being 1) the thermal expansion of the oceans surface layers and 2) the melting of land-based ice sheets, ice caps, and glaciers.
- “Relative sea-level rise” refers to the change in sea level relative to the elevation of the land, which can also rise or subside. Relative sea-level changes include both global sea-level rise and changes in the vertical position of the land surface.

In this report, the term “sea-level rise” refers to “relative sea-level rise.”

This report does not provide a forecast of future rates of sea-level rise. Instead, it evaluates the implications of three sea-level rise scenarios:

- Scenario 1: the 20th century rate, which is generally 3-4 mm/yr in the mid-Atlantic region
- Scenario 2: the 20th century rate + 2 mm/yr acceleration (up to 50 cm by the year 2100)

- Scenario 3: the 20th century rate + 7 mm/yr acceleration (up to 100 cm by 2100)

The 20th century rate of sea-level rise refers to the local long-term rate of sea-level rise that has been observed at tide gauges in the mid-Atlantic study region. Scenario 1 thus assesses the impacts if future sea-level rise occurs at the same rate as was observed over the last century at a particular location. Scenarios 1 and 2 are within the range of those reported in the recent IPCC report (Bindoff *et al.*, 2007), while Scenario 3 exceeds this range by up to 40 cm by 2100. Scenario 3 reflects concerns that the IPCC values might be conservative and are less than high estimates suggested by more recent publications. In addition to these three scenarios, some chapters refer to higher sea-level rise scenarios, such as a 2 m rise over the next few hundred years (a conservative estimate if ice sheet melting on Greenland and Antarctica exceeds IPCC model estimates).

P.3 REPORT ORGANIZATION

This report first provides context and then presents the results of our synthesis and assessment in six parts and eight appendices:

Part I analyzes the effects of sea-level rise on the physical environment. Chapters in Part I discuss (1) the extent of low-lying land that occurs below future sea-level rise scenarios (Chapter 1); (2) the physical changes at the coast that will result in changes to coastal landforms (*e.g.* barrier islands) and shoreline position in response to sea-level rise (Chapter 2); (3) the ability of wetlands to accumulate sediments and survive in response to rising sea level (Chapter 3); and (4) the habitat and species that will be vulnerable to sea-level rise related impacts (Chapter 4).

Part II describes the societal impacts and implications of sea-level rise. Chapter 5 provides a framework for assessing shoreline protection options in response to sea-level rise. Chapter 6 discusses the extent of vulnerable population and infrastructure, and Chapter 7 addresses the implications for public access to the shore. Chapter 8 reviews the impact of sea-level rise to flood hazards.

Part III examines strategies for coping with sea-level rise. Chapter 9 outlines key considerations when making decisions to reduce vulnerability. Chapter 10 discusses what organizations are doing now to adapt to sea-level rise, and Chapter 11 examines possible institutional barriers to adaptation.

Part IV introduces and highlights some mid-Atlantic local case studies of coastal elevations and sensitivity to sea-level rise, which are then explored further in Appendices A-G.

Part V discusses sea-level rise impacts and implications at a national scale and briefly highlights how coasts in other parts of the U.S. are vulnerable to sea-level rise.

Part VI presents some recommendations for future effort to reduce uncertainty and close gaps in scientific knowledge and understanding.

Appendices A-G provide maps and tables showing coastal elevations, scenarios of flooding and erosion mitigation, and discussions of particular areas of environmental significance that may be vulnerable to sea-level rise. **Appendix H** reviews some of the basic approaches that have been used to conduct shoreline change or land loss assessments in the context of sea-level rise and some of the difficulties that arise in using these methods.

While the authors strove to limit technical jargon in the report, technical and scientific terms occur throughout the report. To aid readers with some of these terms, a **Glossary** is included at the end of this Report.

PREFACE REFERENCES

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Executive Summary

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1. SEA-LEVEL RISE IN THE MID-ATLANTIC

Global sea level is rising and is expected to accelerate. Global sea level is primarily affected by the proportion of water that exists in ocean basins and the amount that is held in glaciers and ice sheets. Sea level has risen and declined as the climate has cooled (producing ice ages) and warmed (melting ice sheets) over the past several million years. Sea level has risen about 120 m (390 ft) since the peak of the last ice age approximately 21,000 years ago. During the last 10,000 years, by contrast, global sea level has been relatively stable, enabling development of human civilization along the coasts.

Recent assessments have indicated that the rate of sea-level rise increased between the mid-19th and mid-20th centuries. Global sea level rose at an average rate of 1.7 mm/yr over the 20th century, with an increased rate of 3.1 mm/yr from 1993 to 2003. In the mid-Atlantic region from New York to North Carolina, tide gauge observations indicate that relative sea-level rise rates have exceeded the global rate due to a combination of land subsidence and global sea-level rise. In this region, relative sea-level rise rates ranged between 3 to 4 mm per year (~1ft per century) over the 20th century.

Rising water levels are submerging low-lying lands, eroding beaches, converting wetlands to open water, exacerbating coastal flooding, and increasing the salinity of estuaries and freshwater aquifers. In undeveloped or less-developed coastal areas where the human influence is less, sea-level rise could be accommodated more readily as ecosystems and geological systems are often more capable of shifting upward and landward with the rising water levels than are human systems.

All of the effects may be increased if the rate of sea-level rise accelerates in the future. Rising global temperatures are likely to accelerate the rate of sea-level rise by further expanding ocean water, melting mountain glaciers, and increasing the rate at which Greenland and Antarctic ice sheets melt or discharge ice into the oceans. If the sea rises more rapidly than the rate with which a particular system can keep pace, it could fundamentally change the state of the coast. Wetlands, beaches, coastal barriers, and estuarine systems have always contended with sea-level changes, but accelerated rates of rise may create more difficult conditions for survivability, and continued coastal development may impose additional challenges.

At the current rate of sea-level rise, over recent decades, coastal residents and businesses have been responding by moving out of harm’s way, holding back the sea, or some combination of both approaches. Wildlife species, particularly in areas affected by coastal development and the armoring of coastlines, have been reacting to their changing habitats in a variety of ways: *e.g.*, moving to other, often less suitable areas, or by having fewer offspring.

This report examines the sensitivity of the Mid-Atlantic coast and its inhabitants to continued and accelerated sea-level rise. It does not estimate how much the sea may rise; instead, it relies upon scenarios that broadly represent information in recent scientific literature. This report explores the implications of three future sea-level rise scenarios:

- Scenario 1 is the 20th century mid-Atlantic trend (3-4 mm/yr; 0.1-0.2 in/yr), and would result in a rise in sea level of 30-40 cm (12-16 in) by 2100.
- Scenarios 2 is an acceleration over the 20th century trend by 2 mm/yr (0.1 in/yr), and would result in a rise in sea level of 50-60 cm (20-24 in) by 2100.
- Scenario 3 is an acceleration over the 20th century trend by 7 mm/yr (0.3 in/yr), and would result in a rise in sea level of 100-110 cm (39-43 in) by 2100.

We also discuss the implications of a 2 meter rise in sea level, which may be possible in the next 100 years or longer.

A rise in sea level implies that land that is now barely above sea level will end up below sea level if no shore protection measures are taken to prevent it from being submerged. However, the reality of how the coast will respond to sea-level rise is more complicated than simple inundation. Storms are major forces in causing coastal change and may increase in intensity as the climate warms. Erosion can cause land to be lost even if the sea does not rise enough to inundate it; sediments eroded from one place can accrete the shoreline elsewhere or be transported offshore; and sometimes wetlands can rise along with the sea rather than become inundated, if sediment inputs are sufficient to compensate for the rise in sea level.

Species that rely on coastal habitat may be adversely affected as sea level rises. A key uncertainty and possible determinant of habitat and species loss is whether or not coastal landforms and present-day habitats will have space to migrate inland in response to sea-level rise. As coastal development continues, the ability for habitats to migrate inland along the rest of the coast will depend on how policies evolve.

2. KEY FINDINGS

This report examines what is potentially at risk from sea-level rise, what adaptation actions are available in response to sea-level rise, and which decisions may change the path forward. The information contained in this report was obtained through synthesis and assessment of the current scientific literature, mapping analyses, expert panel assessments, and information from topical experts.

2.1 Sea-Level Rise and the Physical Environment

2.1.1 Coastal Elevations

Approximately one-sixth of the nation’s land close to sea level is in the mid-Atlantic. Sea-level rise is **virtually certain** to cause some areas of dry land to become inundated. Approximately 900-2100 km^2 (350-800 mi^2) of dry land, half of which is in North Carolina, would be flooded during spring high tides if sea level rises 50 cm (20 in), assuming no shore protection measures are taken. For a larger rise, the amount of vulnerable dry land is roughly proportional to the rise in sea level (Chapter 1).

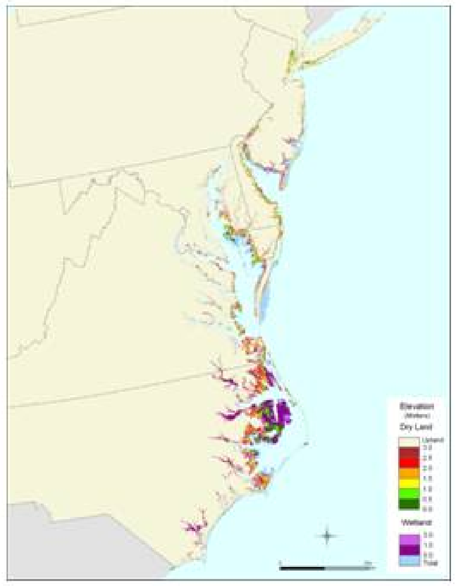

Figure ES.1 Dry land and nontidal wetlands within three meters above the tides in the Mid-Atlantic region.

2.1.2 Ocean Coasts

Nationally, it is **very likely** that erosion will increase in response to sea-level rise, especially in sandy shore environments which comprise all of the mid-Atlantic coast. Within the mid-Atlantic region, it is **virtually certain** that coastal headlands, spits, and barrier islands will also erode in response to future sea-level rise. For the higher sea-level rise scenarios, it is **likely** that some barrier islands in this region will cross a threshold where barrier island migration, segmentation, or disintegration will occur (Chapter 2).

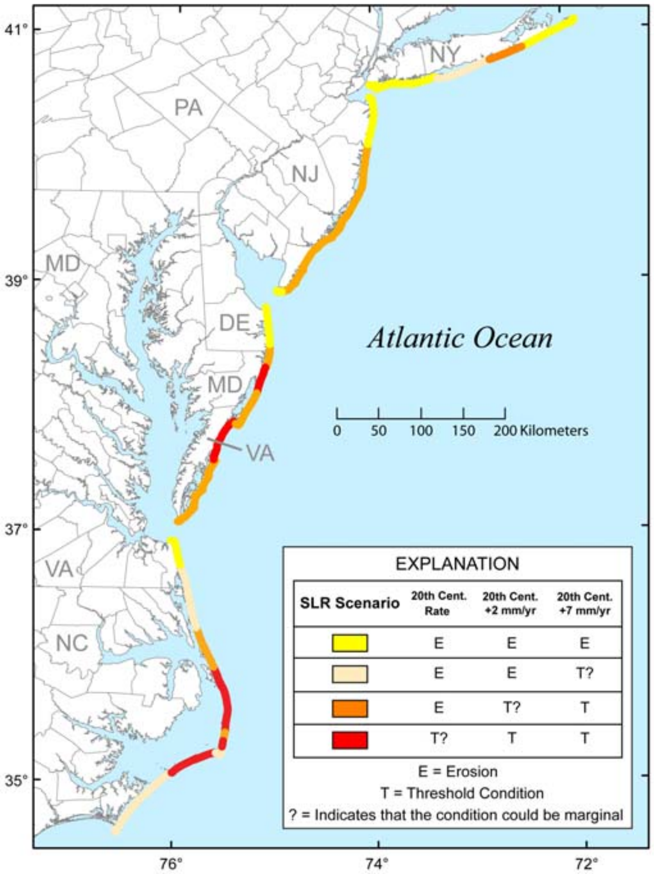

Figure ES.2 Potential coastal landform responses to the three sea-level rise scenarios. Many of the shaded areas are currently experiencing erosion which is expected to increase with future sea-level rise. Coastal segments denoted with a "T" are also expected to undergo erosion and may cross a threshold where barrier island migration, segmentation, or disintegration will occur.

2.1.3 Wetlands

It is **virtually certain** that the Nation's 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 (Chapter 3).

It is **very unlikely** that there will be a net increase in tidally influenced wetland area on a national scale over the next 100 years, given current wetland loss rates and the few occurrences of new tidal wetland expansion (*e.g.*, Atchafalaya Delta in Louisiana) (Chapter 3).

For the mid-Atlantic region, an acceleration in sea-level rise of +2 mm/yr will cause many wetlands to become stressed, and it is **likely** that most wetlands would not survive an acceleration in sea-level rise of +7 mm/yr. Excluding North Carolina, the mid-Atlantic has 4200 km^2 (1600 mi^2) of tidal wetlands, but only 300-1000 km^2 (390 mi^2) of dry land within 50 cm above the tides; therefore, the potential area for wetland migration or formation is small compared to the area of wetlands that may be at risk (chapter 3).

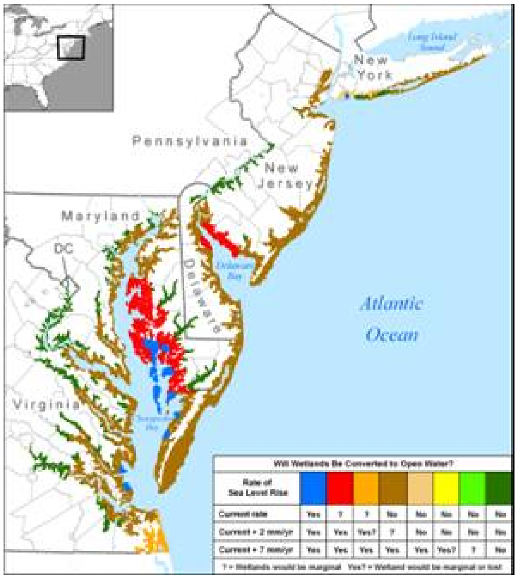

Figure ES.3 Areas where wetlands would be marginal or lost (i.e., converted to open water) under three sea-level rise scenarios.

2.1.4 Vulnerable Species

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 (Chapter 4).

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 (Chapter 4)

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 (Chapter 4).

2.2 Societal Impacts and Implications

2.2.1 Population, Land Use and Infrastructure

The coastal zone has competing interests of increasing population and development building of the necessary supporting infrastructure, while preserving natural coastal wetlands and buffer zones. Increasing sea level will put increasing stress onto the ability to manage these competing interests effectively (Chapter 6).

The available data is sufficient to estimate the number of people who live in the immediate vicinity of land potentially inundated by rising sea level. In the mid-Atlantic, between approximately 900,000 and 3,400,000 people (between 3% and 10% of the total population in the defined region) live on parcels of land or city blocks with at least some land less than 100 cm above spring high water. Approximately 40% of this population is along the Atlantic Ocean or adjacent coastal bays (Chapter 6).

Among the various potential impacts of sea-level rise on infrastructure, the mid-Atlantic transportation infrastructure possibly at risk include ports, highways and rails. For example, in the Port of Wilmington, DE, there is evidence to suggest that for an approximate 50 cm sea-level rise, 70 percent (320 acres) of the port property may be impacted. For the coastal states of Maryland, Virginia, and North Carolina, plus Washington, DC, approximately 3,500 km of our National Highway System, Interstates and other major arterials could be at risk for regular inundation given a sea level rise of 50 cm. Approximately 1,390 km of railway for these same states could be affected for the same scenario (Chapter 6).

2.2.2 Public Access to the Shore

Responses to sea-level rise can increase or decrease public access to the shore. Shoreline armoring generally eliminates public-trust wetlands and beaches, decreasing public access along the shore. Beach nourishment using public funds may increase access to the shore if statutes are in place requiring permanent access (Chapter 7)**.**

2.2.3 Coastal Flooding and Management

Rising sea level increases the vulnerability of coastal floodplains to flooding. Higher sea level provides an elevated base for storm surges to build upon. Sea level rise also diminishes the rate at which low-lying areas drain, thereby increasing the risk of flooding from rainstorms. Increases in shore erosion also contributes to greater flood damages by removing protective dunes, beaches, and wetlands and by leaving particular properties closer to the water's edge (Chapter 8).

In addition to flood damages, many of the other effects, responses, and decisions discussed in this report are likely to occur during or in the immediate aftermath of severe storms. Beach erosion and wetlands loss often occur during storms, and the rebuilding phase after a severe storm often affords the best opportunity for adapting to sea level rise in developed areas. Currently, although the most modern floodplain maps are generally based upon the latest topographic elevations and recent changes in local mean sea level elevations, they do not take into account future sea-level rise (Chapter 8).

Although the Mid-Atlantic coastal zone management community recognizes sea-level rise as a coastal flooding hazard and states are starting to confront the issue of sea level rise, only a limited number of comprehensive analyses and resulting statewide policy revisions to reflect rising sea level have been undertaken (Chapters 8, 10).

2.3 Preparing for Sea-Level Rise

2.3.1 Decision-Making for the Coastal Zone

The prospect of accelerated sea-level rise generally justifies examining the costs and benefits of taking adaptive actions. Determining whether and what specific actions are justified is difficult, due to uncertainty in the timing and magnitude of impacts, and difficulties in quantifying projected benefits and costs (Chapter 9).

Key opportunities for preparing for sea-level rise may include land use planning to ensure that wetlands can migrate inland, siting, and design decisions such as retrofitting (*e.g.*, elevating buildings and homes), and examining whether and how changing risk due to sea-level rise is reflected in flood insurance rates (Chapter 9).

2.3.2 Institutional Barriers

Institutional inertia is a key barrier to change. Responding to sea-level rise requires careful consideration regarding whether and how particular areas will be protected with structures, elevated above the tides, relocated landward, or left alone and potentially given up to the rising sea (Chapter 11).

Today, as people become increasingly interested in more environmentally sensitive shore protection, they are dealing with institutions that have historically responded to requests for hard shoreline structures to hold the coast in a fixed location, and are just beginning to determine how to manage the development of soft shore protection measures (Chapter 11).

3. MEASURES TO IMPROVE UNDERSTANDING

An integrated scientific program of sea-level studies is recommended to reduce gaps in our knowledge and the uncertainty about the potential responses of coasts, estuaries, and wetlands to sea-level rise. This program should focus on insights from the historic and geologic past, monitor ongoing physical and environmental changes, and develop tools and datasets to support and promote sound coastal zone planning. Some measures that are identified in this report include:

Exploit and integrate coastal information from the historic and geologic past and incorporate into computer models to promote improved understanding of coastal processes.

This includes information pertaining to: Past interglacial environmental conditions, barrier island formation and landward migration since the last Ice Age, and thresholds in coastal systems that, if crossed, could lead to rapid changes to coastal and wetland systems.

Further development of a robust monitoring program for all coastal regions, leveraging the existing network of site observations, as well as the growing array of coastal observing systems.

This could be achieved by: expanding and enhancing the network of basic observations and systems, enhanced use of new technologies and nationwide collection of higher resolution data (such as LIDAR), developing homogenous time series data to monitor environmental and landscape changes over time, and assembling and updating baseline data for the coastal zone.

Studies of the past history of sea-level rise and coastal response, combined with extensive monitoring of present conditions, will enable more robust predictions of future sea-level rise impacts.

In order to provide more robust predictions, it will be necessary to develop quantitative assessment methods that identify high-priority areas (geographic or topical) needing useful predictions, and to integrate studies of past and present coastal behavior into predictive models

Develop tools, datasets, and other land management information to support and promote coastal decisions, planning, and policy making.

This includes: providing easy access to data and information resources from this study and forthcoming efforts and applying this information in an integrated framework using such tools as Geographic Information Systems (GIS). There is also a need to develop integrated assessments linking physical vulnerability with economic analyses and planning options, and to assemble and assess coastal zone planning adaptation options to facilitate their use by federal, state and local decision makers.

Context: Sea-Level Rise and Its Effects on the Coast

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The accumulation of scientific evidence over the past several decades unequivocally demonstrates that the global climate is changing, largely due to carbon dioxide emissions from human activities (IPCC, 2001; 2007). Sea-level rise is one effect of climate warming that will have profound impacts on all coastal regions of the United States and around the world. The geologic record shows that sea level and the global climate have been relatively stable over the past 10,000 years and this stability is a significant factor in enabling the development of human civilizations. The significant changes over the past 200 years in atmospheric carbon dioxide, temperature, ecosystems, and ice-sheet melting follow a six-fold increase in global population (Zalasiewicz et al., 2008). Along the ocean and estuarine coasts of most of the United States, sea level has risen over the last century and will continue to do so in the future. The effects are evident in many areas, as shores erode and move landward and formerly dry areas become submerged, more frequently flooded by high tides and storm surges. People are responding to these impacts by taking measures to protect threatened property or by relocating development inland to higher ground. The intent of this report is to assess the potential effects and risks of sea-level rise on coastal regions and provide information needed to understand the implications and options for dealing with sea-level rise.

The effects of sea-level rise are likely to intensify and become more pervasive in the coming decades as the Earth’s climate warms. Throughout geologic history, climate change has been the main factor driving the evolution of Earth and its inhabitants. Now, climate is changing rapidly, largely in response to human activity (IPCC, 2007). Many impacts of human-induced climate change are already occurring, including, melting glaciers and ice sheets; changes in extreme weather, such as heavy downpours and droughts, and an accelerated rise in sea level. These physical changes are also leading to biologic responses such as changes in the range of species, earlier spring events (such as animal migration), and a loss of habitat, such as coastal wetlands (IPCC, 2007). The rates of warming occurring now and those projected for the future may exceed the ability of many living organisms to adapt without major disruptions and extinctions. With future warming and wide spread ice sheet melting too, sea-level rise could accelerate very rapidly on decadal scales and follow non-linear patterns that would have large impacts on coastal regions.

More extreme weather events and storm activity and a world-wide rise in sea level are two of the most likely, most disruptive, and most costly effects of global warming. Often these two elements of climate change act in concert with each other to impact coastal regions. They have most effect on coastal regions where the land relief is generally low, land forms are susceptible to erosion, and human population and development are highly concentrated. This includes much of the coast around the United States, but the mid-Atlantic region (the main focus of this report) is particularly vulnerable due to high rates of relative sea-level rise and dense coastal development.

This report reviews available scientific literature and presents a scientific consensus on the likely effects of sea-level rise on the mid-Atlantic coast of the United States, the human and environmental impacts, likely responses in the context of current policies and economic trends, and possible options for changing planning and management activities so that society and the environment are better able to cope with an accelerated rise in sea level. A summary of implications on a Nation-wide scale are presented in Part V. The Preface of this report contains further information on the process for developing this report, the nature of the regional focus, and the structure of this report.

C.1 WHY IS GLOBAL SEA LEVEL RISING?

The elevation of global sea level is determined primarily by the balance between the volume of ice on land (in glaciers and ice sheets) and the volume of water in ocean basins. During the last 800,000 years, sea level has risen and fallen in response to the buildup and decline of large ice sheets as climate warmed and cooled in natural cycles of approximately 100,000 years. Figure C.1 shows a record of sea level change over the past 400,000 years.

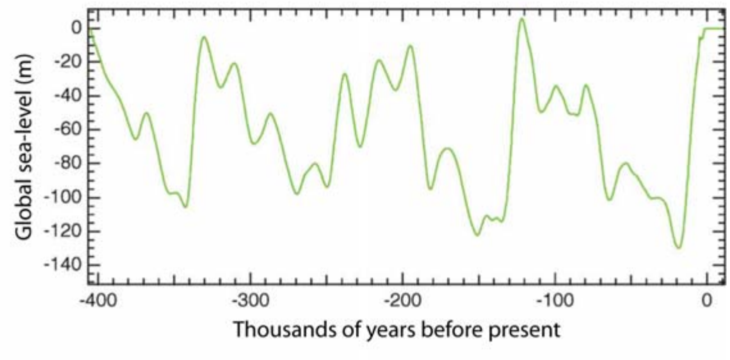

Figure C.1 Sea level change over the last 400,000 years resulting from natural glacial- interglacial cycles. Evidence suggests that sea level was about 4-6 m higher than present during the last interglacial warm period 125,000 years ago, and 120 m lower during the last Ice Age, about 21,000 years ago. Modified from Huybrechts (2002).

In the recent geologic past, sea level has varied from 120 m (400 ft) lower than present during the last Ice Age, when massive glaciers covered much of North America, northern Europe, and Asia, and the shoreline was seaward at the edge of the continental shelf, to about 4 to 6 m (20 ft) higher than present during the previous ‘interglacial’ (non-Ice Age) warm period when the coast was much further inland than present day. As ice sheets melted and climate warmed following the Ice Age, beginning approximately 21,000 years ago, sea level rose. Global sea level reached close to its current position about 3,000 years ago (Figure C.2) and has fluctuated only slightly until the past several decades when tide gauge and satellite data indicate an acceleration in sea-level rise rates. The ocean has absorbed more than 80 percent of the atmospheric warming since 1961, causing sea water to expand, contributing to this recent rise. In addition, rapid melting of land-based glaciers as well as ice sheets on Greenland and Antarctica have very likely increased sea-level rise (IPCC, 2007). The combination of stable sea level and moderate climate during the current interglacial warm period has been a major factor contributing to the growth in human development and our modern civilization (Day *et al.* 2007).

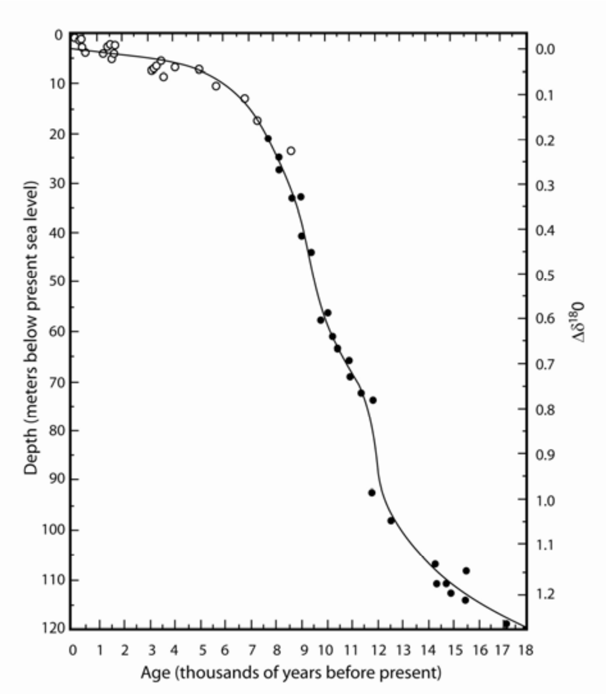

Figure C.2 Rise in global sea-level over the last 18,000 years to the present time reconstructed from oxygen isotope concentrations and radiocarbon dating of geologic samples, shown as data points. (Modified from Fairbanks,1989).

The study of climate change and associated sea-level rise is complex. The most credible and comprehensive body of scientific information on the subject, based on a consensus of approximately 2,500 of the world's scientists, has been compiled by the United Nations' Intergovernmental Panel on Climate Change (IPCC) in a series of reports issued approximately every five years. The most recent IPCC (2007) report, *Climate Change 2007: The Physical Science Basis*, contains a comprehensive review and assessment of climate change trends, expected changes over the next century, and the impacts and challenges that both humans and the natural world are likely to be confronted with during the next century. In addition, the U.S. Climate Change Science Program (CCSP) Synthesis and Assessment Products (SAPs), including this one, are providing detailed climate information for the United States. This SAP, discussing the impacts of sea-level rise on the U.S., relies heavily on IPCC (2007) findings and predictions for sea-level rise. A few key findings of the most recent IPCC reports are summarized in Box C.1

BOX C.1 SELECTED IPCC (2007) FINDINGS ON CLIMATE AND SEA-LEVEL RISE

Recent Global Climate Change:

- Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level

- Carbon dioxide is the most important human-caused greenhouse gas. The atmospheric concentration of carbon dioxide in 2005 exceeds by far the natural range over the last 650,000 years

- Most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in human-caused greenhouse gas concentrations. Discernible human influences now extend to other aspects of climate, including ocean warming, continental-average temperatures, temperature extremes and wind patterns

Recent Sea-Level Rise

- Observations since 1961 show that the average temperature of the global ocean has increased to depths of at least 3000 m and that the ocean has been absorbing more than 80% of the heat added to the climate system. Such warming causes seawater to expand, contributing to sea-level rise

- Mountain glaciers and snow cover have declined on average in both hemispheres. Widespread decreases in glaciers and ice caps have contributed to sea-level rise (ice caps do not include contributions from the Greenland and Antarctic ice sheets)

- New data show that losses from the ice sheets of Greenland and Antarctica have *very likely* contributed to sea-level rise between 1993 and 2003

- Global average sea level rose at an average rate of 1.8 [1.3 to 2.3] mm per year between 1961 and 2003. The rate was faster between 1993 and 2003: about 3.1 [2.4 to 3.8] mm per year. Whether the faster rate for 1993 to 2003 reflects decadal variability or an increase in the longer term trend is unclear. (Figure C.3)

- Global average sea level in the last interglacial period (about 125,000 years ago) was *likely* 4 to 6 m higher than during the 20th century, mainly due to the retreat of polar ice. Ice core data indicate that average polar temperatures at that time were 3°C to 5°C higher than present, because of differences in the Earth's orbit. The Greenland ice sheet and other arctic ice fields *likely* contributed no more than 4 m of the observed sea-level rise. There may also have been contributions from Antarctica ice sheet melting.

Projections of the Future:

- Continued greenhouse gas emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century that would *very likely* be larger than those observed during the 20th century.
- Based on a range of possible greenhouse gas emission scenarios for the next century, the IPCC estimates the global increase in temperature will likely be between 1.1 and 6.4ºC. Estimates of sea-level rise for the same scenarios are 0.18m to 0.59 m, excluding the contribution from accelerated ice discharges from the Greenland and Antarctica ice sheets.

- Extrapolating the recent acceleration of ice discharges from the polar ice sheets would imply an additional contribution up to 20 cm. If melting of these ice caps increases, larger values of sea-level rise cannot be excluded.

- In addition to sea-level rise, the storms that lead to coastal storm surges could become more intense. The IPCC indicate that based on a range of computer models, it is *likely* that hurricanes will become more intense, with larger peak wind speeds and more heavy precipitation associated with ongoing increases of tropical sea surface temperatures, while the tracks of 'winter' or non-tropical storms are projected to shift towards the poles along with some indications of an increase in intensity in the North Atlantic.

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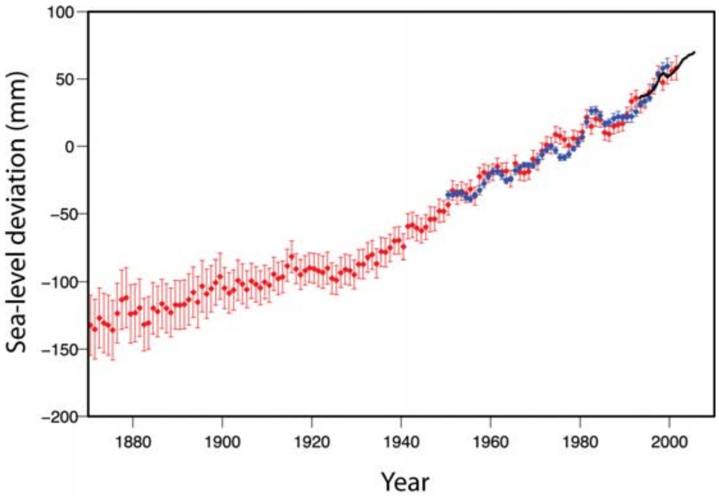

Figure C.3 Annual averages of global mean sea level from IPCC (2007). The red curve shows sea-level fields since 1870 updated from Church and White (2006); the blue curve displays tide gauge data from Holgate and Woodworth (2004), and the black curve is based on satellite altimetry from Leuliette *et al.* (2004). The red and blue curves are deviations from their averages for 1961 to 1990, and the black curve is the deviation from the average of the red curve for the period 1993 to 2001. Error bars show 90% confidence intervals. Modified from Bindoff *et al.* (2007).

Global sea-level rise – resulting from the balance between global ice volume and ocean seawater volume - is a useful measure of the general direction of change; however there are substantial local and regional variations in the rates of sea-level rise. In some locations, subsidence of the land increases the 'effective' or 'relative 'sea-level rise, whereas in other locations, local sea-level rise is less than the global average because the land is still rising (rebounding) from a time when an ice sheet, sometimes a mile thick, covered the area, depressing the Earth's crust. In a few cases, such as in the Pacific Northwest of the U.S., this can lead to a drop in local sea level. In responding to sea-level rise, it is necessary to refer to the local (relative) sea level-rise because it is this combination of global effects and local conditions that impact the coast. Thus in this report, 'sea-level rise' refers to relative sea-level rise. See box C.2 for further discussion.

Box C.2 Relative Sea Level

The term "global sea level", sometimes referred to as eustatic sea level, refers to the average level of tidal waters around the world based on long-term measurements from coastal tide gauges. The most reliable data are from gauges having records of 50 years or longer and are important observation instruments for measuring sea level change trends. Vertical movements of the land surface at the coast can also contribute significantly to sea-level change and the combination of sea level and land-level change is referred to as "relative sea level" (Douglas, 2001). These two terms used by scientists are defined as follows:

- "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 change in sea level relative to the elevation of the land, which includes both global sea-level rise and vertical movements of the land.

In this report, the term "sea-level rise" is used to mean "relative sea-level rise."

Vertical changes of the land surface result from many factors including tectonic processes, adjustment of the Earth's crust, compaction of sediments, and extraction of subsurface fluids such as oil, gas, and water. A principal contributor to this change along the Atlantic coast of North America and northern Europe is the plastic-like adjustment of the Earth's crust to changing ice loads since the Ice Age. The thick accumulation of ice on continental landmasses depressed the Earth's surface in ice-covered regions. This displaced the mantle (the layer of the planet beneath the crust) causing a "peripheral bulge" some distance from the edges of the thick continental ice cover. As a result of these crustal adjustments, relative sea level records vary greatly along the coast from glaciated regions in New England southward to North Carolina. These vertical crustal adjustments have persisted for thousands of years and will continue to persist for some time. In addition to glacial adjustments, sediment loading also contributes to regional subsidence of the land surface. Subsidence contributes to high rates of relative sea level (>100 mm/yr) in the Mississippi River delta where thick sediments have accumulated. Likewise, fluid withdrawal from coastal aquifers causes the sediments to locally compact as the water is extracted. In Louisiana, Texas, and the southern California region, oil, gas and ground-water extraction have contributed markedly to subsidence and relative sea level rise (Gornitz and Lebedeff, 1987, Emery and Aubrey, 1991, Galloway *et al.*, 1999; Morton *et al.*, 2004). Last, tectonic uplift affects the rates of relative sea level rise from Alaska to California. In places where the land surface is uplifted due to tectonic activity, rates of relative sea-level rise may be notably smaller than the rate of global sea level rise or in some cases, reversed, with localized relative sea-level fall. In locations where the land surface is subsiding, rates of relative sea-level rise may exceed the rate of global rise (*e.g.*, the central Gulf of Mexico coast and mid-Atlantic coast).

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C.2 SEA-LEVEL RISE AROUND THE UNITED STATES

Sea level has varied greatly throughout the Earth’s history due to a variety of geologic, oceanographic, and climatic processes (Douglas, 2001) and is influenced by many factors that operate globally to locally over a wide range of time scales, including days to weeks (tides, storms), seasons, decades, and millennia.

The long-term records from tide gauge stations have been the primary measurements of relative sea level trends over the last century (Douglas, 2001). Figure C.3 shows the variations in relative sea level for U.S. coastal regions. Many parts of the eastern and Gulf shores are showing higher rates of sea-level rise than for the world as a whole. For example, sea level is rising 3-4 mm/yr along the mid-Atlantic region compared to the absolute rate of 1.8 mm/yr for the world (Figures C.3, C.4)

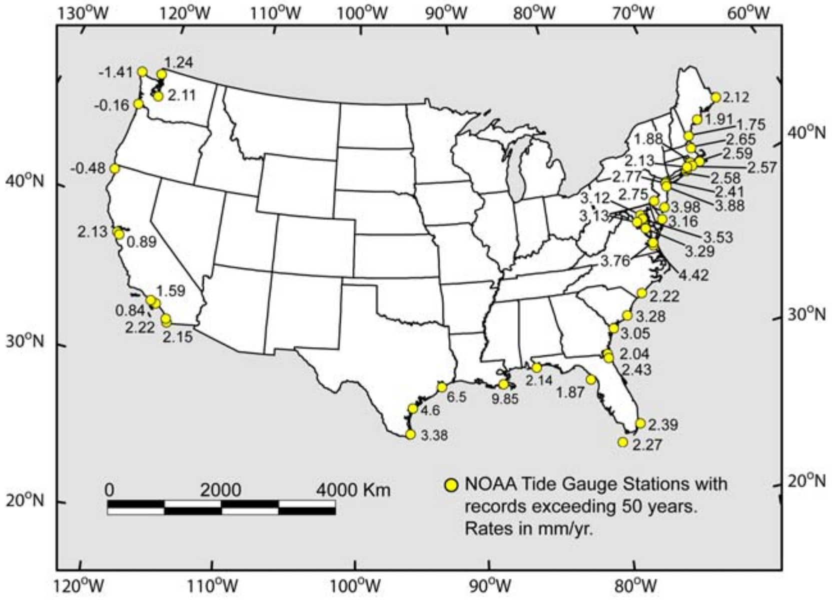


Figure C.4 Map of annual relative sea-level rise rates around the U.S. coast. The high rates for Louisiana (9.9 mm/yr) and the mid-Atlantic region (3-4 mm/yr) are due to land subsidence. Sea level is stable or dropping relative to the land in the Pacific northwest, where the land is tectonically active or rebounding upward in response to the melting of ice sheets (compiled by USGS from Zervas, 2001).

NOAA routinely produces updated estimates of relative sea level trends observed at tide stations around the country and the results show a large variation of trends from very high rates of relative sea level rise in southern Louisiana (+ 9.9 mm/yr (+/- 0.35 mm) at Grand Isle) due to land subsidence, to high rates of relative sea level fall in southeast Alaska (- 16.7 mm/yr (+/- 0.42 mm) at Skagway) due to land rebound as a result of glacier melting (Zervas, 2001). Figure C.5 is an example of the monthly average (mean) sea level record and the computed relative sea-level rise trend at Baltimore, MD. Here, the relative sea level trend is 3.12 mm/yr (+/- 0.08), which, as a result of land subsidence, is nearly 2 times the present rate of global sea-level rise.

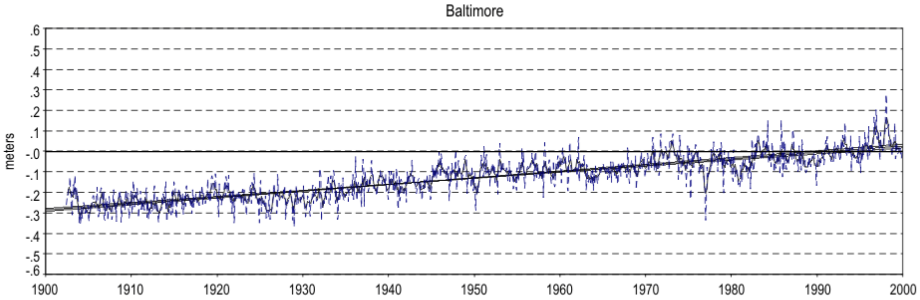


Figure C.5 Sea-level rise for Baltimore, MD from 1900 to 2000. The plot shows the monthly mean sea level with the average seasonal cycle removed (blue dashed line), a 5-month average (black solid line), and the linear trend.

C.2.1 Future Sea-Level Rise Around the United States: Our Approach

This report does not develop new estimates of future sea-level rise. Instead, we use three scenarios of relative sea-level rise along the mid-Atlantic coast:

Scenario 1: Continuation of the 20th century rate (3 mm/yr)

Scenario 2: An acceleration of 2 mm/yr over the 20th century trend (total rate of 5 mm/yr)

Scenario 3: An acceleration of 7 mm/yr over the 20th century trend (total rate of 10 mm/yr)

These three scenarios enable an assessment of the implications of a rise of 30 cm, 50 cm, and 100 cm over the next century.

These scenarios are broadly consistent with recent assessments by the IPCC (2007) and others (see Figure C.6). The IPCC's likely range for a global rise in sea level is 10-59 cm over the next century, excluding the possibility of increased ice melting on Greenland and Antarctica. IPCC also states that extrapolating the central estimate of current accelerated ice discharge would add another 10-20 cm, implying a range of 20-79 cm. The upper end of that range represents a 6 mm/yr acceleration over the 20th century global sea level trend. Scenario 3 is 1mm/yr higher, and substantially less than the high estimates suggested by more recent publications (Rahmstorf, 2007; Rahmstorf *et al.*, 2007; Hansen *et al.*, 2007). Scenario 2 is consistent with the best estimates for the various IPCC emission scenarios, which generally represented an acceleration of 2 mm/yr above the historic rate. Finally, Scenario 1 is consistent with the IPCC's low estimate of future and current sea-level rise.

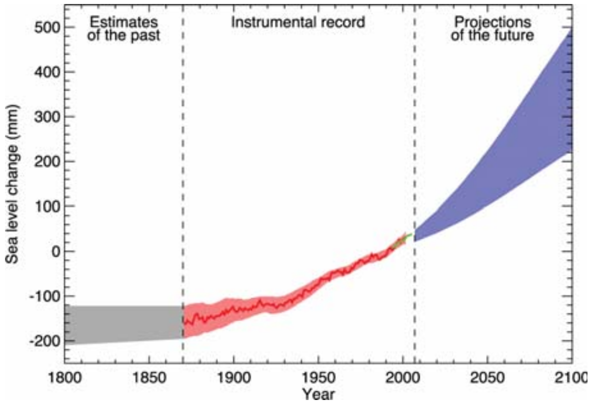


Figure C.6 Past, present, and projected global sea-level rise. Time-series of global mean sea level compiled from the past (grey shading), late 19th and 20th century observations (red and green lines and red shaded region), and future projections (blue shading) determined in the recent IPCC assessment (Bindoff *et al.*, 2007). The grey shading shows the uncertainty in the estimated long-term rate of sea-level change. The red line is a reconstruction of global mean sea level from tide gauges and the shaded area indicates the rage of variations from this line. The green line illustrates the global mean sea level record based on satellite altimeter measurements. The blue shaded region represents the range of model projections complied from the IPCC assessment (Meehl *et al.*, 2007). Figure from Bindoff *et al*.(2007).

The primary focus of this report is over the next century, but the longer term implications are also considered. Recent evaluations of changes in ice cover and glacial melting on Greenland, Antarctica, and smaller glaciers and ice caps from around the world indicate that ice loss could be more rapid than has been measured and predicted (Chen *et al*., 2006; Shepherd and Wingham, 2007; Meier *et al*., 2007). If so, this accelerated melting could significantly raise sea-level predictions to levels (~4-6 m) during the last interglacial period over the next several hundred years (Overpeck *et al*., 2006). The science behind these predictions is not yet well developed, but is worthy of study because of the very significant implications for all coastal regions.

C.3 IMPACTS OF SEA-LEVEL RISE FOR THE UNITED STATES

C.3.1 Coastal Vulnerability Around the United States

Coastal communities and habitats will be increasingly stressed by climate change impacts interacting with development and pollution (Field et al., 2007). Impacts from sea-level rise include: land loss through submergence and erosion of lands in the coastal zone; migration of coastal landforms and changes to coastal environments; increased storm-surge flooding; wetland losses; and increased salinity in estuaries and coastal groundwater aquifers. Each of these effects can have important impacts on both natural ecosystems and human developments and infrastructure. Other impacts of climate change, such as increasingly severe droughts and storm intensity—along with continued rapid coastal development—could amplify the effects of sea-level rise.

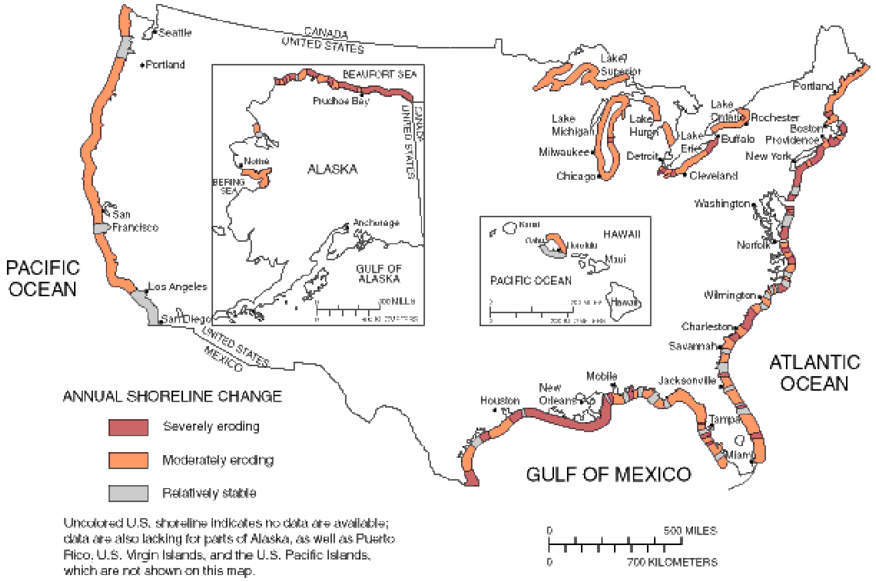
Sea-level rise in combination with other factors is already starting to have significant effects on the coastal zone of the United States. Flooding of low lying regions by storm surges and spring tides is becoming more frequent and causing more damage and disruptions. Around the Chesapeake Bay, wetlands are being submerged, fringe forests are dying and being converted to marsh, farm land and lawns are being converted to marsh; and some roads are routinely flooded at high tides (Douglas, 2001). “Ghost forests” of standing dead trees killed by salt water intrusion are becoming increasingly common in southern New Jersey, Maryland, Virginia, Louisiana, and North Carolina (Riggs and Ames, 2003). Rising sea level is gradually intruding into estuaries and threatening fresh-water aquifers (Barlow, 2003).

Rising sea level will affect to varying degrees entire coastal systems from the shoreline to the landward edge of the Coastal Plain. These physical and ecological changes that are likely to occur in the near future will also have impacts on humans and coastal development. In addition, it is uncertain how current practices in managing coastal systems for mitigating erosion and flooding are likely to affect potential future impacts. Climate change implications should be included in planning and decision making to best accommodate climate change.

Continued rapid coastal development exacerbates both the environmental and the human impact of rising sea level. During the 20th century, an expanding proportion of the U.S. population and associated urban development relocated to the land along the Atlantic, Gulf of Mexico, and Pacific coasts. Coastal populations have doubled in the past 30 years and although the coastal population is currently increasing at approximately the same rate as the national population, continued coastal development increasingly conflicts with the natural processes associated with coastal change from storms and sea-level rise. Currently the majority of the U.S. population lives in the coastal zone and movement to the coast and development continues. Fourteen of the Nation's 20 largest urban centers are located along the coast. In addition, these economic and population pressures have transformed sparsely developed coastal areas into high-density year-round urban complexes. With accelerated rise in sea level and increased intensity of storms, the conflicts between development at the coast and the natural processes are likely to increase dramatically unless new coastal management and planning is employed.

C.3.2 Shoreline Change and Coastal Erosion

The diverse landforms comprising the more than 160,000 km of U.S. coast reflect a dynamic interaction between: 1) natural factors and physical processes that act on the coast (*e.g.*, storms, waves, currents, sand sources and sinks, relative sea level), 2) human activity (*e.g.*, dredging, dams, coastal engineering), and 3) the geological character of the coast and nearshore. Spatial and temporal variations in these physical processes and the geology along the coast are responsible for the variety of coastal landforms. As a result, the majority of the U.S. coast is undergoing long-term net erosion at highly varying rates as shown in Figure C.7.



Uncolored U.S. shoreline indicates no data are available; data are also lacking for parts of Alaska, as well as Puerto Rico, U.S. Virgin Islands, and the U.S. Pacific Islands, which are not shown on this map.

Figure C.7. Coastal Erosion Rates Around the U.S. All 30 coastal states are experiencing erosion at highly variable rates due to natural processes and human activity. From USGS National Atlas 1985.

The complex interactions among these factors make it difficult to identify a precise relationship between sea-level rise and shoreline change and to reach consensus among coastal scientists on quantitative approaches that can be used to predict how shorelines will change in response to sea-level rise. The difficulty in linking sea-level rise to coastal change stems from the fact that shoreline change does not occur directly as the result of sea-level rise. Instead, coasts are in an almost continual state of change in response to many driving forces and subject to the underlying geological character and the availability of sediment to the coastal system. Consequently, while there is strong scientific consensus that climate is changing and affecting coastal regions, there are still uncertainties associated with quantitative predictions of how the coast will respond to likely changes in future sea level.

With current planning and decision making, we often assume that these systems operate in a steady-state. While the factors that influence coastal change in response to sea level rise are well known, our ability to incorporate this understanding into computer models that can be used to predict shoreline change over long time periods is limited and models are in their infancy. Part of the reason for this is the complexity of quantifying the effect of these factors on shoreline change. The models incorporate relatively few factors that influence shoreline change and rely on assumptions that do not always apply to real-world settings. In addition, these assumptions apply best to present conditions, not necessarily those that may exist in the future. The models that do incorporate many of the key factors (*e.g.*, the geological framework and sediment budget) require detailed data (*i.e.*, sediment transport rates, landform evolution feedbacks) on a local scale. To apply over larger coastal regions, the necessary baseline information for most areas is not available. The unfortunate consequence is that our current capability to make long-term reliable predictions is limited. In addition, there is some indication that coastal landforms, such as barrier islands, might have “tipping points” or “thresholds” when limits are exceeded and the landforms become unstable and disintegrate. It is possible that this is already happening to barrier islands along the Louisiana coast and may occur in the near future along the North Carolina and the Maryland-Virginia coast with increased sea-level rise and storm activity (Culver et al., 2007; Sallenger et al., 2007; Riggs and Ames, 2003).

This report reviews the knowledge of how sea-level rise can impact coastal regions and the challenges that we face in planning and coping with these impacts. A large part of this discussion is based on information from new assessments that address the potential impacts of sea level rise on the tidal inundation of low-lying lands, ocean shoreline processes, and the vertical accretion of tidal wetlands in the mid-Atlantic region. Following the terms of our charge from CCSP (2007), we do not evaluate the impacts of sea level rise on coastal flooding; nor do we evaluate the impacts of possible changes in the frequency and severity of coastal storms. That does not mean that the report ignores storm effects or assumes that the seas are always calm. Existing landforms, ecosystems, and human activities are already adapted to a certain level of storminess. Unless otherwise stated, the chapters that follow all assume that storms will continue in the future, and that many of the impacts of sea-level rise—on both people and the environment-- will only be realized after a severe storm.

C.3.3 Managing the Coastal Zone as Sea Level Rises

Coasts are dynamic junctions of water, air, and land. The interactions vary greatly over time and space. Winds and waves, tides and currents, migrating sand dunes, and river deltas combine to form ever-changing coasts, yet development continues in high risk coastal areas. If sea level rise accelerates, all of these landforms will become more dynamic. Some researchers believe that the combination of stable sea level and moderate climate during the current interglacial period has been a major factor contributing to the growth in human development and our modern civilization (Stanley and Warne, 1993; Day *et al.*, 2007). The notion that sea level is constant and that coasts are stable is deeply embedded in many institutions, and in the assumptions of most coastal residents.

Adapting to an accelerated sea-level rise would require changes in both our institutions and our mindset about natural processes.

A key question for coastal zone management is how and where to “mitigate” or adapt to these new coastal conditions. Shoreline erosion problems affecting property and development or coastal wetland habitat losses tend to dominate shore-protection policy rather than sea-level rise explicitly. Today, many property owners and government programs are already engaged in coastal engineering activities designed to protect property and beaches in developed areas by thwarting natural dynamic processes—but in undeveloped areas, the natural processes usually govern. At first, an acceleration of sea-level rise may simply increase the cost of current practices. Eventually, however, policy makers may have to evaluate whether the approach to coastal development and protection assuming a relatively stable sea level should be modified to best respond to the higher sea levels.

To facilitate these decisions, policy makers need credible information. Predicting these changes with the precision that a decision maker would prefer to have is not always possible. Yet there is little doubt that physical changes to the coastal system will also modify coastal ecosystems and the fish and wildlife. Further complicating the picture, are other related effects of climate change: storms, precipitation, run-off, drought, management practices, economic setting, and sediment supply. At present, our scientific understanding of the physical response of the coast to sea-level rise is lacking and in combination with the wide variety of human engineering activities along the shoreline, prediction of future effects with high confidence is challenging.

In most cases, we manage our coasts as if sea level were stable, the shoreline fixed in location, and storms were regular and predictable. In this report, several chapters examine how sea-level rise and increased storminess might require managers to consider longer term perspectives. We also examine some possible tactics for coastal planning and management that might be more effective as sea-level rise accelerates.

We have outlined the three sea-level rise scenarios used in this report, but in addition, we begin to consider how the impacts of sea-level rise may depend on the portion of the shoreline stabilized, as well as on the rate of sea-level rise. Unlike the future rate of sea-level rise, coastal managers collectively have some control over how much of the shore is ultimately protected, at least for the short term. Follow-on efforts will examine scenarios assuming continuation of existing policies, and will consider whether the cumulative environmental impacts might lead to a different set of choices for dealing with sea-level rise.

In summary, continued sea-level rise, at current or accelerated rates, coupled with increasing storm intensity, will result directly in increasing vulnerability for people, property, and ecosystems and indirectly have national implications. Coasts are likely to erode and retreat more than we would expect from inundation by sea-level rise alone, especially for fragile barrier islands and low-lying delta regions. We need continued improvement in the science of coastal change, more comprehensive systems of data collection and analysis, observation, monitoring, modeling, and communication of results to the public and policy makers. Planning and decision making for the coastal zone across all levels of government needs to reflect the new scientific understanding of climate change and effects of sea-level rise and increased storms. Improvements in communication are needed to ensure that science is more relevant to inform policy. We hope that this report sets the stage for coastal decision makers to fully incorporate the ramifications of climate change and its effects on sea-level rise into long-term management and planning.

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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.

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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.

End text box

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.

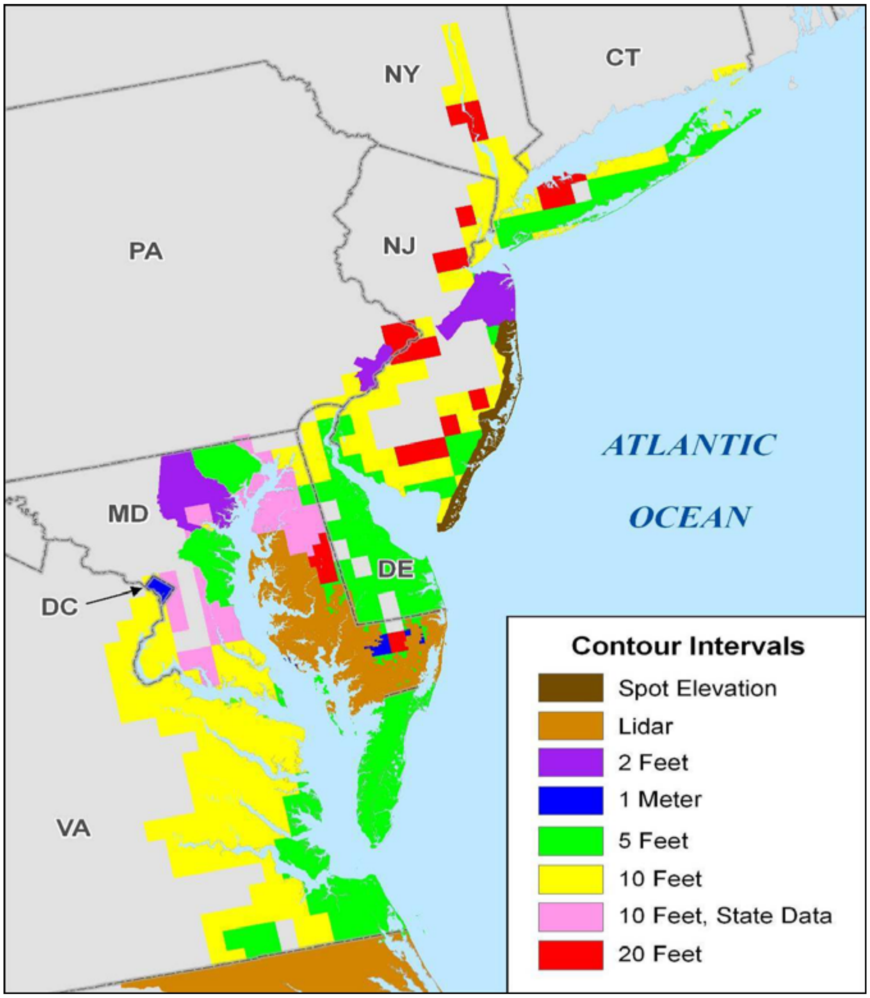


Figure 1.1 Variations in the precision of elevation data available in 2006. Rectangles generally signify USGS 1:24,000 data. The USGS maps had a 20-ft contour interval for the (pink) quads in Maryland where EPA used state data. Spot elevation data provided by the Corps of Engineers had approximately 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.

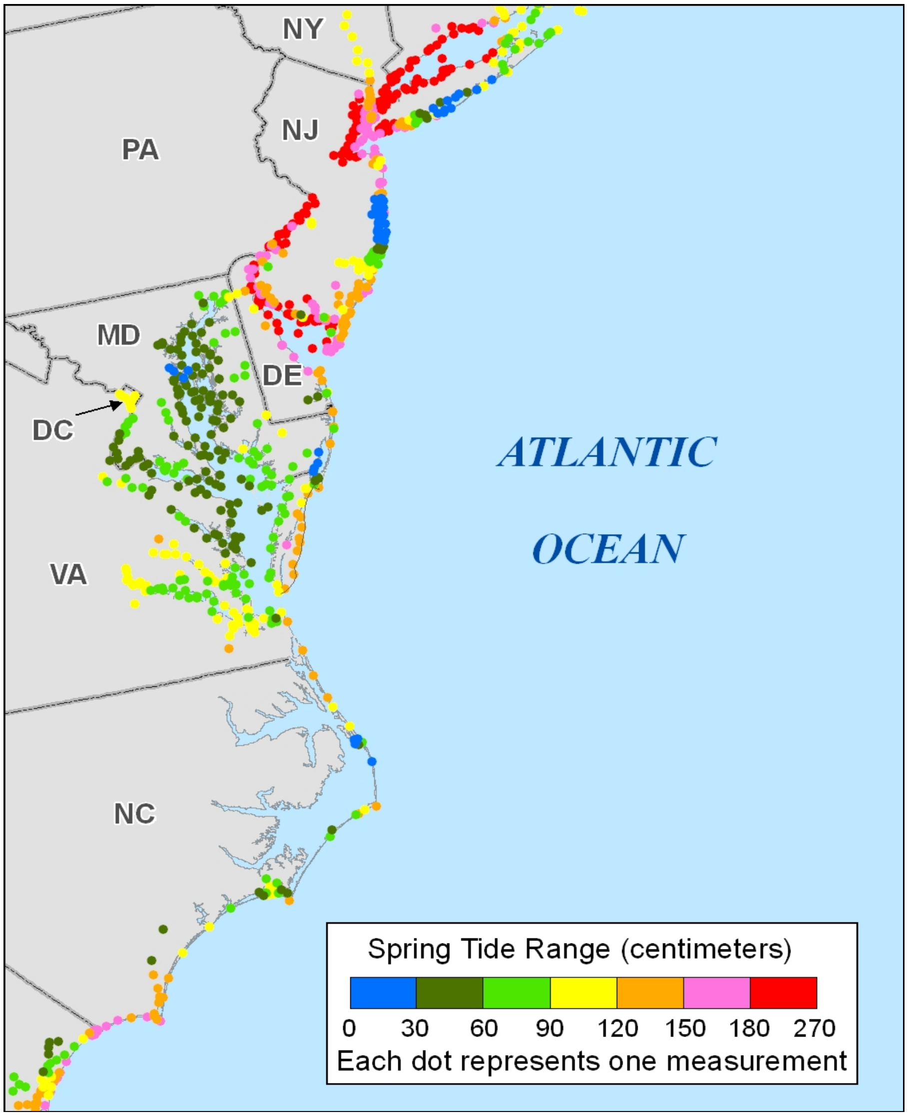
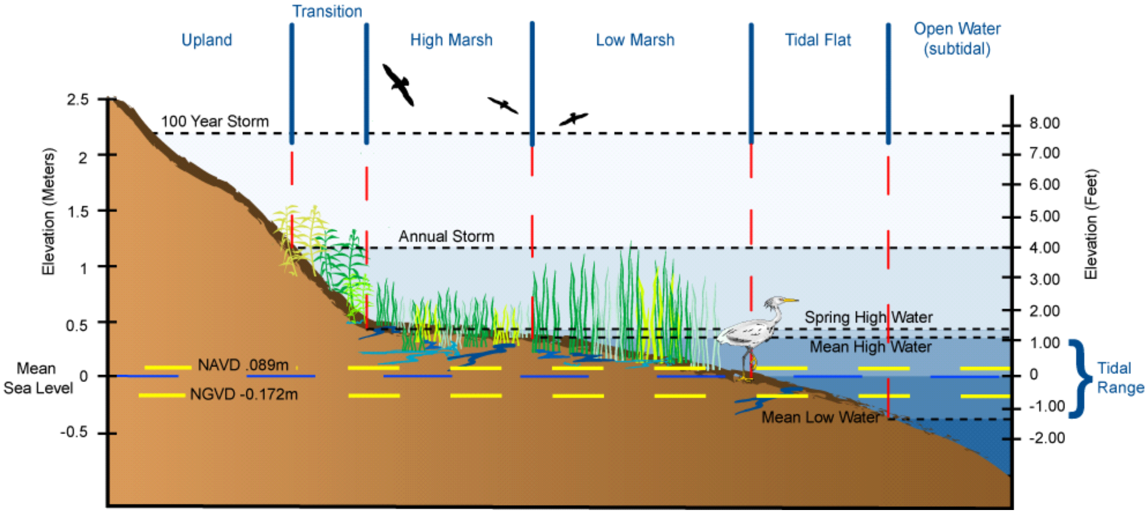


Figure 1.2 Observations of tide ranges used in this study. This figure depicts the 768 observations from NOAA's Tide Tables used to create a surface depicting spring tide range. When dots overlap, the dot with the lower tide range is shown on top. (Titus and Wang, 2008).

********* 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.

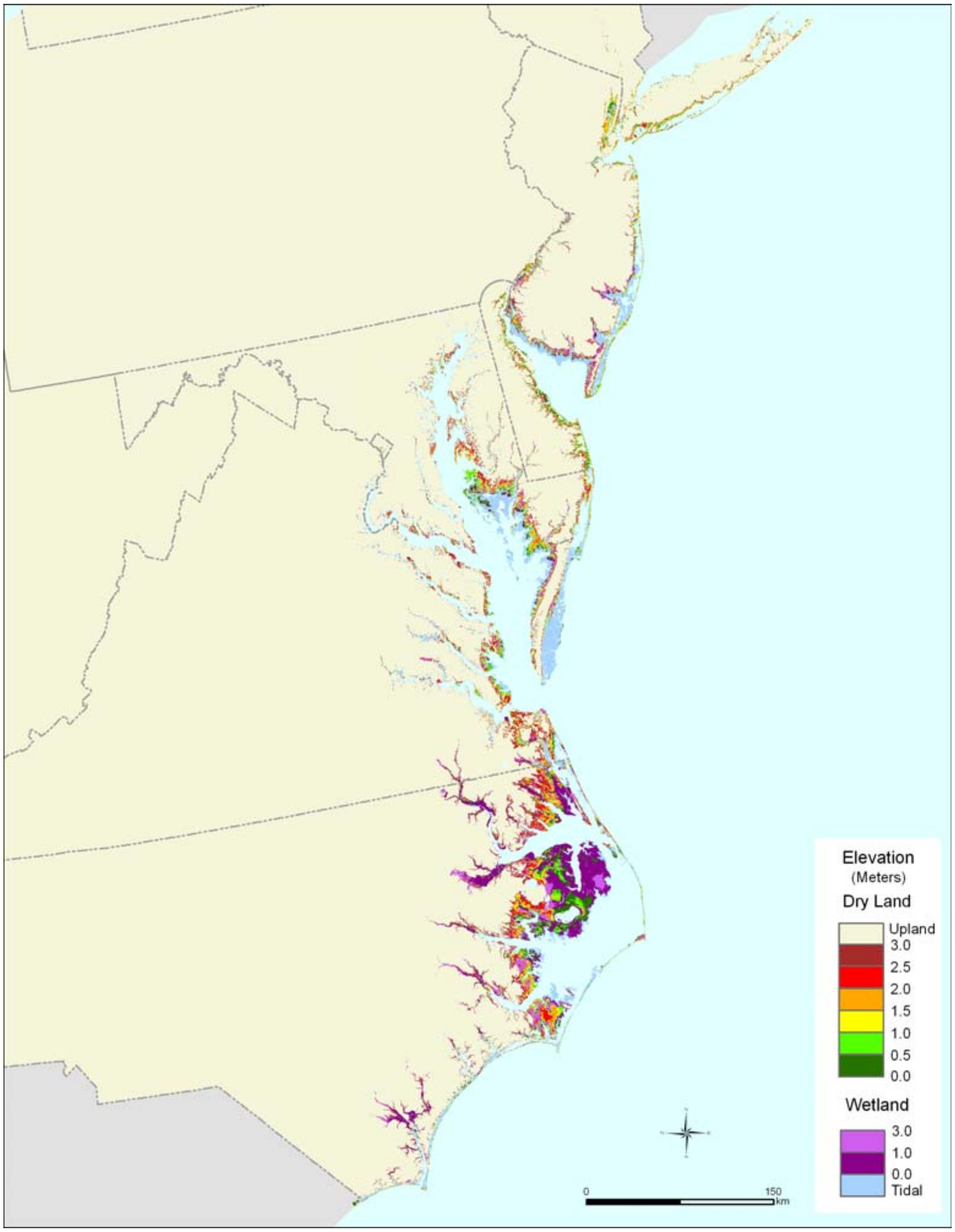

Figure 1.3 Dry land and nontidal wetlands within three meters above the tides in the mid-Atlantic region.

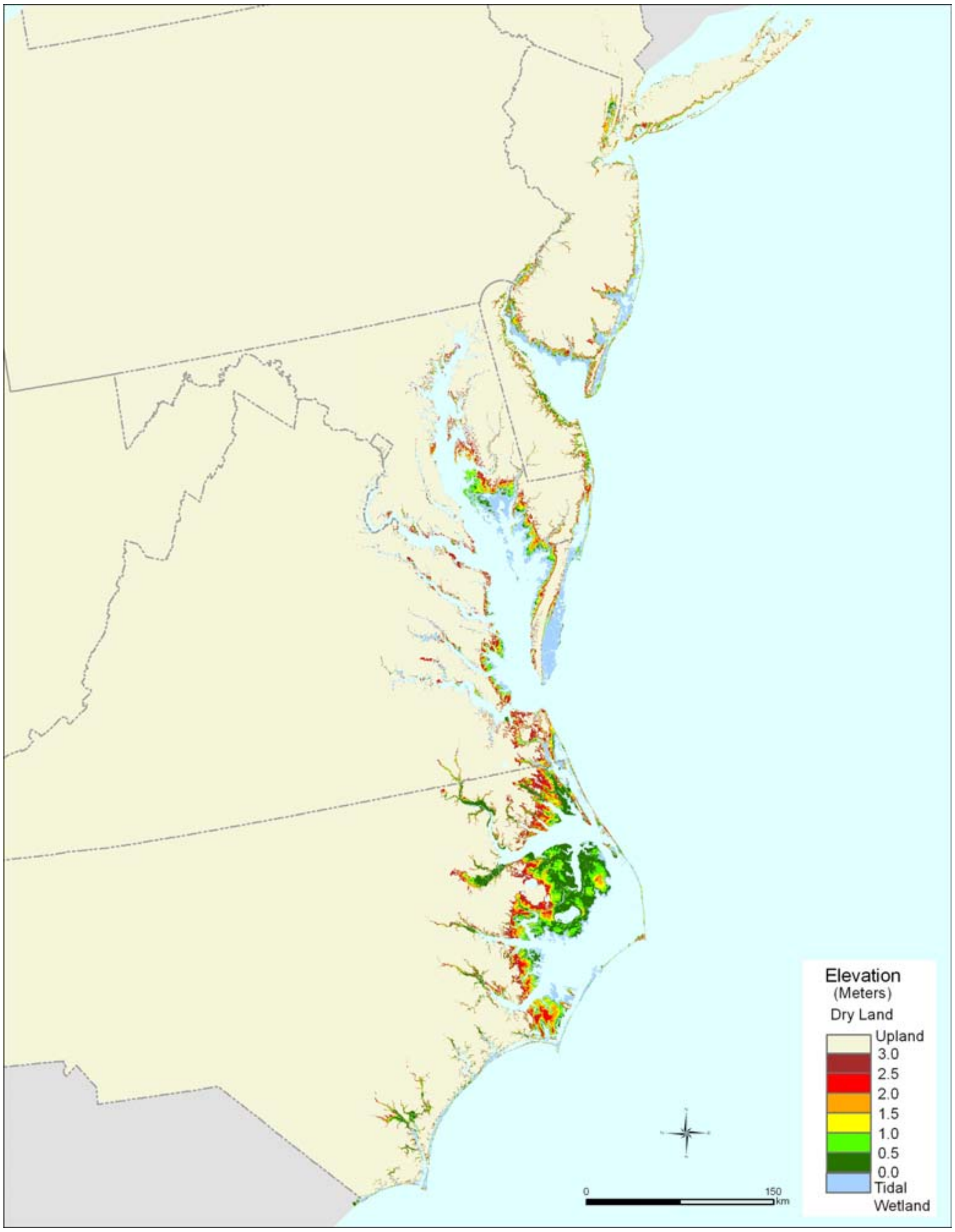

Figure 1.4 Land within six meters above the tides in the Mid-Atlantic.

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)

Sub-Region	Tidal wetlands	Meters above Spring High Water											
		0.5		1.0		2.0		3.0		4.0		5.0	
		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

	Tidal wetlands	Meters above Spring High Water											
		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.

State	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:	
	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.

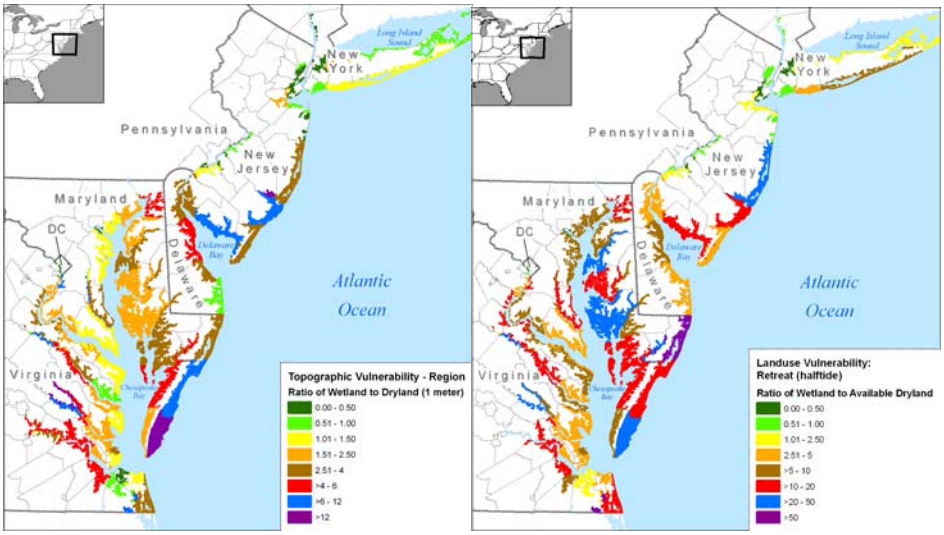

Figure 1.5 Dry land available for potential wetland migration or formation (New York to Virginia). a) County-by-county ratios of the area of tidal wetlands to the area of dry land within 1 meter above spring high water. The figure shades polygons from the tidal wetlands data set. Small polygons are exaggerated 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.

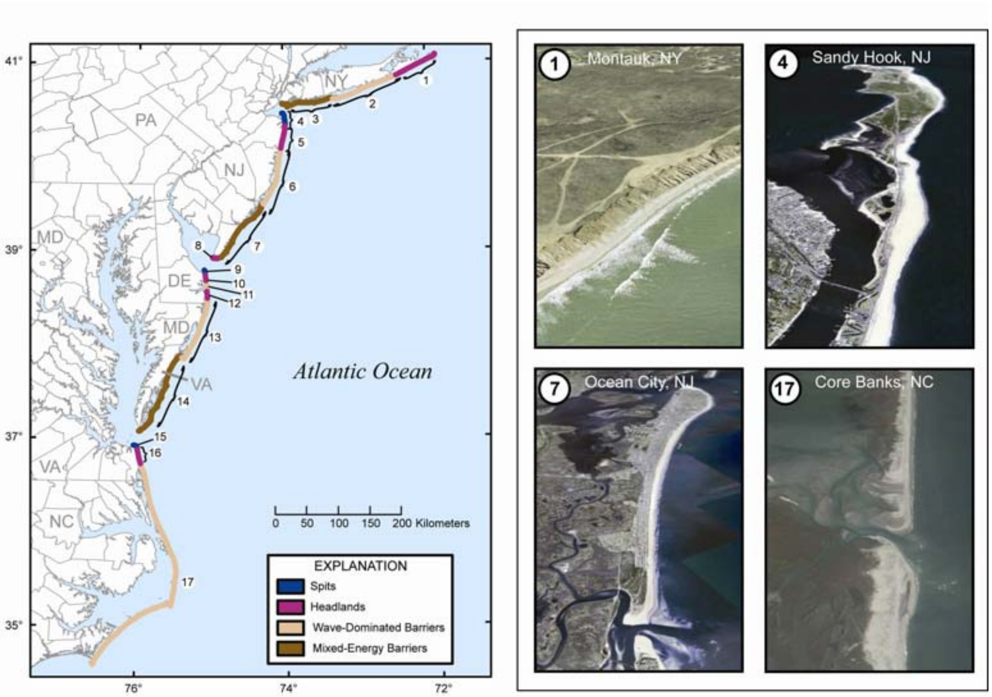


Figure 2.1 Map of the Mid-Atlantic coast of the U.S. showing the seventeen coastal compartments and their coastal geomorphic type**.** Numbers on the map specify specific coastal compartments and refer to the discussions in Sections 2.5 and 2.8. Numbers on the photographs refer to specific coastal compartments 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 back-barrier 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

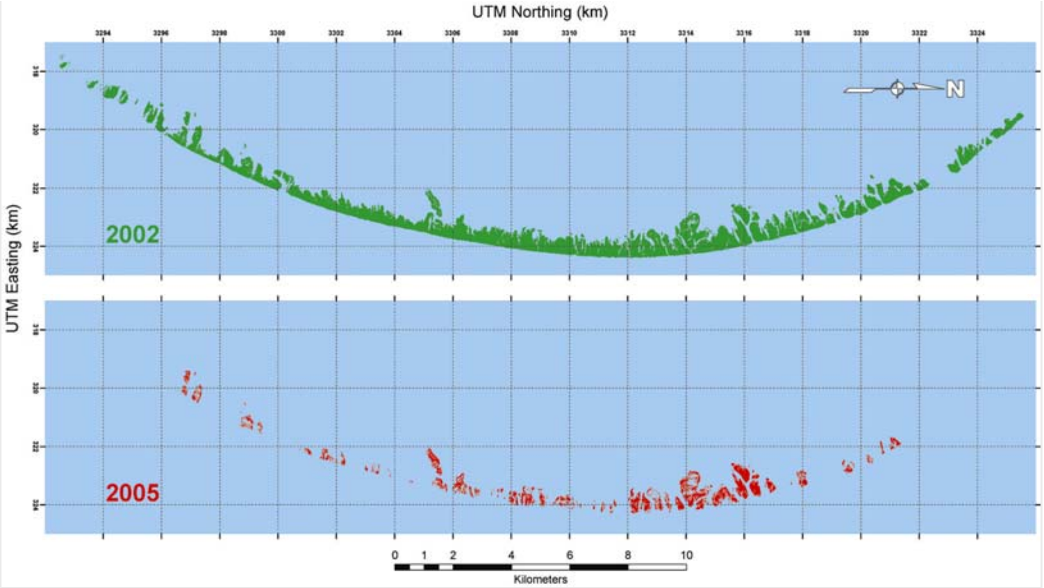
It has been generally thought by coastal scientists that barrier islands change and evolve in subtle and somewhat predictable ways over time in response to storms, changing sediment supply, and sea-level rise. Recent field observations, however, suggest that some barrier islands can reach a “threshold” 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

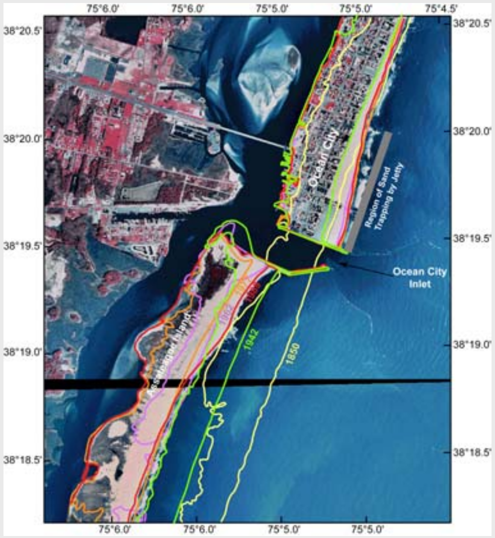
In the Chandeleur Islands, the high storm surge (~ 4 m) and waves associated with Hurricane Katrina in 2005 completely submerged the islands and eroded about 85 percent of the sand from the beaches and dunes (Sallenger *et al.*, 2007). Box Figure 2.1a (UTM Northing) shows the configuration of the barriers 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.

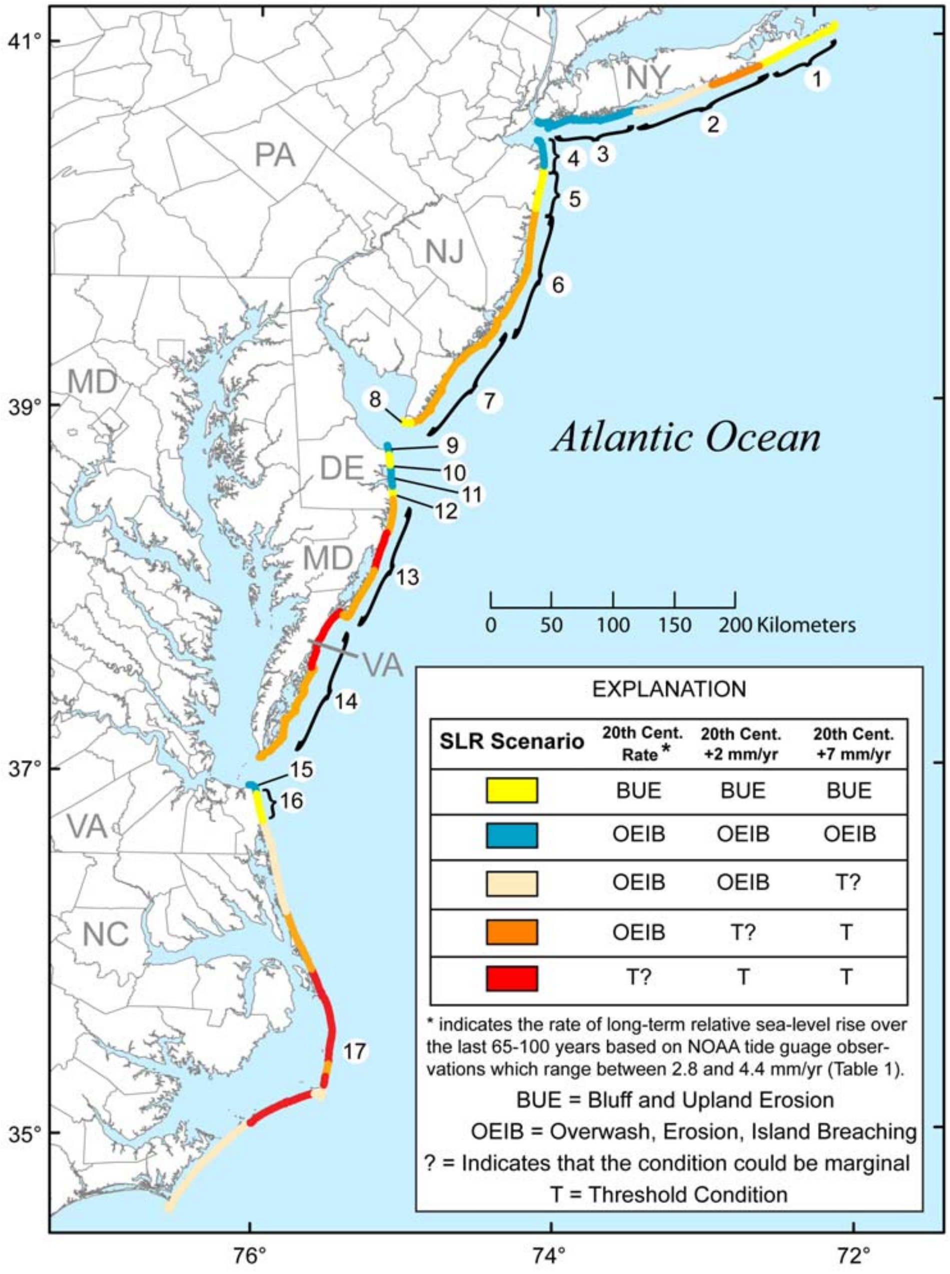


Figure 2.2 Map showing the potential sea-level rise responses for each coastal compartment. Colored portions of the coastline indicates the potential response for a given sea-level rise scenario according to the inset table. Numbers designate coastal compartments shown in Figure 2.1 (Gutierrez *et. al.*,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

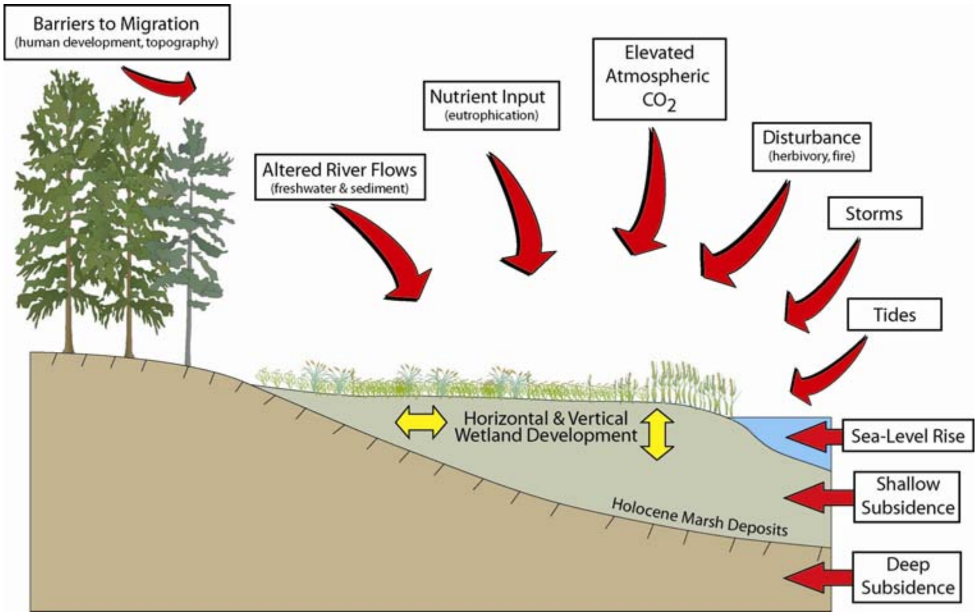


Figure 3.1 Climate and environmental drivers influencing vertical and horizontal wetland development.

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.

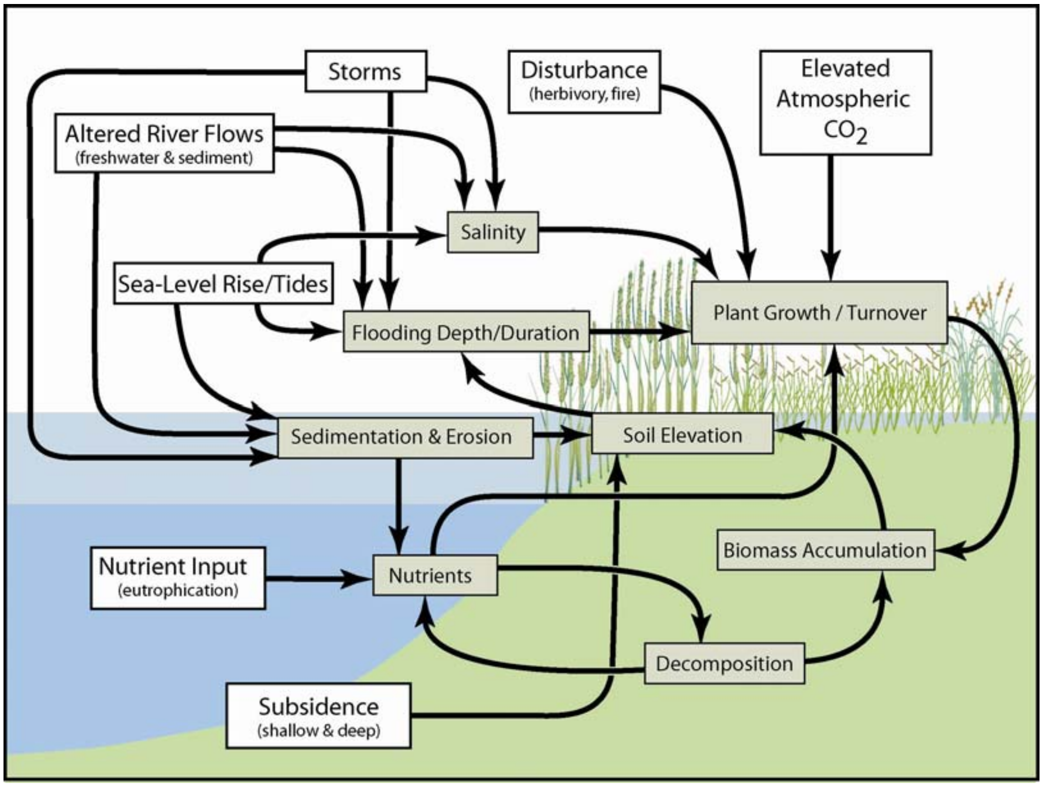


Figure 3.2 A conceptual diagram showing how environmental drivers and accretionary processes influence vertical wetland development.

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.

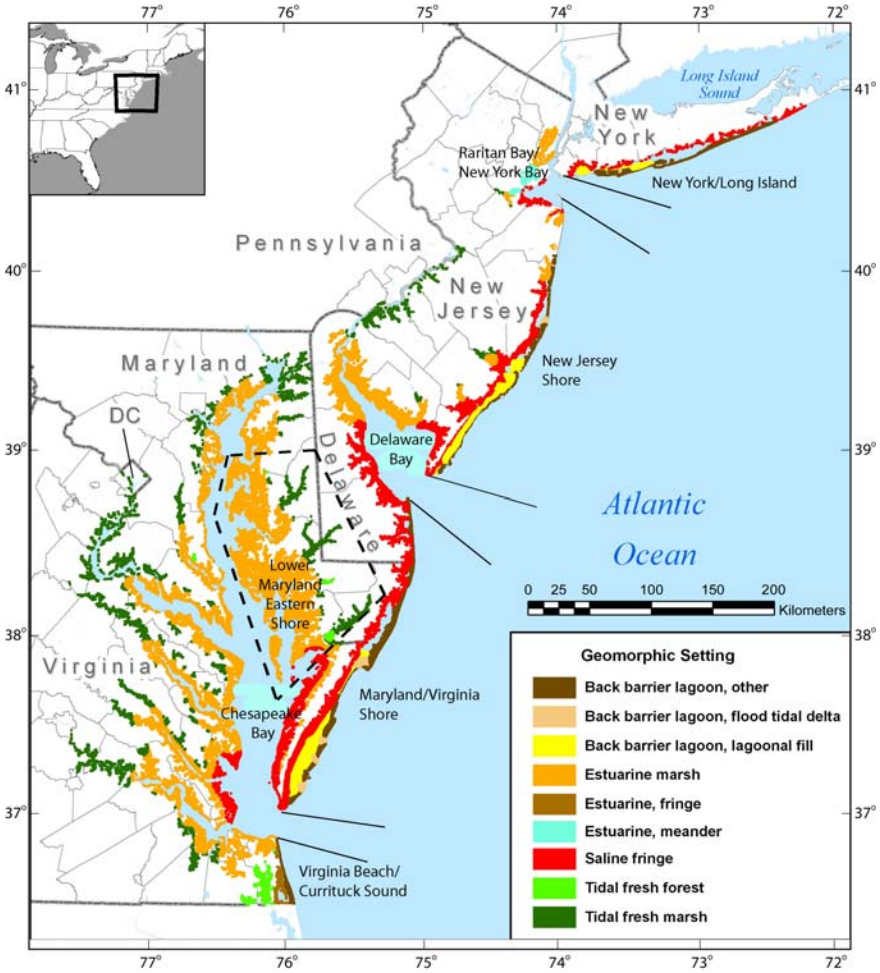
For example, the magnitude of coastal storms will increase as sea-surface temperatures increase (Webster *et al.*, 2005), likely resulting in an increase in storm sedimentation and oceanic sediment inputs. And the importance of peat accumulation is expected to increase in response to sea-level rise, 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.

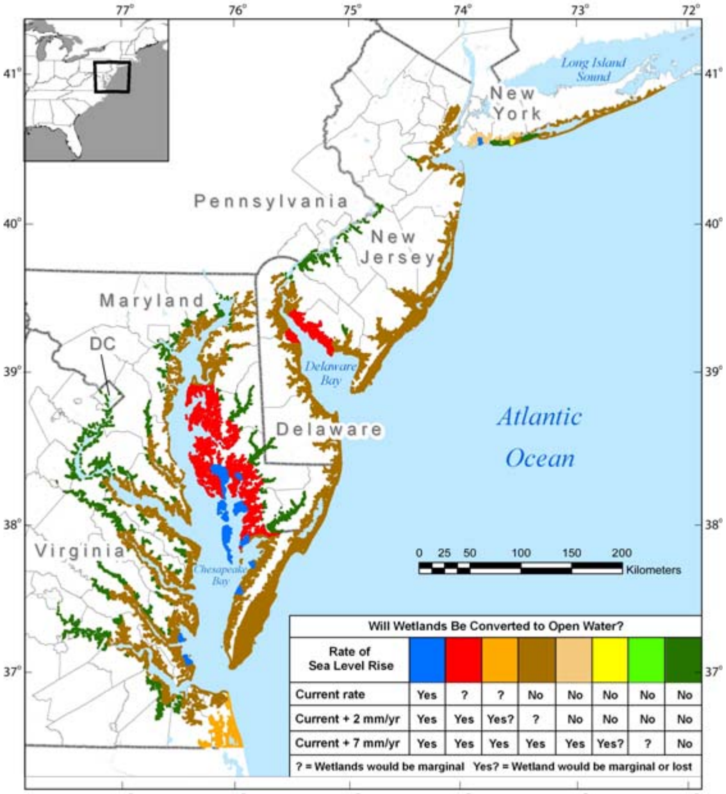


Figure 3.3 Wetland survival in response to three sea-level rise scenarios (data source: Reed *et al.*, 2007; map source: Titus *et al.*, 2008).

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).

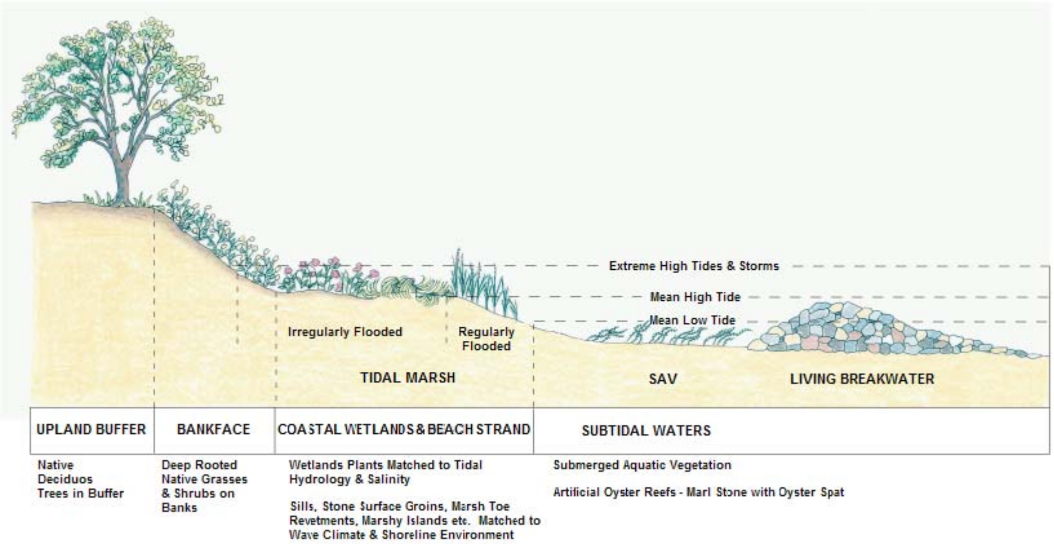
Shoreline construction and armoring will impede shoreward movement of SAV beds (Short and Neckles, 1999). First, hard structures tend to affect the immediate geomorphology as well as any adjacent seagrass habitats. Particularly during storm events, wave reflection off of revetments can increase water 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.

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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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Part II Overview: Societal Impacts and Implications

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The first set of chapters examined some of the physical and environmental impacts of sea-level rise on the Mid-Atlantic, with a focus on the natural environment. Part I closed by looking at the species that depend on the wetlands and beaches potentially threatened by rising sea level.

This part of the report examines the implications of sea-level rise for the built environment. Although the direct effects of sea-level rise would be similar to those on the natural environment, people are part of the built environment, and people will want to respond to changes as they emerge, especially if important assets are threatened. The choices that people make could be influenced by the physical setting, the properties of the built environment, human aspirations, and the constraints of laws and economics.

The following chapters examine the impacts on four human activities: shore protection/retreat and habitation, public access, and flood hazard mitigation. This assessment does not predict the choices that people *will* make; instead it examines some of the available options and assesses actions that federal and state governments and coastal communities can take in response to sea-level rise.

II.1 THE CONNECTION BETWEEN THE PART II CHAPTERS

As rising sea level threatens coastal lands, the most fundamental choice that people face is whether to attempt to hold back the sea or allow nature to takes its course. Both choices have important costs and uncertainties. “Shore protection” or preservation of the status quo allows homes and businesses to remain in their current locations, but often damages coastal habitat and requires substantial expenditure. “Retreat” can avoid the costs and environmental impacts of shore protection, but often at the expense of lost land and—in the case of developed areas—the loss of homes and possibly entire communities. In nature reserves and major cities, the preferred option may be obvious. But because both choices have some unwelcome consequences, in many areas it may be very difficult to decide whether to protect or retreat. Until this choice is made, however, preparing for long-term sea-level rise in a particular location may be impossible.

Chapter 5 begins a dialogue in examining issues related to shores that may be protected and which are likely to retreat. These efforts are not meant to be a prediction of what will occur (that is not yet possible), but recognize that assessing current policies and trends is a starting point. Most areas lack a plan that specifically addresses whether the shore will be protected or retreat. Even in those areas where a state plans to hold the line or a park plans to allow the shore to retreat, the plan is based on existing conditions. Current plans consider the costs or environmental consequences of sustaining shore protection for the next century and beyond. Future examination of these issues has two motivations:

- investigate whether existing land use trends pose a risk to the landward migration of tidal wetlands necessary to sustain those ecosystems as sea level rises; and

- motivate dialogues within communities about which shores should be protected and which should retreat.

One of the most important decisions that people make related to sea-level rise is the decision to live or build in a low-lying area. Chapter 6 quantifies the population and number of households within the land potentially inundated by rising sea level. The results are based on Census data for the year 2000, and thus are not estimates the number of people or value of structures that *will* be affected, but rather estimate the number of people who have a stake *today* in the possible future consequences of rising sea level. The calculations in this chapter build quantitatively on the elevation results from Chapter 1 and existing shore protection measures (*e.g.*, coastal armoring). As one would expect, most of the people and investments are in the areas where shore armoring has occurred. Chapter 6 also summarizes a study sponsored by the U.S Department of Transportation on the potential impacts of global sea-level rise on the transportation infrastructure.

Chapter 7 looks at the implications of sea-level rise for public access to the shore. The assessment concludes that only impacts examined in the literature are the impacts of responses taken to armor the shore, or to address sea-level rise.. One class of shore “protection” approaches (shoreline armoring) tends to decrease public access *along* the shore; while another method of shore “protection” (beach nourishment) sometimes increases public access.

Lastly, Chapter 8 examines the implications of rising sea level for flood hazard mitigation, with a particular focus on the implications for the Federal Emergency Management Agency (FEMA) and other coastal floodplain managers. Rising sea level increases the vulnerability of coastal areas to flooding because higher sea level increases the frequency of floods by providing a higher base for flooding to build upon. Erosion of the shoreline could also make flooding more likely because there is less protection against storm forces or the incursion of high tides, waves, or storm surge. Higher sea level also raises groundwater levels, increasing runoff and thereby increasing flooding from rainstorms.

Chapter 8 opens with results of studies on the relationship of coastal storm tide elevations and sea-level rise in the Mid-Atlantic. It then provides background on government agency floodplain management and on state activities related to flooding and sea-level rise under the Coastal Zone Management Act. Federal agencies, such as FEMA, are beginning to specifically plan for future climate change in their strategic planning. Some coastal sates, such as Maryland, have conducted state-wide assessments and studies of the impacts of sea-level rise and have taken steps to integrate this knowledge with local policy decisions.

The four chapters in Part II incorporate the underlying sea-level rise scenarios of this report differently, because of the differences in the underlying analytical approaches. The Census data analyses in Chapter 6 evaluated population and property in 50-cm elevation increments from 50 to 300 cm above spring high water. Chapters 7 and 8 both provide qualitative analyses that are not especially sensitive to the rate of sea-level rise. Both chapters assess various scenarios with rates of sea-level rise that are higher than the 20th century trend.

Chapter 5. Shore Protection and Retreat, Land Use and Wetland Migration: Adapting to Sea-Level Rise

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5.1 BACKGROUND

As discussed in previous chapters, many types of shoreline will become increasingly vulnerable as sea level continues to rise. Decisions about how to moderate or adapt to the impacts of sea-level rise will be different for different land uses and will rely not just on a variety of physical and geological considerations, but will also have to consider the value of land (monetary, resource-value, and perceived value), public opinion, public safety and risk assessments, ecosystem survival, legacy policy, as well as multiple other factors.

In the mid-Atlantic region, the land along the ocean coast that is not part of a park or conservation area is almost entirely developed. There is increasing pressure to develop land along tidal creeks, rivers, and bays—and barrier islands are in a continual state of redevelopment in which seasonal cottages are replace with larger homes and high-rises. Coastal development generally does not consider the need for future adaptation to sea-level rise. For example, a local planning decision to allow a housing subdivision near the shore may not explicitly consider the potential cost of taking measures to prevent that land from being inundated by the sea in several decades, the potential risk to ecosystems associated with those measures, or other options such as the possibility of allowing the land to be gradually submerged by rising water.

EPA has undertaken studies assessing the likelihood of different adaptation options (Nicholls *et al.*, 2007, p. 343). Although the methods and output of those studies have been peer-reviewed and presented at several conferences (*e.g.* Clark, 2001; Nuckhols, 2001; Coyman, 2003; Kean, 2003), the results are only available in books (Titus, 2005) and conference proceedings (Hudgens and Neumann, 2000; Titus, 2004). Since these studies have yet to appear in the peer-reviewed scientific literature, this synthesis report makes limited use of their results, and for that reason this chapter gives only a brief overview of adaptation options. For example, shoreline armoring or elevating land, through actions such as beach nourishment, are part of a suite of options to adapt to sea-level rise. Such options are commonly referred to as “shore protection”, although the term *protection* usually implies stabilizing the existing shoreline to protect real estate, buildings, and infrastructure. However, one of the consequences of shore protection can be to alter the normal shoreline processes that act to sustain wetlands and the ecosystems that depend on them. Although these methods may adequately protect existing land use, they may not account for the ability of ecosystems to adapt to sea-level rise.

Many of the options for responding to sea-level rise have both advantages and disadvantages; it is not the role of this assessment to advocate one option over another in different regions for different land uses, nor to predict what coastal managers might do.

Table 5-1 provides a summary of various “protection and “retreat” mechanisms, purposes, and environmental effects.

Lastly, this chapter synthesizes information on areas where wetlands may be able to accommodate sea-level rise by migrating, and areas where that cannot currently occur because of the limits of land use. In chapter 9, there is further discussion on implications for decision-making along the coast.

5.2 SHORE PROTECTION AND RETREAT

Most of the chapters in this report examine measures or impacts related to shore protection and retreat. This section provides an overview of the key concepts and common measures for holding back the sea or facilitating a landward migration.

5.2.1 Shore Protection

The term “shore protection” generally refers to a class of activities that prevent flooding, erosion, or inundation of land and structures. The term is somewhat of a misnomer because shore-protection measures protect land and structures immediately inland of the shore, rather than the shore itself. Shore protection is often the antithesis of shoreline preservation. In common use, “shore protection” often includes measures that prevent wetlands from eroding. However, this report uses the term more narrowly, to refer to activities that prevent dry land from being flooded or converting to wetland or open water.

Shore protection measures can be broadly divided into two categories: shoreline armoring, and elevating land surfaces. Shoreline armoring replaces the natural shoreline with an artificial shore, but areas inland of the shore are generally untouched. Elevating land surfaces, by contrast, can maintain the natural character of the shore, but requires rebuilding all the vulnerable land. Some methods are hybrids of both approaches. The *Coastal Engineering Manual* (U.S. Army Corps of Engineers, 2002) provides a comprehensive discussion, however brief descriptions are provided below for context in this report.

5.2.1.1 Shoreline Armoring

Shoreline armoring involves the use of structures to keep the shoreline in a fixed position or to prevent flooding when water levels are higher than the land.

Keeping the shoreline in a fixed position

Sea walls are impermeable barriers designed to withstand the strongest storm waves, and to prevent overtopping during a storm. During calm periods, they may either be landward of a beach, or their seaward side may be in the water. During storms, they often reflect the wave energy downward, causing additional beach erosion. Sea walls are often used along important transportation routes such as highways or railroads (Figure 5.1a).

Figure 5.1 a). Galveston Seawall, and b) Bulkhead between marsh and shorefront home. *Monmouth County, New Jersey.*

Bulkheads are vertical walls designed to prevent the land from slumping toward the beach. They must resist waves and currents to accomplish their design intent, but they are not designed to be sea walls that can withstand punishing storm conditions. They are usually found on lower energy estuarine shorelines, particularly in marinas, harbors, and places where boats are docked, and many residential areas where homeowners prefer a tidy shoreline. Like seawalls, they may either be landward of a beach or their seaward may be in the water. In the latter case, they reflect wave energy both downward and back into the estuary. Bulkheads hold soils in place, but they do not normally extend high enough to keep out foreseeable floods. (Figure 5.1b).

Retaining structures include several types of structures that serve as a compromise between a sea walls and a bulkhead. They are often placed at the rear of beaches, and are often intended to be unseen. Sometimes they are sheet piles that are driven into the sand, sometimes they are long, cylindrical, sand-filled “geo-tubes” (Figure 5.2 a and b). Often they are concealed as the buried core of an artificial sand dune. Like seawalls, they are intended to be a final line of defense against waves; but they can not survive continuous wave attack for long.

Figure 5.2. Geotube before (a) and after (b) being buried by beach sand. *Bolivar Peninsula, Texas.*

Revetments are walls whose sea side follows the slope of the beach. Like the beach they replace, they are more effective at absorbing the energy of storm waves than bulkheads and seawalls. As a result, they are less likely to fail during a storm, and reflect less energy. Some revetments are smooth walls, while others have a very rough appearance. (Figure 5.3 a and b).

Figure 5.3 Two types of stone revetments a) *Near Surfside Texas and b) Jamestown, Virginia.*

Protecting Against Flooding or Permanent Inundation

Dikes are high, impermeable earthen walls designed to keep the area behind them dry. They can be set back from the shoreline if the area to be protected is a distance inland. To be effective, they require a drainage system compatible with their objective. Land below mean low water requires a pumping system to remove rainwater and any water that seeps through the dike. Land whose elevation is within the range of the tides, can be drained with tide gates except during storms (Figure 5.4a).

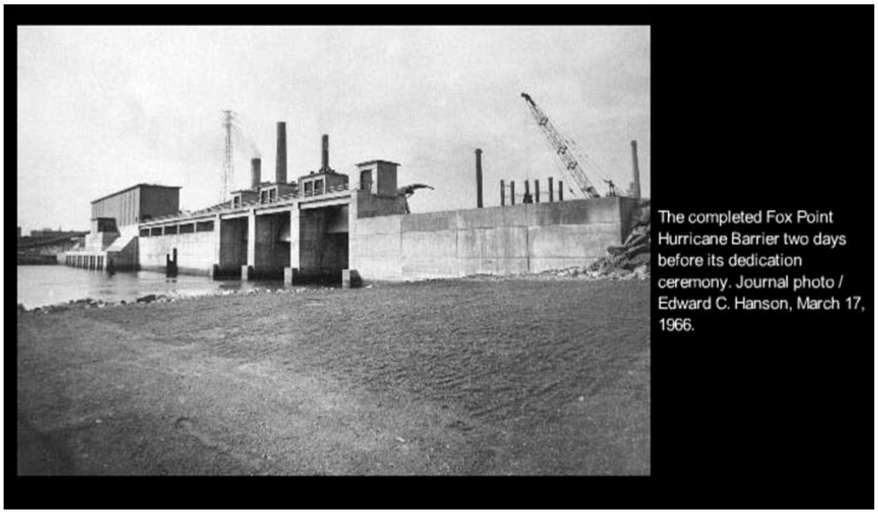
Dunes are accumulations of windblown sand, but they often function as a temporary barrier against wave runup and overwash (Figure 5.4b).

Figure 5.4 a) A Dike bin Miami-Dade County, Florida, and b) a newly–created dune in Surf City, New Jersey

Tide gates are barriers across small creeks or drainage ditches. By opening during low tides and closing during high tides, they enable a low-lying area above mean low water to drain without the use of pumps. (Figure 5.5).

Figure 5.5: The tide gate at the mouth of Army Creek on the Delaware side of the river. The tide gate drains flood and rain water out of the creek to prevent flooding. The five circular mechanisms on the gate open and close to control water flow (courtesy NOAA Photo Library).

Storm surge barriers operate on the same principal as tide gates, except on a much larger scale and only during storms. They close a river mouth or inlet to prevent storm surges or high wave energy from entering an estuary. The rest of the time they are open. These barriers must be strong enough to hold back water flowing from the river and also the storm waves and surge on their seaward side. People make management decisions about when to close the gates or raise the submerged barriers (Figure 5.6).



The completed Fox Point Hurricane Barrier two days before its dedication ceremony. Journal photo / Edward C. Hanson, March 17, 1966.

Figure 5.6. The storm surge barrier/gate for Providence, RI.

5.2.1.2 Elevating Land Surfaces

Beachfill, also known as *Beach Nourishment* and *Sand Replenishment* involves the purposeful addition of sand to a beach. Sand from offshore or an inland source is dumped onto a shoreline, often in tremendous quantities, to provide a buffer against wave action and flooding (National Ocean Service, 2000b). Placing sand onto an eroding beach can reverse erosion for a time; but unless radically new conditions are established, erosion generally resumes, necessitating periodic re-nourishment.

Dunes are shore parallel features that when designed and constructed by people are intended to intercept wind-transported sand and keep it from being blown inland and off the beach. The effectiveness of dunes is often increased by planting dune grass or installing sand fencing.

Elevating land and structures is the equivalent of a beachfill operation in the area landward of the beach. After a severe hurricane in 1900, most of Galveston was elevated by more than one meter. Unlike beach nourishment, this form of shore protection can be implemented by individual property owners. Several federal and state programs exist for elevating homes, which has become commonplace in some coastal areas, especially after a severe flood.

Dredge and fill is rarely used today because of the resulting loss of tidal wetlands, but the legacy remains with a large number of very low-lying communities along estuaries. It involved converting tidal wetlands to a combination of dry land suitable for home construction and navigable waterways to provide boat access to the new homes. Channels were dredged through the marsh, and the dredge material was used to elevation the remaining marsh to create dry land.

5.2.1.3 Hybrid Approaches to Shore Protection

A number of hybrid approaches are also available. Generally the goal of these approaches is to retain some of the storm-resistance of a hard structure, while also maintaining some of the features of natural shorelines. Some of the traditional approaches include breakwaters and groins, hard structures that reduce the extent to which waves and current can cause erosion, without replacing the beach with a structure. Recently, several state agencies, scientists, and others have become interested in measures that reduce erosion along estuarine shores, while preserving more habitat than bulkheads and revetments. Those measures are commonly known as *living shorelines*, and are extensively discussed in a recent assessment by the National Research Council (2006).

5.3.2 Retreat

The alternative to shore “protection” is commonly known as “retreat”. A retreat can either occur as an unplanned response in the aftermath of a severe storm, or as a planned response to avoid the adverse effects of shore protection. Some studies have concluded that a retreat requires a longer lead time than shore protection (*e.g.*, Titus, 1998; IPCC CZMS, 1992; O’Callahan, 1992).

Measures for shore protection generally involve civil engineering activities to control the forces of nature, along with some level of environmental engineering to avoid adverse impacts. Some measures that facilitate retreat involve engineering, but institutional and planning measures are also part of the mix.

Relocating Structures is possibly the most important engineering activity involved in a retreat. Perhaps the most ambitious relocation in the Mid Atlantic has been the landward relocation of the Cape Hatteras Lighthouse (Figure 5.7a) More commonplace is the routine structural moving activity involved in moving a house back several tens of meters within a given shorefront lot, as well as the removal of structures threatened by shore erosion (Figure 5.7b).

Figure 5.7 a) Cape Hatteras Lighthouse after Relocation. The original location is in the foreground, and b) a home threatened by shore erosion. The geotextile sand bags are protecting the septic system. *Kitty Hawk, North Carolina*.

Erosion-based setbacks are a common planning tool to facilitate a retreat. North Carolina prohibits new structures based on the current erosion rate times 30 years (in the case of easily moveable homes) or 60 years (in the case of large immoveable structures). Maine's setback considers accelerated sea-level rise over the next century.

Buyout programs provide funding to compensate landowners for losses due to coastal hazards, by purchasing vulnerable property. In effect, these programs transfer some of the risk of sea-level rise from the property owner to the public, which pays the cost.

Rolling easements are regulatory mechanisms or interests in land that prohibit shore protection and instead allow wetlands and beaches to potentially migrate inland as sea level rises. In effect, rolling easements transfer some of the risk of sea-level rise from the environment or the public, to the property owner.

Purchase programs involve the anticipatory purchase of undeveloped lands vulnerable to sea-level rise before the can become developed.

Density restrictions allow some development but limit densities near the shore. Although the original motivation may be to reduce pollution runoff into estuaries, they also facilitate retreat by limiting development.

Table 5.1 is a summary of the purposes for various methods for shore "protection", shore "retreat' and their environmental effects.

Table 5.1 Potential Environmental Effects of Responses to Sea-Level Rise

Method	**Purpose**	**Environmental effects**
Using structures to interfere with waves and currents		
Breakwater	Reduce erosion	May attract marine life; downdrift erosion
Groin	Reduce erosion	May attract marine life; downdrift erosion
Using structures to define a shoreline		
Sea wall	Reduce erosion, protect against flood and wave overtopping	Elimination of beach; scour and deepening in front of wall; erosion exacerbated at terminus
Bulkhead	Reduce erosion, protect new land fill	Prevents inland migration of wetlands and beaches. Wave reflection erodes bay bottom, preventing SAV. Prevents amphibian movement from water to land.
Revetment	Reduce erosion, protect land from storm waves, protect new land fill	Prevents inland migration of wetlands and beaches. May create some habitat for oysters and refuge for some species.
Retaining structure	Reduce storm-based erosion	Separates habitats if exposed; otherwise little effect
Using structures to protect against floods and/ or permanent inundation		

Dikes	Prevents flooding and permanent inundation (when combined with a drainage system).	Prevents wetlands from migrating inland. Thwarts ecological benefits of floods (*e.g.*, annual sedimentation, higher water tables, habitat during migrations, productivity transfers)
Tide gates	Reduces tidal range by draining water at low tide and closing at high tide.	Reduced tidal range reduces intertidal habitat. May convert saline habitat to freshwater habitat.
Storm surge barriers	Eliminates storm surge flooding; could protect against all floods if operated on a tidal schedule	Necessary storm surge flooding in salt marshes is eliminated.
Elevating land as the sea rises		
Dunes	Protect inland areas from storm waves, provide a source of sand during storms to offset erosion.	Can provide habitat; can set up habitat for secondary dune colonization behind it
Beachfill	Reverses shore erosion, and provide some protection from storm waves.	Short-term loss of shallow marine habitat; could provide shore habitat for endangered species; would provide sediment to augment dune growth
Elevate land and structures	Avoid flooding and inundation from sea-level rise by elevating everything as much as sea rises.	Deepening of estuary unless bay bottoms are elevated as well.
Retreat		
Setback	Avoid the need for shore protection by keeping development out of threatened lands	Impacts avoided until shore erodes up to the setback line. Environmental impacts of development also reduced.
Density Restriction	Reduce the benefits of shore protection and thereby make it less likely.	Depends on whether owners of large lots decide to protect shore. Environmental impacts of development also reduced.

5.3 OVERVIEW OF LAND USE ALONG THE MID-ATLANTIC

The land uses along the mid-Atlantic coast include residential, commercial, industrial, government, military, agriculture, forest, and wetland. If threatened by rising sea level, many land uses (*e.g.*, urban, residential, commercial, industrial, transportation) would require shore protection for current land uses to continue. This is not to suggest that all of these lands *should* be protected, but researchers have generally concluded that most land owners will at least attempt to protect their investments or seek assistance from government agencies for such protection. The costs of armoring, elevating or nourishing shorelines are generally less — often far less — than the value of the land to the landowner. But there are also some land uses for which the cost and effort of shore protection may be less attractive than allowing the land to convert to wetland, beach or shallow water. Those land uses might include marginal farmland, conservations lands, portions of some recreational parks, and perhaps even portions of back yards where lot sizes are large.

Different categories of land use dominate different portions of the mid-Atlantic Coast. The greatest concentrations of low-lying undeveloped lands along estuaries are in North Carolina, along the Eastern Shore of Chesapeake Bay and along portions of Delaware Bay. Development has come more slowly to the lands along the Albemarle and Pamlico Sounds than other parts of the mid-Atlantic Coast. Maryland law prevents development along much of the Chesapeake Bay shore, and a combination of floodplain regulations and aggressive agricultural preservation programs limit development along the Delaware Bay shore in Delaware.

The Mid Atlantic has approximately 1,100 km of shoreline along the Atlantic Ocean. Along approximately two fifths of this coastline are ocean beach resorts with dense development and high property values. Federal shore protection has been authorized along almost all of these shores. These lands are fairly evenly spread throughout the Mid-Atlantic states, except for Virginia. Along approximately one third of the ocean coast, by contrast, landowners such as The Nature Conservancy and the U.S. Department of Interior are committed to allowing natural shoreline processes to operate. These shores include all of Virginia’s Atlantic Coast except for part of Virginia Beach, and a large part of North Carolina’s Outer Banks. The remaining quarter of the coast is lightly developed, yet shore protection is possible for these coasts as well due to the presence of important coastal highways and recreational areas, such as the Outer Banks (NC) and Fire Island (NY).

Despite momentum toward coastal development (and excluding land that is already given over to conservation uses), options still appear to be open for more than half of the dry land in the Mid-Atlantic within 1 m above the tides, and it may be possible to design land use plans that could accommodate both development and wetland migration in these areas.

Decisions to moderate the encroachment of the sea are based on physical, ecological, social, historic, and political reasons, and not just on the basis of land-use categories. Nonetheless, good data sets regarding land use and planned future land use must be an essential component in making decisions about the sort of adaptation measures to implement, if any. It is clearly of great value to make decisions about land use and development by including consideration of the impact of sea-level rise, with and without adaptation measures.

State-by-state differences in development plans and management practices lead to significant regional variations in the land available for wetland migration, and in appendices A-G more detail is provided at this scale. In the next section, we provide a broad overview of the potential for wetlands to migrate inland or otherwise form on lands that are dry today along the mid-Atlantic coast.

5.4 LAND AVAILABLE FOR LANDWARD MIGRATION AND FORMATION OF TIDAL WETLANDS

Wetlands and beaches provide important natural resources, wildlife habitat, and buffering of the coast (Chapter 4). As sea level rises, wetlands and beaches can potentially migrate inland as new areas become subjected to waves and tidal inundation—but not if human activities prevent such a migration.

Tidal wetlands have two important mechanisms for surviving as sea level rises: Vertical accretion (discussed in Chapter 3) and wetland migration. In this context, “survive” means maintaining the area of wetlands, not the survival of a particular plant community; and “wetland migration” means the natural process by which tidal wetlands, including marshes and beaches, move inland as sea level rises or beaches erode. For the last several thousand years, the relatively slow rate of sea-level rise allowed the area of tidal wetlands to increase in many areas: wetland accretion allowed the existing wetlands to keep pace with rising sea level, while wetland migration enabled a landward expansion of wetlands as dry land became submerged.

The two key relationships determining future wetland area are the relationship between wetland vertical development and sea-level rise, and between the rates of seaward erosion and inland migration. If wetland vertical development keeps pace with sea-level rise, wetland area will expand if inland migration is greater than seaward erosion, remain unchanged if inland migration and seaward erosion are equal, and decline if seaward erosion is greater than inland migration. If wetland vertical development lags behind sea-level rise (*i.e.*, wetlands do not keep pace), the wetlands will eventually become submerged and deteriorate even as they migrate inland, resulting in a loss of wetland area.

The prospect of accelerated sea-level rise along with coastal development, however, could potentially disrupt both of the processes by which tidal wetlands have been sustained in the past. Chapter 3 addresses the accretion issue in detail, concluding that in the high scenario in which sea-level rise accelerates by 7mm/yr, most existing tidal wetlands could not keep pace. Although the creation of wetlands due to wetland migration can occur whether or not wetlands are lost at their lower seaward boundary, existing policy and planning studies have assumed that wetland creation would be more important if existing wetlands are lost, than if they are maintained (IPCC CZMS, 1990; Titus 1991, 1998). For example, early estimates (*e.g.*, EPA, 1989) suggested that a 70 cm rise in sea level over the course of a century would convert 65% of the existing mid-Atlantic wetlands to open water, and that this region would experience a 65% net loss if all shores were protected so that no new wetlands could form inland. That loss would only be 27%, however, if new wetlands were able to form on undeveloped lands and 16% of developed areas converted to marsh as well.

The fact that intertidal zones migrate inland does not necessarily mean that they will be of high environmental quality, or even that they will be able to sustain themselves as sea level continues to rise. For example, as upland forest or nontidal wetlands become exposed to saline water for a sufficient amount of time, freshwater plants may become stressed (water logging, salt stress, or sulfide toxicity) and eventually die. Forests may give way to shrub species that can tolerate some salt, and eventually a community of salt tolerant high marsh plants may be established (Brinson *et al.*, 1995). While the transition from freshwater to tidal salt environment is slowly occurring, the existing marsh may also be accreting if there is enough sediment available. In order for wetlands to have a greater chance of survival under conditions of sea-level rise (and especially accelerated sea-level rise), migration inland will be necessary in some cases.

Very little land has been set aside for the express purpose of ensuring that wetlands can migrate inland as sea level rises. But those who own and manage estuarine conservation lands do allow wetlands to migrate onto adjacent dry land. With a few notable exceptions[18], the managers of most conservation lands along the ocean and large bays allow beaches to erode as well. Numerous studies have pointed out that the potential for landward migration of coastal wetlands is limited by the likelihood that many shorelines will be preserved for existing land uses (EPA, 1989; IPCC CZMS, 1990). Chapter 1 showed that without shore protection, the amount of dry land close to sea level which might potentially convert to tidal wetlands as sea level rises is approximately 20% of the area of existing wetland.

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[18] Exceptions include Cape May Meadows in New Jersey, beaches along Delaware Bay nourished for horseshoe crab habitat, and northern portions of Assateague Island being nourished to prevent that part of the island from disintegrating.

Some preliminary studies (*e.g.* Titus, 2004) indicate that the land potentially available for new wetland formation would be almost twice as great if future shore protection is limited to lands that are already developed, than if developed and legally developable lands are protected. If erosion of the seaward marsh boundary increases, the wetlands that formed on these formerly dry lands through wetland migration will account for an increasing fraction of all wetlands. This has significant implications for decision-making in the future, and efforts to better quantify the effect of shore protection and other adaptation measures in the face of rising sea level must be a priority if coastal managers, planners and policy-makers are to be able to incorporate appropriate information.

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Chapter 6. Population, Land Use, and Infrastructure

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The coastal zone has competing interests of increasing population accompanied by building of the necessary supporting infrastructure, while preserving natural coastal wetlands and buffer zones. Increasing sea level will put increasing stress onto the ability to manage these competing interests effectively and in a sustained manner.

This chapter quantifies the current population, infrastructure, and socioeconomic activity that may potentially affected by sea-level rise. The first study draws upon a methodology and approach prepared for this particular report. For population and land use, the assessment combines a GIS analysis of information on elevation and preliminary information on shore protection along with census statistics and land use statistics that are presented in geospatial distributions. This approach also provides specific numerical estimated information down to the county level which is of most benefit to local coastal managers. It is not without uncertainty and the statistical results are presented in terms of high and low estimates.

For understanding the impacts if sea-level rise of the nation’s transportation infrastructure, a recent study (DOT, 2007) performed for the U.S Department of

Transportation Center for Climate Change and Environmental Forecasting using a similar GIS analysis is summarized.

At the end if this discussion Table 6.9 provides a summary of the data sources, approaches, and limitations of the analysis.

KEY FINDINGS

- The available data prevents a precise estimate of the number of people whose homes would be inundated by a rise in sea level. Based on a set of optimistic assumptions, at least 25,000 people live on land within one meter above spring high water. But the actual figure is likely to be much greater.
- The available data is sufficient to estimate the number of people who live in the immediate vicinity of land potentially inundate by rising sea level. In the mid-Atlantic, between approximately 900,000 and 3,400,000 people (between 3 and 10% of the total population in the defined region) live on parcels of land or city blocks with at least some land less than 100 cm above spring high water. Approximately 40 percent of this population is along the Atlantic Ocean or adjacent coastal bays.
- Among the various potential impacts of sea-level rise on infrastructure, the mid-Atlantic transportation infrastructure possibly at risk include ports, highways and rails. For example, in the Port of Wilmington, DE, there is evidence to suggest that for an approximate 50 cm sea-level rise, 70 percent (320 acres) of the port property may be impacted. For the coastal states of Maryland, Virginia, and North

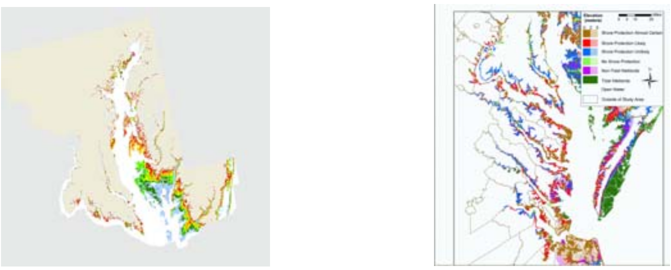
Carolina, plus Washington, DC, approximately 3,500 km of our National Highway System, Interstates and other major arterials could be at risk for regular inundation given a sea-level rise of 50 cm. Approximately 1,390 km of railway for these same states could be affected for the same scenario.

- The lower lying, less developed watershed regions like Pamlico and Albemarle Sounds, which are less developed and have more wetland acreage than watersheds to their north, may have a higher percentages of their populations in regions that are unlikely to take shoreline armoring or elevation measures.
- The top four land use categories in the lower elevation areas that are likely to be impacted by a 50cm sea-level rise for the Mid-Atlantic are, in order: Agriculture, Wetland, Forest, and Developed lands.

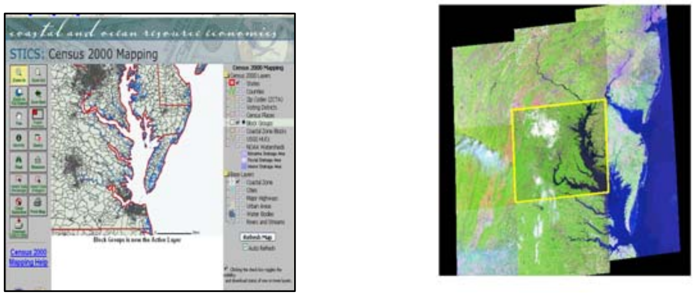
6.1 INTRODUCTION

The methodology for addressing population and land use uses a GIS analysis approach, creating overlays and joining GIS tables to provide useful summary information.

Figure 6.1 illustrates the four layers used in the analysis: the elevation layer (Chapter 1), the response layer reflecting preliminary information on existing approaches to shore protection, a census block layer NOAA Spatial Trends in Coastal Socioeconomics (STICS) Tool (NOAA, 2006) Census 2000 data base (U.S. Census Bureau, 2000), and a land use database.



Elevation **Existing Actions on Shore Protection**

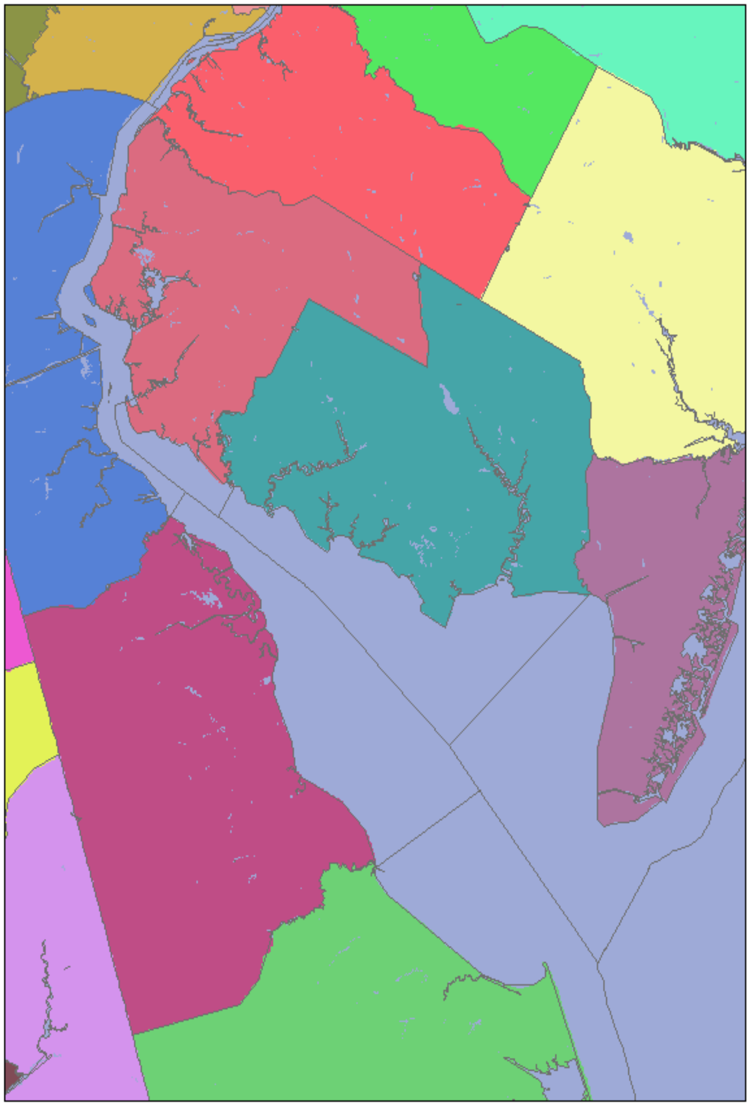


Census **Land Use**

Figure 6.1 Input layers to Question 6 GIS analysis.

To illustrate the layers, Figures 6.2 thru 6.4 provide a look at the fundamental underlying layers being use in this study, using Delaware Bay as an example. These will be used in conjunction with the elevation and protection overlays for Delaware found in Part IV of this report. Figure 6.2 provides is an example of the census block overlay, Figure 6.3 is an example of the county overlay, and Figure 6.4 is the example of the census tract overlay.

Figure 6.2 The block overlay example for Delaware Bay.



5017
5018
5019 **Figure 6.3** The county overlay example for Delaware Bay.

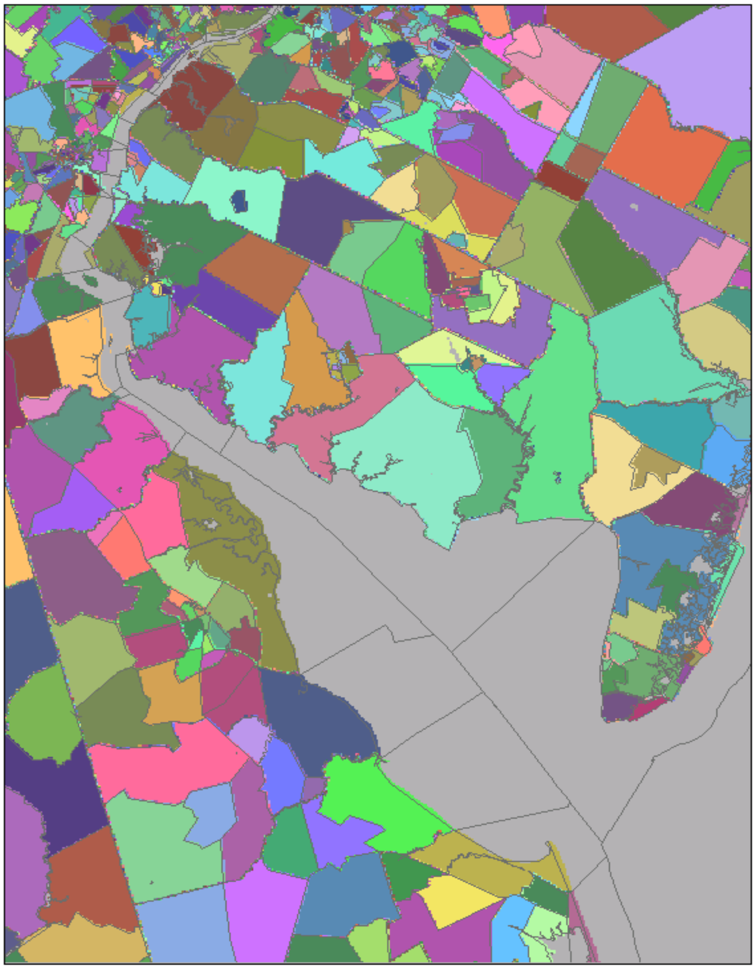


Figure 6.4 The tract overlay example for Delaware Bay.

A Census Block is a subdivision of a census tract (or, prior to 2000, a block numbering area). A block is the smallest geographic unit for which the Census Bureau tabulates 100-percent data. Many blocks correspond to individual city blocks bounded by streets, but blocks – especially in rural areas — may include many square miles and may have some boundaries that are not streets. The Census Bureau established blocks covering the entire nation for the first time in 1990. Previous censuses back to 1940 had blocks established only for part of the nation. Over 8 million blocks are identified for Census 2000 (U.S. Census Bureau, 2007).

A Census Tract is a small, relatively permanent statistical subdivision of a county delineated by a local committee of census data users for the purpose of presenting data. Census tract boundaries normally follow visible features, but may follow governmental unit boundaries and other non-visible features in some instances; they always nest within counties. Census tracts are designed to be relatively homogeneous units with respect to population characteristics, economic status, and living conditions at the time of establishment, census tracts average about 4,000 inhabitants. They may be split by any sub-county geographic entity.

The methodology and process used in the construction of the regional and state summary tables is completed using an area-adjusted system that includes as a lowest common denominator areas that 1) are greater than the zero contour of a Spring High Water vertical datum adjusted elevation model, and 2) not considered a wetland or open water according to the best possible compiled state and National Wetlands Inventory (NWI) wetlands data (FWS, 2007). Uncertainties are expressed and presented in the tables in terms of low and high estimates. The four layers are as follows:

- Elevation data: The elevation data is the driving parameter in the population analysis. The elevation data is gridded into 30 meter pixels throughout the region. All other input datasets described below are gridded to this system from their source format. Compiled for CCSP, this dataset is created individually for each state using the best data sources available. The elevations are adjusted such that the zero-contour line is set relative to the Spring High Water vertical datum.

- Census data: Census 2000 dataset contained in the NOAA Spatial Trends in Coastal Socioeconomics Program (STICS) is used in the analysis. Block boundaries are the finest scale data available, and are the building blocks of the Census analysis. Tracts, counties and states boundaries are derived from appropriate aggregations from their defining blocks. Tract and county boundaries also extend fully into water bodies, so for this analysis, they are cropped back to the sea-level boundary, but source Census data remain intact.
- Land use data: Land use/land cover is a difficult dataset to find in high resolution throughout large regions. The National Land Cover Data (USGS, 2001) product is used in this analysis. This is a 30 meter pixel classification from circa 2001 satellite imagery and is consistently derived across the region.
- Protection Zones: Compiled for CCSP, this dataset combines a number of protection and urban layers to describe the likelihood of the shoreline being protected in the event of sea-level rise.

The analysis evaluates several different datasets (Census blocks/tracts, land use) within sea-level rise zones of 25-cm intervals, up to a 3-meter rise (0-25, 0-50, 0-300cm). Census block statistics include area and percent of block affected, number of people and households affected based two methods: uniform distribution throughout the block, and a best-estimate based on assumptions concerning elevation and population density. These numbers are aggregated to the county and state level for reporting. Statistics are provided at the county level for different sea-level rise scenarios and percent inundation of blocks.

The Census tract boundaries are the smallest census unit that contains property and tax values. The same analysis is completed for tracts, and aggregated to show values affected at the tract, county and state level for 25-cm increments of sea-level rise.

This chapter examines the broad mid-Atlantic region and makes some inferences on the population that may be affected and this assessment divides the mid-Atlantic Region into sub-regions defined by watershed, as shown in Figure 6.5. The general populations within the various watersheds, although crossing over states, have to address common problems in response to sea-level rise driven by common topographies, physical and meteorological regimes. The impacts of sea-level rise will also tend to be common within the low-lying areas of each watershed. Most of the watershed boundaries are straightforward, for instance the Potomac River and Chesapeake Bay. The watershed boundaries do not include the upland portions of the watershed, however those portions are not required for the analyses of the low lying areas. The Atlantic Ocean watershed is the most complex as it is not defined by a discrete estuarine river watershed boundary, but by exposure to the outer coastline, and it has components in several states. The more localized effects at the county are discussed in the various appendices found in Part IV of this report.

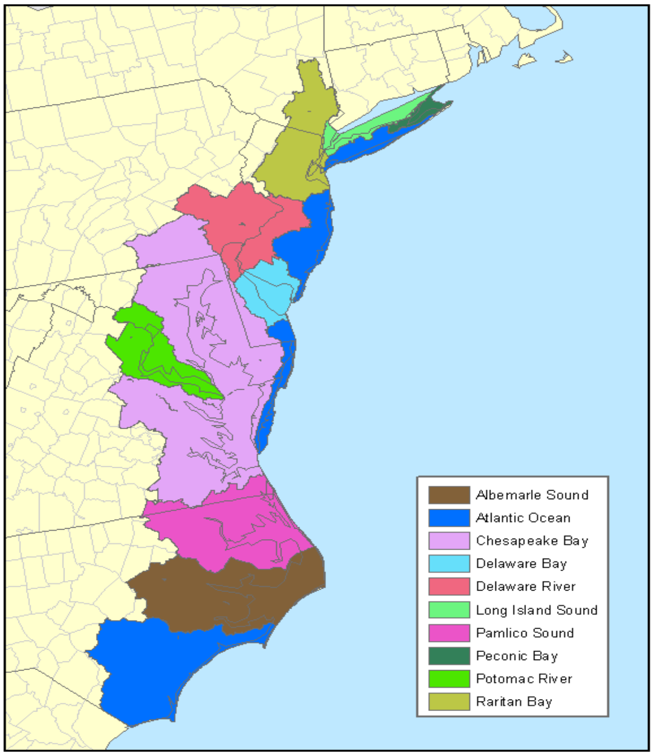


Figure 6.5 The mid-Atlantic region generalized watersheds.

6.2 POPULATION

Table II.1 in the overview provides total statistics for each of the watersheds. Not everyone in those watersheds lives in a low-lying area at risk to be inundated by sea-level rise. Table 6.1 is a summary analysis of those populations in each watershed at potential risk for various rates of sea-level rise (50cm, 1m, 2m, and 3m). These statistics represent the overall totals from which following tables and maps will show subsets in various levels of potential risk, inundation and shore protection. The low and high estimates in Table 6.1 provide the range of uncertainty by using the low and high Digital Elevation Models (DEM) for each of the scenarios of sea-level rise (50cm, 1m, 2m, and 3m). The high and low DEMs are required because of the varying scales and resolutions of the data on the various overlays (for instance the overlay of the census block on the elevation layer). The uncertainty in how much of a particular census tract or block may be inundated must also be addressed by listing high and low estimates. Table 6.1 is the high estimate of the potential populations because it is for census blocks that could have any inundation at all and thus includes a maximum count.

Of note in Table 6.1a are the relatively high population statistics for the Chesapeake Bay and the Atlantic Ocean, the Atlantic Ocean population counts increasing faster than those for the Chesapeake as the inundation scenario worsens.

Table 6.1a Subset of the population from census blocks within watershed tracks using any inundated blocks for various sea-level rise scenarios.

Population								
	50cm		1m		2m		3m	
Watershed	Low	High	Low	High	Low	High	Low	High
Long Island Sound	1,641	173,786	1,641	191,218	93,752	234,593	138,016	298,162
Peconic Bay	7,871	20,415	7,871	29,147	15,484	37,091	26,789	41,696
NHY-Raritan Bay	24,298	577,285	35,960	678,676	132,176	931,241	351,176	1,211,728
Delaware Bay	18,762	56,688	22,665	62,778	41,203	84,551	58,551	100,835
Delaware River	14,553	200,962	19,381	239,481	79,750	361,014	118,273	442,054
Chesapeake Bay	291,571	698,778	326,833	807,728	617,314	1,156,241	884,889	1,390,546
Potomac River	0	95,043	0	124,516	32,248	145,610	92,873	171,611
Albemarle Sound	39,628	64,687	61,146	75,830	82,804	96,638	101,772	111,048
Pamlico Sound	50,876	116,638	69,724	147,290	134,906	249,726	190,889	292,949
Atlantic Ocean	225,367	860,120	362,801	1,109,285	925,171	1,434,265	1,346,607	1,727,375
All Watersheds	674,567	2,864,402	908,022	3,465,949	2,154,808	4,730,970	3,309,835	5,788,004

There is also uncertainty regarding where in the block the population resides and thus the relationship between the portion of a block’s area that is lost and the portion of the population residing in the vulnerable area. This analysis estimates vulnerable population based on the percentage of a census block that is inundated. For instance, the total population low and high estimated counts for a 1 m sea-level rise or all watersheds are 908,022 and 3,465,949 for “any inundation” of census block (see columns 4 and 5 above in Table 6.1). But homes are not necessarily distributed uniformly throughout a census block. If 10% of a block is very low, for example, that land may be part of a ravine, or below a bluff, or simply the low part of a large parcel of land. Therefore, the assumption of uniform density would often overstate the vulnerable population. Table 6.1b provides estimates for alternate assumptions regarding the percentage of a block that must be vulnerable before one assumes that homes are at risk. (This table presents the results by state rather than by subregion.) If we assume that 90% of a block must be lost before home are at risk, and that the population is uniformly distributed across the highest 10% of the block, then 26,059-883, 981 people live within one meter above spring high water, allowing for our low and high elevation estimates. Combining the low elevation estimate with the 90% assumption is a combination of very optimistic assumptions; therefore, we can be extremely confident that the number of people vulnerable to a one meter rise in sea level is greater than 26,000.

Table 6.1b Population living on land within one meter above spring high water
(Alternate assumptions about how much of the land must be lost before homes are lost)

	Percentage of block within one meter above spring high water									
	99[1]		**90[2]**		**50[2]**		**0[3]**		**Best**	
	Low	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
NY	**784**	**421,900**	**784**	**470,906**	**2,617**	**685501**	**42326**	**1126292**	**21286**	**941938**
NJ	**12,547**	**302,804**	**15,775**	**352,517**	**41,268**	**498655**	**177509**	**834446**	**65182**	**596519**
DE	**483**	**7,205**	**816**	**9,237**	**2,048**	**16653**	**44295**	**85480**	**4990**	**22327**
PA	**646**	**7,835**	**646**	**8,949**	**1,539**	**15092**	**10365**	**43456**	**2894**	**26977**
DE	**483**	**7,205**	**816**	**9,237**	**2,048**	**16653**	**44295**	**85480**	**4990**	**22327**
MD	**610**	**4,847**	**1,895**	**8,044**	**4,386**	**17719**	**46890**	**137494**	**4224**	**17669**
DC	**0**	**0**	**0**	**0**	**0**	**46**	**0**	**9596**	**0**	**168**
NC	**1,924**	**14,144**	**5,327**	**25,091**	**17,453**	**60096**	**283592**	**345534**	**12982**	**39704**
Total	**17,477**	**765,940**	**26,059**	**883,981**	**71,359**	**1310415**	**649272**	**2667778**	**116548**	**1667629**

(1) Population estimates in this column assume that no homes are vulnerable unless 99% of the dry land in census block is within one meter above spring high water.
(2) Same as 1 but for 90 and 50 percent.
(3) Assumes uniform population distribution.

The census information also allows further breakout analysis of the population by owner and renter occupied residences. This Census information gives a sense of the characterization of permanent home owners versus the more transient rental properties that could translate to infrastructure and local economy at risk as well. The number of owner occupied and renter occupied housing units in each watershed by various sea-level rise scenarios are shown in Tables 6.2 and 6.3. Similar to the estimates in Table 6.1., these are high estimates for which any portion of a particular census block is inundated. The actual coastal population potentially affected by sea-level rise also includes people staying in hotels for a few days and population census data on coastal areas rarely are able to fully reflect all of the population and resultant economic activity. It is noted that this present analysis does not include that subset of vacant properties used for seasonal, recreational, or occasional use as a way to characterize the "transient" population that the outer coasts typically have. This follow-on will be important because in many areas, the permanent populations are expected to increase as retirees occupy their seasonal homes for longer portions of the year.

Table 6.2 Number of Owner occupied residences in each watershed region for various sea-level rise scenarios – low and high estimates.

Owner occupied residences								
Watershed	**50cm**		**1m**		**2m**		**3m**	
	Low	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Long Island Sound	0	0	0	0	0	0	0	0
Peconic Bay	3,407	8,633	3,407	11,655	6,661	14,940	11,207	16,802
NYH-Raritan Bay	9,112	229,550	13,446	269,421	50,379	369,924	137,679	480,239
Delaware Bay	7,202	21,274	8,723	23,615	15,076	31,422	21,139	37,595
Delaware River	4,100	75,358	6,014	89,713	30,382	133,454	45,483	162,355
Chesapeake Bay	106,863	258,163	120,793	299,554	225,985	435,312	330,319	524,999
Potomac River	0	35,176	0	46,078	11,272	54,803	35,128	66,404
Albemarle Sound	14,365	24,278	22,760	28,729	31,466	37,089	39,192	42,985
Pamlico Sound	19,191	41,910	26,731	52,459	48,932	87,136	68,665	101,805
Atlantic Ocean	81,677	328,053	140,676	423,546	360,496	550,293	520,329	656,902
All Watersheds	245,917	1,022,395	342,550	1,244,770	780,649	1,714,373	1,209,141	2,090,086

Table 6.3 Number of renter occupied housing units by watershed for various sea-level rise scenarios.

Renter occupied residences								
	50cm		**1m**		**2m**		**3m**	
Watershed	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Long Island Sound	78	27,540	78	31,018	15,524	39,200	23,132	53,216
Peconic Bay	528	1,696	528	2,465	1,197	3,260	2,190	3,746
NYH-Raritan Bay	2,634	153,190	4,279	178,793	24,219	245,645	85,914	324,632
Delaware Bay	2,396	5,499	2,639	5,887	4,182	8,536	5,757	10,221
Delaware River	1,370	27,509	2,112	32,767	10,833	48,533	15,651	56,514
Chesapeake Bay	32,531	72,366	35,881	84,632	66,616	142,433	100,221	179,513
Potomac River	0	12,900	0	17,478	3,722	22,160	14,480	27,627
Albemarle Sound	3,052	5,688	5,269	6,834	7,994	9,837	10,458	11,794
Pamlico Sound	3,977	8,073	6,009	10,663	10,435	20,143	15,115	23,267
Atlantic Ocean	23,226	111,853	40,222	154,509	122,097	204,643	193,791	244,601

6.3 LAND USE

The NLCD 2001 (USGS, 2001) is used to overlay land use onto the DEMs for various scenarios of sea-level rise. Land use categories include Agriculture, Barren land, Developed Land, Forest, Grassland, Shrub-scrub, Water, and Wetland. An estimate of the area of land categorized by land use for all watersheds for the mid-Atlantic is found in Table 6.4 below. In the land use tables, ranges of uncertainty are provided by showing the area statistics (in hectares) for the sea-level rise scenarios using a high DEM (for a low estimate) and a low DEM for a high estimate. At the 25 cm sea-level rise scenario shown in Table 6.4, the Wetlands land use category dominates the acreage, along with Agriculture and Forests. However with increasing sea-level rise, Agriculture, Developed lands, and Forests become much more affected than Wetlands. The high and low estimates show a significant spread around the standard estimate.

Table 6.4 Mid-Atlantic All Watersheds Summary for Land Use.

Hectares	**Sea Level Rise (cm) Standard Estimate (regular DEM)**				
Land Use	**25**	**50**	**100**	**200**	**300**
Agriculture	15,443.10	34,839.40	83,336.40	196,095.80	329,297.30
Barren Land	3,756.20	5,781.60	9,587.40	16,903.40	25,300.80
Developed	9,399.80	19,202.40	43,833.30	101,468.20	162,609.50
Forest	14,694.20	26,921.70	55,454.50	108,129.30	179,750.80
Grassland	1,915.70	4,893.60	10,211.00	18,537.80	26,163.40
Shrub-scrub	1,193.00	2,666.30	5,601.60	9,528.10	13,002.50
Water	1,362.60	1,905.40	2,644.30	3,539.40	4,329.60
Wetland	19,320.80	31,843.70	46,446.40	64,800.30	84,500.00

Hectares	**Sea Level Rise (cm) Low Estimate (high DEM)**				
Land Use	**25**	**50**	**100**	**200**	**300**
Agriculture	2,585.60	8,643.00	43,179.90	142,684.60	258,845.00
Barren Land	799.6	1,537.70	5,044.50	12,385.40	19,909.30
Developed	438.9	1,687.70	11,978.20	55,459.40	101,914.20
Forest	1,221.60	5,373.90	27,054.10	76,845.20	129,126.90
Grassland	765.7	2,041.20	7,640.60	16,477.70	24,208.50
Shrub-scrub	292.7	1,065.20	3,791.90	8,388.30	11,904.80
Water	690.4	1,045.50	1,967.90	2,960.10	3,693.70
Wetland	4,691.10	13,987.20	34,724.90	56,227.30	72,970.80

Hectares	**Sea Level Rise (cm) High Estimate (low DEM)**				
Land Use	**25**	**50**	**100**	**200**	**300**
Agriculture	58,529.10	87,441.80	141,805.50	280,661.10	402,413.40
Barren Land	8,859.20	10,889.70	14,759.50	23,159.30	29,343.00
Developed	49,457.30	66,660.90	92,951.60	157,392.00	205,031.40
Forest	42,557.20	58,642.90	94,281.80	163,058.50	219,751.60
Grassland	7,130.00	9,804.60	14,206.50	22,293.30	29,844.50
Shrub-scrub	3,906.40	5,422.10	7,726.00	11,239.60	15,025.40
Water	3,257.60	3,619.60	4,118.20	4,987.30	5,648.10
Wetland	46,962.90	54,931.20	66,597.70	84,084.60	101,410.30

Table 6.5 below shows the same information in Table 6.4, except broken out at a higher resolution by watershed. The Developed category acreage dominates northeast water sheds like Long Island Sound and New York harbor (HYH)-Raritan Bay. Agriculture and Forest dominate the Chesapeake Bay. Not surprisingly, the Developed land category dominates the Atlantic Ocean watershed. Table 6.6 provides the low and high estimates for the values of the standard estimate in Table 6.5.

Table 6.5 Area by land use category for the mid-Atlantic for standard estimate for various sea-level rise scenarios.

	(in hectares)	Sea Level Rise (cm) Standard Estimate (regular DEM)				
Watershed	**Land Use**	**25**	**50**	**100**	**200**	**300**
Long Island Sound	**Agriculture**	4.8	7.7	15.1	23.4	29.7
Long Island Sound	**Barren Land**	83.7	108.2	123.2	177.2	184.3
Long Island Sound	**Developed**	556	785.1	1,190.60	2,729.40	3,788.80
Long Island Sound	**Forest**	33.1	49.1	72.9	158.9	238.8
Long Island Sound	**Grassland**	26.1	35.3	46.8	82.4	104
Long Island Sound	**Shrub-scrub**	14.9	19.4	25.7	56.3	65.9
Long Island Sound	**Water**	26.3	45.2	57.6	80.6	95.9
Long Island Sound	**Wetland**	126.5	197.8	275	447.8	562.1
Peconic Bay	**Agriculture**	37.1	61.1	207.9	391.6	870.9
Peconic Bay	**Barren Land**	103.7	154.1	244.4	314.6	396.4
Peconic Bay	**Developed**	204.3	366.8	912.2	1,499.70	2,929.20
Peconic Bay	**Forest**	111.4	164.3	389.3	708.4	1,481.80
Peconic Bay	**Grassland**	36	47.2	83.7	137	269.7
Peconic Bay	**Shrub-scrub**	14.9	21.6	44.5	64.6	101.7
Peconic Bay	**Water**	32.5	65.8	112.8	157.1	218.9
Peconic Bay	**Wetland**	193.8	286.3	512.7	711	1,076.00
NYH-Raritan Bay	**Agriculture**	112.4	207.4	393.1	780.2	920.9
NYH-Raritan Bay	**Barren Land**	24.5	53	177.8	384.2	456.9
NYH-Raritan Bay	**Developed**	1,152.50	2,963.30	6,119.80	18,570.40	23,238.20
NYH-Raritan Bay	**Forest**	41.4	97.7	230	642.7	929.2
NYH-Raritan Bay	**Grassland**	0	1.4	4	10.2	21.6
NYH-Raritan Bay	**Shrub-scrub**	1.6	3.1	6.6	14.1	14.8
NYH-Raritan Bay	**Water**	21.2	41.3	91.4	194.2	234.9
NYH-Raritan Bay	**Wetland**	422.5	757.7	1,282.60	2,199.80	2,468.70
Delaware Bay	**Agriculture**	1,203.20	3,048.70	4,887.80	10,789.60	16,886.70
Delaware Bay	**Barren Land**	320.2	476.4	634.1	1,007.30	1,414.00
Delaware Bay	**Developed**	200.6	372.1	610.5	1,723.10	2,962.00
Delaware Bay	**Forest**	705.7	1,407.70	2,075.00	4,321.30	6,484.10
Delaware Bay	**Water**	89	107.2	119.6	143.6	160.7
Delaware Bay	**Wetland**	976.6	1,379.60	1,647.00	2,208.10	2,500.10
Delaware River	**Agriculture**	574.2	1,628.50	2,562.50	7,364.50	10,123.60
Delaware River	**Barren Land**	56.2	147.4	216.3	502.9	670.9
Delaware River	**Developed**	631.9	1,655.70	3,114.50	9,231.20	12,790.40
Delaware River	**Forest**	154.4	448.8	676.4	1,800.50	2,360.00
Delaware River	**Water**	30.2	84.1	113.5	155.6	172.4
Delaware River	**Wetland**	466.4	949.4	1,277.90	2,362.70	2,805.80
Chesapeake Bay	**Agriculture**	4,748.90	8,864.90	24,250.50	52,599.30	89,988.70
Chesapeake Bay	**Barren Land**	1,533.40	2,423.50	3,688.00	5,098.10	6,711.50
Chesapeake Bay	**Developed**	2,075.00	2,974.20	7,462.50	15,191.40	36,832.40
Chesapeake Bay	**Forest**	6,951.30	10,951.70	22,694.30	40,836.50	71,245.40
Chesapeake Bay	**Water**	374.8	436.5	565.7	703.4	848.2
Chesapeake Bay	**Wetland**	4,987.60	7,324.20	10,634.80	14,193.30	19,190.20
Potomac River	**Agriculture**	790.6	987.8	1,407.30	2,077.80	10,226.10
Potomac River	**Barren Land**	148.1	165.4	198.4	248.7	762.1
Potomac River	**Developed**	331.1	381.8	623.5	1,067.30	2,819.10
Potomac River	**Forest**	855.2	1,015.00	1,381.00	2,123.60	8,373.50
Potomac River	**Water**	60.1	64.6	85.4	109.8	165.7
Potomac River	**Wetland**	488	533.3	624.7	781.1	1,534.10

Table 6.5 - continued. Area by land use category for the mid-Atlantic for standard estimate for various sea level rise scenarios.

	(in hectares)	Sea Level Rise (cm) Standard Estimate (regular DEM)				
Watershed	**Land Use**	**25**	**50**	**100**	**200**	**300**
Albemarle Sound	**Agriculture**	3,758.00	9,968.00	20,535.80	46,916.40	
Albemarle Sound	**Barren Land**	39.8	69.8	145.6	368	
Albemarle Sound	**Developed**	503.3	1,546.40	3,877.80	7,993.30	
Albemarle Sound	**Forest**	2,253.20	5,708.70	12,806.70	25,124.90	
Albemarle Sound	**Grassland**	1,111.70	3,071.00	6,145.60	11,379.30	
Albemarle Sound	**Shrub-scrub**	753	1,736.90	3,599.80	5,795.80	
Albemarle Sound	**Water**	168.8	301.7	480.8	674.3	
Albemarle Sound	**Wetland**	5,095.80	9,609.80	14,147.40	19,260.00	
Pamlico Sound	**Agriculture**	3,361.70	8,698.40	24,578.80	64,187.50	110,577.90
Pamlico Sound	**Barren Land**	150	321.5	775.4	2,168.30	4,311.80
Pamlico Sound	**Developed**	362.4	1,049.10	2,964.70	6,469.70	12,064.10
Pamlico Sound	**Forest**	2,036.00	4,239.90	8,635.80	18,454.20	30,514.00
Pamlico Sound	**Grassland**	520	1,225.60	2,684.20	3,995.00	5,085.50
Pamlico Sound	**Shrub-scrub**	176.1	424.7	1,062.10	1,893.40	2,553.20
Pamlico Sound	**Water**	68.5	118.6	179.6	264.3	356
Pamlico Sound	**Wetland**	3,701.30	6,136.70	8,872.90	12,163.80	17,184.20
Atlantic Ocean	**Agriculture**	852.2	1,367.00	4,497.60	10,965.50	20,725.20
Atlantic Ocean	**Barren Land**	1,296.60	1,862.30	3,384.30	6,634.00	9,612.50
Atlantic Ocean	**Developed**	3,382.70	7,107.80	16,957.10	36,992.70	53,481.50
Atlantic Ocean	**Forest**	1,552.40	2,839.00	6,493.10	13,958.50	25,044.90
Atlantic Ocean	**Grassland**	221.9	513.2	1,246.80	2,931.80	4,883.80
Atlantic Ocean	**Shrub-scrub**	232.5	460.6	862.9	1,703.90	2,635.70
Atlantic Ocean	**Water**	481.3	627	821.4	1,012.00	1,134.90
Atlantic Ocean	**Wetland**	2,862.50	4,669.00	7,171.40	10,472.80	13,196.30

Table 6.6 Area by land use category for mid-Atlantic for low and high estimates for various sea level rise scenarios

	Low Estimate (high DEM)					High Estimate (low DEM)				
Land Use	**25**	**50**	**100**	**200**	**300**	**25**	**50**	**100**	**200**	**300**
Long Island Sd										
Agriculture	0	0	1.4	5.9	16.7	20.5	22	24.8	38.1	46.9
Barren Land	0	0	0.3	40.9	65.5	179	180.6	183.4	194.3	201.8
Developed	0	0	98.9	467.6	1,432.40	2,519.70	2,763.40	3,286.40	4,585.30	5,964.50
Forest	0	0	4.5	31.1	95.9	158.9	174	211	418.4	561.4
Grassland	0	0	0.5	7.1	23.1	82.6	89.8	100.4	136.5	159.4
Shrub-scrub	0	0	3.3	8.2	21.9	52.6	55.9	61.5	71.9	75
Water	0	0	5.7	10.6	17.7	83.6	87.4	92.7	109.6	120.7
Wetland	0	0	5.9	71.5	156.6	459.4	485.6	534.9	706.2	820.6
Peconic Bay										
Agriculture	0	0	22.4	186.2	399.4	220.2	262.5	361.2	814.6	1,108.90
Barren Land	0	0	22.5	102.8	216.5	274.8	290.3	343.3	391.8	422.8
Developed	0	0	101.7	741.2	1,417.70	998.6	1,128.40	1,589.20	2,849.30	3,655.60
Forest	0	0	56.7	337.6	796.4	438.1	505.2	766.5	1,444.90	1,855.50
Grassland	0	0	7.3	42.9	124.2	98.7	112.2	178.4	271.8	322.5
Shrub-scrub	0	0	5.5	26.9	51.9	54	58	76.1	100.8	113.2
Water	0	0	11	53.8	88.3	120.4	129.2	157.5	214.7	241.4
Wetland	0	0	73.8	262.2	494.4	562.1	610	770.4	1,073.50	1,239.80
NYH-Raritan Bay										
Agriculture	0	13.2	32.3	269.9	547.3	665.9	794.1	878.4	1,054.60	1,170.40
Barren Land	0	12.3	43	179.3	358.9	226.6	279.5	347.6	469.3	515.2
Developed	0.3	96.8	335.9	4,000.80	10,626.40	14,407.90	18,580.40	21,093.60	26,278.70	30,108.00
Forest	0.1	5.9	40.9	246.2	496.3	428	545.9	719.6	1,048.10	1,363.90
Grassland	0	0	0.1	2.9	7.7	8.8	10.8	16.8	21.3	28.1
Shrub-scrub	0	0	0	4.4	11.2	12.7	15.6	15.7	16.2	16.4
Water	0	4.2	9.4	44.5	104.6	189.5	210.7	232.5	258.1	275.7
Wetland	0.3	72.3	142.7	926.1	1,695.70	2,227.10	2,438.20	2,608.90	2,841.60	3,029.80
Delaware Bay										
Agriculture	0	5	953.4	5,633.60	11,505.20	5,849.60	7,297.30	9,598.90	16,499.30	24,764.60
Barren Land	0	2	280.3	701.7	1,090.30	737	855	1,043.20	1,496.50	1,732.50
Developed	0	18.5	218.3	841.4	1,662.40	825.2	1,255.10	1,759.80	3,005.40	4,104.00
Forest	0	12.4	591.8	2,302.70	4,167.80	2,501.10	3,315.20	4,287.20	6,576.00	8,969.80
Water	0	0.5	84.7	120.6	143.6	118.2	124.4	134.6	158.7	176.4
Wetland	0	23.3	901.5	1,812.00	2,245.30	2,036.60	2,204.90	2,422.40	2,777.40	3,036.10
Delaware River										
Agriculture	4.1	8.4	312.1	2,417.40	5,254.00	4,558.10	6,675.80	8,192.00	11,682.80	14,253.80
Barren Land	0.4	0.8	27.6	201.7	383.4	360.4	472.6	565.8	766.2	935.9
Developed	42.1	88.1	439	2,961.90	6,509.60	6,509.90	8,668.90	10,967.20	18,521.70	22,406.80
Forest	7.8	11.4	90.9	663.3	1,274.70	1,259.90	1,770.80	2,136.20	3,226.90	3,912.30
Water	2.6	4.2	23.5	77.6	112.5	167.9	188.2	200.2	299	321.1
Wetland	7.7	15.4	333	1,167.80	1,775.20	2,234.10	2,722.30	3,012.30	3,843.50	4,273.90

Table 6.6 - continued. Area by land use category for mid-Atlantic for low and high estimates for various sea level rise scenarios

	Low Estimate (high DEM)					High Estimate (low DEM)				
Land Use	**25**	**50**	**100**	**200**	**300**	**25**	**50**	**100**	**200**	**300**
Ches. Bay										
Agriculture	149	1,261.10	11,183.00	40,154.90	66,196.40	14,606.60	22,563.50	40,462.70	76,856.20	105,666.40
Barren Land	45.7	478.2	2,073.10	3,746.30	4,918.30	2,869.40	3,663.90	4,649.90	6,498.50	7,297.00
Developed	33.7	304	2,223.80	9,146.00	17,784.30	6,685.30	8,730.20	13,180.50	32,408.60	46,113.80
Forest	103.5	1,224.50	9,100.10	26,703.50	45,419.30	17,060.20	22,886.90	38,373.10	66,326.80	86,409.50
Water	15.1	62.2	165.3	356.1	467	506.9	571.6	667.3	823.7	911.7
Wetland	150.6	1,362.90	5,013.50	9,073.40	12,196.30	8,596.40	10,501.40	14,287.40	18,529.90	21,038.00
Potomac River										
Agriculture	0	0	0	693.7	1,854.80	1,746.20	1,975.40	4,904.80	12,432.70	15,752.70
Barren Land	0	0	0	103.4	205.5	223.4	238.1	462.6	890.2	1,109.80
Developed	0	0	0	408.2	1,004.70	753.3	861.8	1,836.50	3,105.00	4,073.20
Forest	0	0	0.4	550.5	1,596.30	1,822.30	2,073.20	4,632.50	10,103.90	13,325.90
Water	0	0	0	28.3	45.9	94.3	100	130	168.5	177.8
Wetland	0	0	0.2	236	482.3	713.4	752	1,124.70	1,627.80	1,838.10
Albemarle Sd.										
Agriculture	1,646.40	4,613.70	16,441.60	39,134.20	66,244.10	4,375.40	7,204.00	12,819.00	28,024.00	42,663.20
Barren Land	227.8	254.9	321.4	502.6	792.4	2,463.30	3,600.50	5,907.30	8,888.80	10,963.90
Developed	122.2	438.2	2,463.30	6,738.50	10,679.90	2,334.50	3,931.60	8,279.40	22,998.20	25,717.00
Forest	513.5	1,946.00	8,683.50	21,889.80	31,430.50	2,366.30	3,298.00	4,950.40	8,969.80	13,395.90
Grassland	386.5	1,127.80	4,792.00	10,051.90	14,831.80	31,694.80	38,649.70	44,721.10	54,623.60	61,626.10
Shrub-scrub	207.1	794.7	2,724.20	5,472.20	7,314.00	4.5	7.8	18.9	69.8	188.5
Water	349.2	513.8	749.9	983.3	1,215.80	2,465.60	3,963.40	8,440.70	18,219.20	24,805.50
Wetland	2,052.30	6,311.50	14,486.10	20,617.00	25,118.20	422	584.9	928.6	1,780.70	3,011.20
Pamlico Sd.										
Agriculture	740.9	2,616.80	13,138.40	46,894.80	92,312.40	12,448.10	22,623.80	39,676.90	84,532.10	137,202.50
Barren Land	81	149	474.7	1,623.40	3,540.00	496.2	735.8	1,326.80	2,923.30	5,163.50
Developed	62.5	260.1	1,626.80	5,033.80	8,469.40	1,499.90	2,510.60	4,582.80	9,565.20	14,457.90
Forest	237.5	1,398.80	5,497.50	14,011.50	25,119.50	5,806.10	8,877.40	13,802.80	23,805.70	35,877.30
Grassland	229.7	629.6	2,015.50	3,998.50	5,018.40	1,805.10	2,564.80	3,577.50	4,618.30	5,845.30
Shrub-scrub	26.2	150.9	677.6	1,699.50	2,362.80	581.8	906.2	1,434.60	2,136.10	2,919.80
Water	80.6	123	213.8	310	380	214.8	245.9	295.9	383.8	509.5
Wetland	974.6	3,761.50	8,507.10	12,618.50	16,680.00	8,649.00	10,191.10	12,079.20	15,376.30	21,956.40
Atlantic Ocean										
Agriculture	45.3	124.8	1,095.50	7,294.00	14,514.80	3,649.20	5,034.50	8,219.70	17,314.20	26,206.40
Barren Land	444.7	640.5	1,801.70	5,183.30	8,338.60	3,178.70	3,828.90	5,411.20	8,853.50	10,780.10
Developed	178.2	482	4,470.60	25,120.20	42,327.50	13,105.10	18,843.80	29,210.00	47,568.70	61,291.20
Forest	359.1	775	2,987.90	10,109.10	18,730.20	5,398.00	7,211.30	11,540.20	21,036.20	31,506.80
Grassland	149.6	283.8	825.3	2,374.30	4,202.40	830	1,221.00	2,017.90	3,806.10	5,742.70
Shrub-scrub	59.4	119.6	381.2	1,177.10	2,143.10	739.4	966.1	1,365.50	2,148.10	3,052.70
Water	242.9	337.5	698.7	962.1	1,096.30	994.1	1,093.10	1,209.60	1,358.70	1,454.90
Wetland	1,505.70	2,440.40	5,261.00	9,443.00	12,127.00	7,767.40	8,959.20	10,878.30	13,756.00	16,010.40

Similar analyses to those found above for the watershed regions were also completed for each county within the Mid-Atlantic States. These tables are included in the chapters in Part IV of this report, which assess impacts at local, state, and county levels. A higher order statistical analysis than the GIS analysis presented, such as a hedonic pricing method, was not attempted due to lack of time and resources.

6.4 INFRASTRUCTURE

6.4.1 Public Works and Infrastructure

One impact of sea-level rise would be that the clearance under bridges will decrease. As a result some boats will no longer fit under fixed bridges, and some drawbridges will need to increase either the number or the duration of their openings. When a drawbridge opens on a busy coastal highway on a summer weekend, the effects on traffic can be a spectacle. Hundreds of cars can be backed up for miles, and if intervening traffic lights allow cross traffic over the highway it can take some time to clear the effects of a recently closed drawbridge. Bridges connecting coastal barriers and spans that connect the mainland to islands spend their entire lives in salty water. This is a continual threat to their structural integrity, both from immersion and from the salty aerosols in the coastal atmosphere. Coastal bridges need constant maintenance. If sea-level rise pushes salinity farther upstream, raises local salinity, immerses more of a bridge’s support structure, or brings the deck that much closer to the water, then maintenance problems will grow. Exposure to salt water is bad for transportation and it is bad for other infrastructure too. Pipelines, storm water outfalls, and industrial cooling water intakes all sit in water that may become increasingly saline as time goes by.

Estuarine navigation channels may need to be extended landward from where they terminate now to provide access to a retreating shoreline. Disposing of dredge spoils is a common problem in the mid-Atlantic. The corollary benefit is that not as much dredging will be required in deeper water because a rising elevation will provide extra clearance.

If decisions are made to de-couple developed areas from the effects of rising sea levels by not stabilizing shorelines, then eventually places will be abandoned. Before they can be completely left to nature they will need to be unbuilt. Structures will need to be demolished and removed. Ideally foundation slabs and paved streets will be torn up. Underground pipelines could remain, but pump stations and manholes should be filled. Underground storage tanks, particularly those that held fuels, need to be removed, and contaminated soils will have to be remediated before a site is allowed to revert back to nature.

6.4.2 Public Health and Safety

Higher sea levels may shorten evacuation windows during coastal storms. If highways and causeways flood now as storms approach, they are going to be flooded sooner if the sea is higher. Many of the coastal cities and urbanized barriers already need more hours to completely evacuate than they have now. Higher sea level that shortens the evacuation period could be a grave threat. If rising seas translate to rising water tables in developed areas, places on estuarine shorelines that don’t have sanitary sewers and instead rely on septic systems to treat human waste may have additional problems. Many of these places already have septic problems because of high coastal water tables. Any increase may force abandonment or the implementation of expensive measures to process sanitary waste.

6.4.3 Transportation Infrastructure

ICF International recently completed the first phase of a study sponsored by the U.S. Department of Transportation (US DOT, 2007) on "The Potential Impacts of Global Sea-Level Rise on Transportation Infrastructure". This recent study uses a GIS-based analytical approach that is similar to that used by EPA and NOAA in the previous sections for population and land use. The following paragraphs provide a summary of the Phase 1 report.

The study also covers the mid-Atlantic region and is being implemented in two phases: Phase 1 focuses on North Carolina, Virginia, Washington, DC and Maryland and was recently completed. Phase 2 focuses on New York, New Jersey, Pennsylvania, Delaware, South Carolina, Georgia, and the Atlantic coast of Florida and is expected to be completed in 2008. This study was designed to produce rough estimates of how future climate change, specifically sea-level rise and storm surge, could affect transportation infrastructure on a portion of the East Coast of the United States. The study's major purpose is to aid policy makers, specifically transportation officials at the Federal, State and local levels, by providing quantified estimates of these effects as they relate to roads, rails, airports and ports.

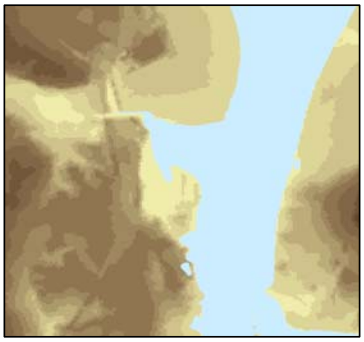
The GIS approach produces maps and statistics that demonstrate the location and quantity of transportation infrastructure that could be affected under a range of potential increases in sea level, which are based on estimates of global sea-level rise included in the United

Nations Intergovernmental Panel on Climate Change's Third Assessment Report (IPCC, 2001).

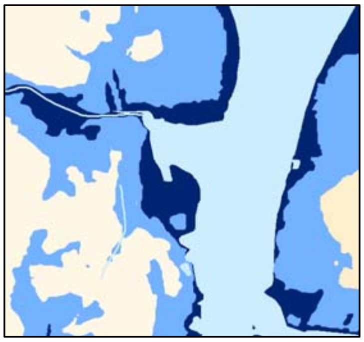
The report considers that the rising sea level, combined with the possibility of an increase in the number of hurricanes and other severe weather related incidents, could cause increased inundation and more frequent flooding of roads, railroads, and airports, and could have major consequences for port facilities and coastal shipping. Many of the low-lying railroads, tunnels, ports, runways, and roads are already vulnerable to flooding and a rising sea level will only exacerbate the situation by causing more frequent and more serious disruption of transportation services and also introduce problems to infrastructure not previously affected by these factors.

The following is an excerpt from the US DOT study approach to assess impacts of sea-level rise on transportation infrastructure, and defines the four basic steps involved in the analysis. These steps are elaborated on below:

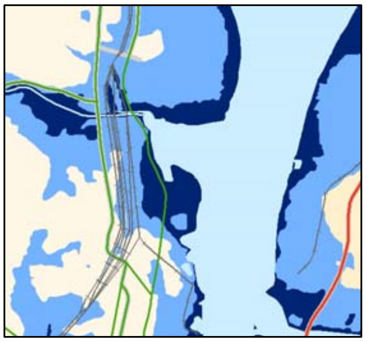
- *Using Digital Elevation Models (DEM) evaluated the elevation in the coastal areas and created tidal surfaces to describe the current and future predicted sea water levels.* This spatial information helped identify areas that are, without proper protection, expected to be ***regularly inundated*** or that are ***at-risk*** of periodic inundation due to storm surge.



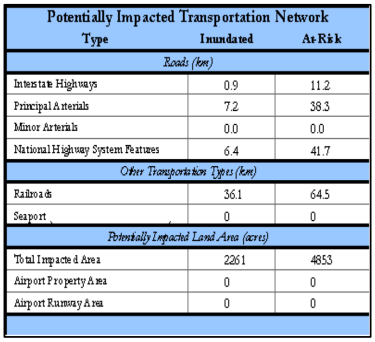
- *Identified land that, without protection, will regularly be inundated by the ocean or is at-risk of periodic inundation due to storm surge at the given temporal intervals.* From this spatial information it is possible to plan for the protection of current infrastructure and to prevent the building of infrastructure in areas that are, without proper protection, expected to be ***regularly inundated*** or that are ***at-risk*** of periodic inundation due to storm surge.



- *Identified the transportation infrastructure that, without protection, will regularly be inundated by the ocean or at-risk of periodic inundation due to storm surge at the given temporal intervals.* The maps and GIS data produced by this study detail the infrastructure that is expected to be ***regularly inundated*** or that is ***at-risk*** so that measures may be taken to protect, reroute, or remove the infrastructure as the ocean encroaches upon them.



- *Provided statistics to demonstrate the potential amount of inundated and at-risk land at the given temporal intervals.* The statistics calculated describe both the total amount of inundated and at-risk land and the total length of roads, railroads and other infrastructure that may be ***regularly inundated*** or that is ***at-risk*** of periodic inundation.



Potentially Impacted Transportation Network

Type	Inundated	At-Risk
Roads (km)		
Interstate Highways	0.9	11.2
Principal Arterials	7.2	38.3
Minor Arterials	0.0	0.0
National Highway System Features	6.4	41.7
Other Transportation Types (km)		
Railroads	36.1	64.5
Seaport	0	0
Potentially Impacted Land Area (acres)		
Total Impacted Area	2261	4853
Airport Property Area	0	0
Airport Runway Area	0	0

The US DOT study compares current conditions (2000) to estimates of future conditions resulting from increases in sea level. The estimates of increases in sea level are based upon the *range of averages* of the Atmosphere-Ocean General Circulation Models (AOGCMs) for all 35 SRES (Special Report on Emission Scenarios) as reported in figure 11.12[19] from the IPCC's Third Assessment Report (IPCC 2001). The study examines the effects of a range of potential increases in sea level, from 6 cm to 48.5 cm. The sea-level rise scenarios used in this US DOT study are similar to the previous scenarios discussed in Part I of this report.

The study first established the areas that would be *regularly inundated* or *at-risk* during storm conditions, given eight potential increments of sea-level rise. It defines regularly inundated areas or base sea level as NOAA's Mean Higher High Water (MHHW) tidal datum (NOAA, 2000). (Note that MHHW is used instead of Spring High Water, however those elevations are very similar in the Mid-Atlantic.) The eight regularly inundated areas that the study examines are those sections of the coast that fall between MHHW in 2000 and the adjusted MHHW levels (MHHW in 2000 plus a sea-level rise increment of 6 cm, 6.5 cm, 13 cm, 17.5 cm, 21 cm, 30 cm, 31 cm or 48.5 cm). For at-risk areas or areas that could be affected by storm conditions, the study uses a base level of NOAA's highest observed water levels (HOWL) for 2000, and adjusts this upwards based on the eight sea-level rise increments. The *at-risk* areas examined are those areas falling between the adjusted MHHW levels and the adjusted HOWL levels.

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[19] IPCC3, WG1, c.11, page 671. http://www.grida.no/climate/ipcc_tar/wg1/pdf/TAR-11.PDF

The caveats and limitations of the study are discussed in context with the objectives of the study and are in line with those expressed earlier in this overall report (Executive Summary):

> The study was not intended to create a new estimate of future sea levels, or to provide a detailed view of a particular area under a given scenario. Instead, the study explored existing predictions of global sea-level elevations from the United Nations Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (TAR) and examined large areas for study. The inherent value of this study is the broad view of the subject and the overall estimates identified.
>
> This study was meant to provide a broad first look at potential sea-level changes on the Atlantic coast, and the results should not be viewed as defining specific changes in water levels at specific points in time. Due to the overview aspect of this study, and systematic and value uncertainties in the involved models, this analysis appropriately considered sea-level rise estimates from the IPCC TAR as eustatic occurrences. The confidence stated by IPCC in the regional distribution of sea-level change is *low* due to significant variations in the included models; thus it would be inappropriate to use the IPCC model series to estimate local changes. Local variations, whether caused by erosion, subsidence or uplift, local steric factors or even coastline protection, were not considered in this study. The unpredictability of anthropogenic mitigation was also not taken into consideration. Some studies are underway that may, in the future, allow for this to be considered, but are not currently publicly available.

Statistics and maps of affected transportation infrastructure at the State and county level were created for each scenario. For each scenario the maps and statistics identify:

- Kilometers of ***Interstate Highways*** potentially impacted
- Kilometers of Non-Interstate ***Principal Arterial*** roads potentially impacted
- Kilometers of ***Minor Arterial*** roads potentially impacted
- Kilometers of ***National Highway System*** facilities potentially impacted
- Kilometers of ***Railroads*** potentially impacted

- Total acres of ***Land*** potentially impacted
- Acres of ***Airport Property*** potentially impacted
- Acres of ***Airport Runways*** potentially impacted
- Acres of ***Port Property*, **for large freight ports**,** potentially impacted

Sample outputs maps and tables for Washington, DC:

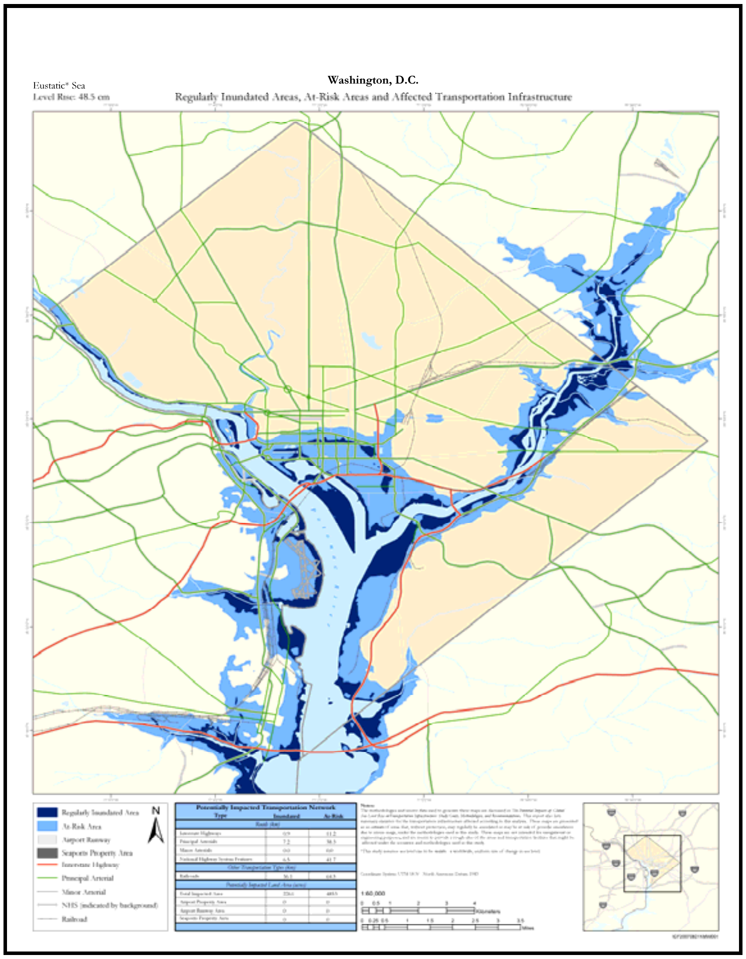

Figure 6.6 From US DOT (2007), a representative output map from this study showing regular and at-risk areas at the 48.5 cm scenario.

Table 6.7 From US DOT (2007), a representative output table from the US DOT study showing regular and at-risk areas at the 48.5 cm scenario, the highest level examined in the US DOT study.

DC State Statistics	48.5 cm					
Increase in Eustatic SLR	**Regular Inundation**		**At-Risk**		**Total**	
Length	**Km**	**% Affected**	**Km**	**% Affected**	**Km**	**% Affected**
Interstates	0.9	4%	11.2	49%	12.1	53%
Non-Interstate Principal Arterials	7.2	4%	38.3	22%	45.6	26%
NHS Minor Arterials	0.0	0%	0.0	0%	0.0	0%
National Highway System (NHS)	6.4	5%	41.7	32%	48.1	37%
Rails	3.8	5%	29.4	38%	33.3	43%
Area	**Acres**	**% Affected**	**Acres**	**% Affected**	**Acres**	**% Affected**
Ports	0	0%	0	0%	0	0%
Airport Property	0	0%	0	0%	0	0%
Airport Runways	0	0%	0	0%	0	0%
Total Land Area Affected	2,261	5%	4,853	11%	7,114	16%

The maps and tables above for the Washington, DC region indicate there is considerable transportation infrastructure at risk under a 48.5cm sea-level rise scenario, the highest of the eight sea-level rise scenarios. Four to five percent (0.9 km of Interstates, 7.2 km of non-interstate Principal arterials) of the Washington, DC highways examined in the US DOT study would be regularly inundated, while an additional 22% to 49% (11.2 km of Interstates, 38.3 km of non-Interstate principal arterials) could be affected by storm conditions. (It should be noted that the elevation data for the transportation facilities is of the land upon which the highway or rail line is built). Looking at the results across the range 6 to 48.5 cm range of SLR examined in the US DOT study across the four states, several trends become clear. Sea-level rise has the potential to affect many kilometers of highways and roads across the region. While in percentage terms Washington, DC appears more vulnerable, in absolute terms both Virginia and North Carolina could see disruption across still more kilometers of highways and rails under the sea-level rise scenarios analyzed in the study. It is also useful to note that for roads, this study focuses on larger roads. Generally, there are many miles of local roads and collectors that could also be affected. This report output should be obtained and looked at in tandem with the regional and state and county data contained in the appendices of this overall report (CCSP 4.1) to obtain a complete assessment of the impacts of various scenarios of sea-level rise. Overview maps were created for each state for each scenario and specific maps for each county that was affected for each scenario were also created.

The study examined effects on three large ports: Baltimore, MD, Norfolk, VA, and Wilmington, NC. All three ports could be vulnerable to even gradual sea-level rise, especially the port in Wilmington. At the 48.5 cm SLR scenario, it is estimated that 70 percent (320 acres) of the port property at risk for inundationl. For Norfolk, the estimated percentage is 48 percent (659 acres), while for Baltimore port it is 31 percent (291 acres).

For airports and rail, the picture is less stark. According to the analysis 2 percent of rail would be vulnerable to SLR of 48.5 cm (164.0 km in Virginia, 52.7 km in Maryland, and 194 km in North Carolina), except in Washington, DC, where 5 percent (3.8 km) would be vulnerable. For airports, 3 percent of airport runways/tarmacs in Maryland (22 acres) and 5 percent in Virginia (164 acres) and North Carolina (132 acres) could be vulnerable at the high end. (Washington Ronald Reagan National Airport is included in the Virginia totals.)

Table 6.8 below is a statistical summary of the US DOT (2007) Phase 1 States and Washington, DC for the totals (sum of) of the Regularly Inundated and At-Risk categories for the low (30cm) and high (48.5cm) scenarios.

Table 6.8 Summary of statistics for the total of regularly inundated and at risk infrastructure for 30cm and 48.5cm increase in SLR (US DOT (2007)).

Total Regularly Inundated and at Risk								
For a 30 cm increase in SLR	**Washington DC**		**Maryland**		**Virginia**		**North Carolina**	
Length	**Km**	**% Affected**	**Km**	**% Affected**	**Km**	**% Affected**	**Km**	**% Affected**
Interstates	11.7	52%	23.2	3%	159.2	9%	8.5	1%
Non-Interstate Principal Arterials	42.9	25%	178.1	7%	510.2	11%	393.6	6%
NHS Minor Arterials	0.0	0%	176.6	11%	55.7	1%	358.6	7%
National Highway System (NHS)	45.9	36%	160.0	7%	527.7	5%	656.5	9%
Rails	31.9	41%	338.2	13%	543.6	7%	389.3	5%
Area	**Acres**	**% Affected**	**Acres**	**% Affected**	**Acres**	**% Affected**	**Acres**	**% Affected**
Ports	0	0%	938	100%	1323	96%	412	90%
Airport Property	0	0%	1,566	12%	4,064	11%	4,147	11%
Airport Runways	0	0%	89	13%	426	14%	307	11%
Total Land Area Affected	6,898	16%	929,929	14%	1,157,959	4%	3,388,800	11%

Total Regularly Inundated and at Risk								
For a 48.5 cm increase in SLR	**Washington DC**		**Maryland**		**Virginia**		**North Carolina**	
Length	**Km**	**% Affected**	**Km**	**% Affected**	**Km**	**% Affected**	**Km**	**% Affected**
Interstates	12.1	53%	24.0	3%	167.9	9%	8.7	1%
Non-Interstate Principal Arterials	45.6	26%	204.1	8%	533.1	11%	419.9	6%
NHS Minor Arterials	0.0	0%	193.4	12%	64.4	1%	370.5	8%
National Highway System (NHS)	48.1	37%	178.9	8%	555.0	5%	682.6	10%
Rails	33.3	43%	365.6	14%	579.6	8%	411.8	5%
Area	**Acres**	**% Affected**	**Acres**	**% Affected**	**Acres**	**% Affected**	**Acres**	**% Affected**
Ports	0	0%	938	100%	1335	97%	439	95%
Airport Property	0	0%	1,865	15%	4,198	12%	4,291	12%
Airport Runways	0	0%	104	16%	434	14%	323	12%
Total Land Area Affected	7,114	16%	1,008,427	15%	1,232,183	5%	3,491,490	11%

Of note in the table are the high percentage of arterial lengths affected in Washington, DC in either of the two scenarios and the high percentage of acreage of ports affected in all the other states. Washington, DC has no freight ports sufficiently large to include in the study. The differences in the statistics for these two scenarios are a result of the uncertainty in potential SLR.

6.5 SUMMARY

Table 6.9 is a summary of the limitations of the information and how it is applied in this chapter and covers both the population and land use analysis in the center column and the DOT study analysis in the right column. The two studies both rely upon methodologies to use a baseline elevation surface, include elevation information related to tidal influence, and then overlay additional information layers of varying spatial and temporal resolutions. The baseline elevation maps themselves rely upon GIS interpolation techniques for integrating source elevation contours and imagery. Chapter 1 of this report discusses these limitations and uncertainties. Although, these methodologies and processes are "state-of-the-art", the reader needs to use the resulting information in the context of the estimated uncertainty estimates.

Table 6.9 Information Provided in this Chapter and Its Limitations.

Question Analyzed	Population, Land use	Kilometers of Transportation Infrastructure
Format of Information	Result Tables	Maps and Result Tables
Key Assumptions	Population has uniform density within inhabited portion of census block.	Direct Overlay of Data
Underlying Study	N/A	[USDOT 2007]
Information Sources for Underlying Studies	Elevation Data (See Chapter 1) Shore Protection (See Chapter 5) Census Data on Population and Structures	Elevation Data (See Chapter 1) DOT data sets: [National Highway Planning Network; Federal Railroad Admin.; TelaAtlas; USGS DOQQ's]
Limitations of Study	Census Data provides no information on where in a particular block the population resides. Analysis assumes that all population is in highest x% of the dry land in a block, using different values of x.	Elevation of rails and roads are often higher than the surrounding land for which study had data. Interpolation of DEM elevation data required for the incremental scenarios.
Treatment of Uncertainty	Incorporates the uncertainties in the data layers (census block, elevation, etc..) Considers alternate values of "x".	Incorporates various SLR scenarios, with various estimates of storm surge effects. Estimates of uncertainties in elevation are not addressed.
Sea-Level Scenarios	Results based on elevation from 50 to 300 cm above spring high water.	Results based on elevations [from 6 to 48.5cm] above mean higher high

		water (regular inundation) ; and highest observed water level (storm surge)
Other Limitation of this Chapter	Does not assess economic activity. Assessment of infrastructure only includes DC, Maryland, Virginia and North Carolina only and is limited to transportation.	

CHAPTER 6 REFERENCES

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Chapter 7. Public Access

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Rising sea level does not inherently increase or decrease the public's access to the shore, but the response to sea-level rise can. Beach nourishment tends to increase public access along the shore, because federal (and some state) laws preclude beach nourishment funding unless the public has access to the beach that is being restored. Shoreline armoring, by contrast, can decrease public access along the shore, because the intertidal zone along which the public has access is eliminated.

This chapter describes existing public access to the shore, and the impact of shoreline changes and responses to sea-level rise on public access.

7.1 EXISTING PUBLIC ACCESS AND THE PUBLIC TRUST DOCTRINE

The right to access tidal waters and shores is well-established. Both access and the ownership of tidal wetlands and beaches is defined by the "public trust doctrine", which is part of the common law of all the mid-Atlantic states. According to the public trust doctrine, navigable waters and the underlying lands were publicly owned at the time of statehood and remain so today.

The public trust doctrine is so well-established that it often overrides specific governmental actions that seem to transfer ownership to private parties (Lazarus, 1986;

Rose, 1986). Many courts have invalidated state actions that extinguished public ownership or access to the shore (*Illinois Central R.R. v. Illinois; Arnold v. Mundy)*. Even if a land deed says that someone's property extends into the water, the public trust doctrine usually overrides that language and the public has access along the shore. Even when government agencies transfer coastal land to private owners, the public still has the right to use the shore unless the state explicitly indicates otherwise (Lazarus, 1986; Slade *et al.*, 1990).

Figure 7.1 illustrates some key terminology for this chapter. Along sandy shores with few waves, the wet beach lies between *mean high water* and *mean low water*. (Along shores with substantial waves, the beach at high tide is wet inland from the mean high water mark, as waves run up the beach). The *dry beach* extends from approximately mean high water inland to the seaward edge of the dune grass or other terrestrial plant life, sometimes called the *vegetation line* (Slade *et al.*, 1990). The dune grass generally extends inland from the point where a storm in the previous year struck with sufficient force to erode the vegetation, (Pilkey *et al.*, 1984) which is well above mean high water. Along marshy shores, mudflats are found between mean low water and mean sea level, *low marsh* is found between mean sea level and mean high water, and *high marsh* extends from mean high water to *spring high water*.[20] Collectively, the lands between mean high water and mean low water (mudflats, low marsh, and wet beaches) are commonly known as *tidelands*.

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[20] See Text Box in Chapter 1 for a discussion of tides and wetland zonation.

The public trust doctrine includes these wetlands and beaches because of the needs associated with hunting, fishing, transportation along the shore, and landing boats for rest or repairs. In most states, the public owns all land below the high water mark (Slade *et al.*, 1990) which is generally construed as mean high water. (The precise boundary varies in subtle ways from state to state. The portion of the wet beach inland of mean high water resulting from wave runup has also been part of the public trust lands in some cases. See *e.g. State v. Ibbison* and Freedman and Higgins (undated). Thus, in general, the public trust includes mudflats, low marsh, and wet beach, while private parties own the high marsh and dry beach. In New York the inland extent of the public trust varies; in some areas the public owns the dry beach as well.[21] In Pennsylvania, Delaware, and Virginia, by contrast, publicly owned land extends only up to the low water mark (Slade *et al.*, 1990). Figure 7.2 provides an overview for coastal states.

Ownership, however, is only part of the picture. In Pennsylvania, Delaware, and Virginia, the public trust doctrine provides an easement along the tidelands for hunting, fishing, and navigation. In New Jersey, the public trust doctrine includes access along the *dry* part of the beach for recreation, as well as the traditional public trust purposes (*Matthews v. Bay Head).* The other states have gradually obtained easements for access along some dry beaches either through purchases or voluntary assignment by the property owners in return for proposed beach nourishment. The federal policy precludes funding for beach nourishment unless the public has access (USACE, 1996). Some state laws specify that

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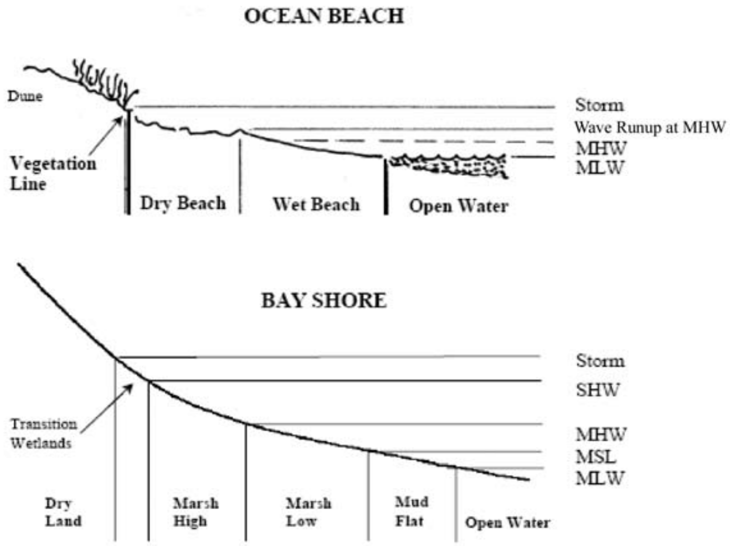
[21] E.g. Dolphin Lane Assocs. v. Town of Southampton, 333 N.E.2d 358, 360 (N.Y. 1975)

any land created with beach nourishment belong to the state (*e.g.*, MD. CODE ANN., NAT. RES. II 8-1103 (1990)).

The right to access *along* the shore, however, does not mean that the public has a right to cross private land to get *to* the shore. (New Jersey is an exception in some cases.) Unless there is a public road or path to the shore, access along the shore is thus only useful to those who either reach the shore from the water or have permission to cross private land. Although the public has easy access to most ocean beaches and large embayments like Long Island Sound and Delaware Bay, the access points to the shores along most small estuaries are widely dispersed (*e.g.*, Titus, 1998 n. 49). Given the federal policy promoting access, the lack of access to the shore has held up several beach nourishment projects; and to secure the funding many communities have improved public access to the shore, not only with more access ways to the beach, but also by upgrading availability of parking, restrooms, and other amenities (*e.g.*, New Jersey 2006).



MSL = Mean Sea level
MLW = Mean Low Level
MHW = Mean High Water
SHW = Spring High Water
Storm = Average Annual Storm Tide

Figure 7.1 Legal and geological tideland zonation. The area below mean high water is usually publicly owned, and in all cases is subject to public access for fishing and navigation. Along the ocean, the dry beach above mean high water may be privately owned, but in several states the public has an easement; along the bay, the high marsh above mean high water is also privately owned, but wetland protection laws generally prohibit or discourage development.

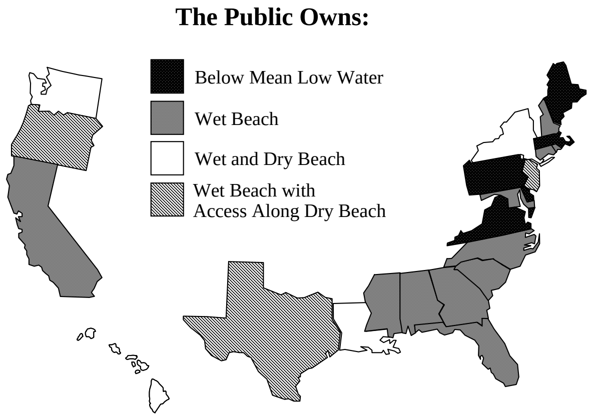


Figure 7.2 The public's common law interest in the shores of various coastal states.

7.2 IMPACT OF SHORE EROSION ON PUBLIC ACCESS

The rule that property lines retreat whenever shores erode has been part of the common law for over one thousand years (*St. Clair v. Lovingston; DNR v. Ocean City*), assuming that the shoreline change is natural. When riparian landowners cause the shorelines to advance seaward, the common law did not vest owners with title to land reclaimed from the sea, although legislatures sometimes have (ALR, 1941). A majority of states (*e.g.*, MD. CODE ANN., ENVIR. 16-201) award the riparian owner the artificially formed land if he or she is not responsible for the accretion, such as a federal navigation jetty causing the shore to advance seaward (Slade *et al.*, 1990); but some states (*e.g.*, New Jersey) vest the state public trust with the new land.

The literature does not evaluate whether states might change between the majority and minority rules in response to sea-level rise; but Slade *et al.* (1990) and others have evaluated the existing rules in the analogous context of shore erosion. The majority rule has two practical advantages. Determining what portion of a shoreline change resulted from artificial causes, such as sedimentation from a jetty or a river diversion, is much more difficult than determining how much the shoreline changed when the owner filled some wetlands. Moreover, the majority rule prevents the state from depriving shorefront owners of their riparian access by pumping sand onto the beach and creating new land (*e.g.*, Larmar Corp*)* But granting the newly created land to riparian owners delayed the beach nourishment project at Ocean City, Maryland when some of the owners insisted upon reaping the additional benefit of title to the newly created beach. (Titus, 1998 p. 373).

Sea-level rise causes shores to retreat both through inundation and erosion. Although the case law generally assumes that the shore is moving as a result of sediment being transported, inundation and shore erosion are legally indistinguishable. Among the causes of natural shoreline change, the major legal distinction has been between gradual and imperceptible" shifts, and sudden shifts that leave land intact but on the other side of a body of water, often known as "avulsion." Shoreline erosion changes ownership; avulsion does not. If an inlet formed 100 m north of one's home during a storm in which an existing inlet 100 m south of the home closed, an owner would still own her home because this shoreline change is considered to be avulsion. But if the inlet gradually migrated 200 m north, entirely eroding the property but later creating land in the same location, all of the newly created land will belong to the owner to the south.

Because the public has access to the intertidal zone as long as it exists, the direct effect of sea-level rise on public access depends on how the intertidal zone changes. Along an undeveloped or lightly developed ocean beach, public access is essentially unchanged as the beach migrates inland (except perhaps where a beach is in front of a rocky cliff, which is rare in the Mid-Atlantic). If privately owned high marsh becomes low marsh, then the public will have additional lands on which they may be allowed to walk (provided that environmental regulations to protect the marsh do not prohibit it). Conversely, if sea-level rise reduces the area of low marsh, then access may be less.

7.3 IMPACT OF REPONSES TO SEA-LEVEL RISE ON PUBLIC ACCESS

Although sea-level rise appears to have a small direct effect on public access to the shore, responses to sea-level rise can have a significant impact, especially in developed areas. Along developed bay beaches, by contrast, public access along the shore can be eliminated if the shorefront property owner erects a bulkhead, because the beach is eventually eliminated. A number of options are available for state governments that wish to preserve public access along armored shores, such as including public access in permits for shore protection structures. Connecticut has done so in some cases; but there is no general requirement in the Mid-Atlantic states. Therefore, sea-level rise has reduced public access along many estuarine shores and is likely to do so in the future as well.

Government policies related to beach nourishment, by contrast, set a minimum standard for public access (USACE, 1996), which often increases public access along the shore. Along the ocean shore from Delaware to North Carolina, the public would not have access along the dry beach under the public trust doctrine (except in New Jersey). But once a federal beach nourishment project takes place, the public has access. Beach nourishment projects increased public access *along* the shore in Ocean City, Maryland; and Sandbridge (Virginia Beach), Virginia, where property owners had to provide easements to the newly created beach before the projects began (Titus, 1998; Virginia Marine Resources Commission, 1988).

Areas where public access *to* the beach is currently limited by a small number of access points include the area along the Outer Banks from Southern Shores to Corolla; northern

Long Beach Township, New Jersey; and portions of East Hampton, South Hampton, Brookhaven, and Islip along the south shore of Long Island. In West Hampton, landowners had to provide 6 easements for perpendicular access from the street to the beach to meet the New York state requirement of public access every one-half mile. A planned $71 million beach restoration project for Long Beach Island has been stalled (Urgo, 2006) pending compliance with the New Jersey state requirement of perpendicular access every one-quarter mile (USACE, 1999). An additional 200 parking spaces for beachgoers must also be created (USACE, 1999). Private communities along Delaware Bay have granted public access to the beaches in return for state assistance for beach protection (Beach 2000 Planning Group, 1988).

If other communities with limited access seek federal beach nourishment in the future, public access would similarly increase. Improved access to the beach for the disabled may also become a requirement for future beach nourishment activities (*e.g.*, Rhode Island CRMC, 2007). This is not to say that all coastal communities would provide public access in return for federal funds. But the Mid-Atlantic has no privately owned gated barrier islands, unlike the Southeast, where some communities have chosen to expend their own funds on beach nourishment rather than give up their exclusivity.

Ultimately, the impact of sea-level rise on public access will depend on the policies and preferences that prevail over the coming decades. Sometimes the desire to protect property as shores erode will come at the expense of public access. Sometimes it will promote an entire re-engineering of the coast, which under today’s policies generally favors public access. It is possible that rising sea level is already starting to cause people to rethink the best way to protect property along estuarine shores (NRC, 2007) to protect the environmental benefits of natural shores. If access along estuarine shores becomes a policy goal, techniques are available for preserving public access as sea level rises.

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Chapter 8. Coastal Flooding, Floodplains and Coastal Zone Management Issues

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This chapter examines the effects of sea level rise on coastal floodplains and on coastal flooding management issues confronting the U.S. Federal Emergency Management Agency (FEMA), the floodplain management community, the coastal zone management community, and the public, including private industry. Sea level rise is just one of numerous complex scientific and societal issues these floodplain groups face. The chapter is a status report and assessment of ongoing activities, and briefly discusses future needs and barriers to progress in addressing flood hazards.

The information in this chapter is an assessment of a range of complex activities of many state and federal agencies and other groups. Some key findings are:

- There is a clear need for integrated solutions to adequately understand and prepare for the impacts of sea level rise on coastal flooding. Rising sea level increases the vulnerability of coastal areas to flooding. The higher sea level provides a higher base for storm surges to build upon. It also diminishes the rate at which low-lying areas drain, thereby increasing the risk of flooding from rainstorms. Increases shore erosion can further increase flood damages, by removing protective dunes, beaches, and wetlands and by leaving particular properties closer to the water's edge. In addition to flood damages, many of the other effects, responses, and decisions discussed in this report are likely to occur during or in the immediate aftermath of severe storms. Beach erosion and wetlands loss often occur during storms, and the rebuilding phase after a severe storm often affords the best opportunity for adapting to sea level rise in developed areas.

- Analysis of historical tide station records for the highest storm tides shows that storms today with slightly lesser storm surge than historical storms have had slightly higher storm tide elevations relative to the land due to sea level rise. This suggests that any given storm could have higher flooding potential in the future due to higher sea levels than it would if it occurred today.
- In a 1991 FEMA study, it was found that the projected rise in population and sea level rise scenarios would increase the expected annual flood damage by 2100 for an average NFIP insured property by 36–58 percent for a 0.30m (1-foot) rise and 102–200 percent for a 0.91m (3-foot) rise. This would lead to actuarial increases in insurance premiums for building subject to sea level rise of 58 percent for a 1-foot rise and 200 percent for a 0.91m (3-foot) rise. The study estimated that a 10.30m (1-foot) rise would gradually increase the expected annual national Flood Insurance Program (NFIP) flood losses by $150 million by 2100. Similarly, a 0.91m (3-foot) rise would gradually increase expected losses by about $600

million by 2100. Per policy holder, this increase would equate to $60 more than in 1990 for the 0.30m (1-foot) rise and $200 more for the 0.91m (3-foot) rise.

- The mid-Atlantic Coastal Zone Management community is increasingly recognizing sea level rise has a high risk coastal hazard, however to date only Maryland has performed the comprehensive analyses and studies need to make recommendations for state policy formulation.

This chapter first provides some more focused description and practical definition of floodplains and then describes some of the more detailed impacts of sea level rise on coastal flooding and the interaction with storm surge, the national floodplain management response, and closes with an assessment of the coastal zone management response.

8.1 PHYSICAL CHARACTERISTICS

8.1.1 Floodplain Definition

In general terms, a floodplain is any normally dry land surrounding a natural water body that holds the overflow of water during a flood. Because they border water bodies, floodplains have been popular sites to establish settlements, which subsequently become susceptible to flood-related disasters. Most management and regulatory definitions of floodplains apply to rivers; however, open-coast floodplains characterized by beach, dunes, and shrub-forest are also important since much of the problematic development and infrastructure is concentrated in these areas. Chapter 2 provides much more detailed description of this environment.

The federal regulations governing FEMA (2008) via Title 44 of the Code of Federal Regulations defines floodplains as "any land area susceptible to being inundated by flood waters from any source". The FEMA (2002) Guidelines and Specifications for flood hazard mapping partners Glossary of Terms defines floodplains as:

1. A flat tract of land bordering a river, mainly in its lower reaches, and consisting of alluvium deposited by the river. It is formed by the sweeping of the meander belts downstream, thus widening the valley, the sides of which may become some kilometers apart. In time of flood, when the river overflows its banks, sediment is deposited along the valley banks and plains.
2. Synonymous with the 100-year floodplain. The land area susceptible to being inundated by stream derived waters with a 1 percent annual chance of being equaled or exceeded in a given year.

The National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) defines floodplains as the portion of a river valley that has been inundated by the river during historic floods (NWS Glossary of Terms). None of the formal definitions of floodplains include the word "coastal". However, as river systems approach coastal regions, river base levels approach sea level, and the rivers become influenced not only by stream flow, but also by coastal processes such as tides, waves, and storm surges. This complex interaction takes place near the governing water body, either open ocean, estuaries, or the Great Lakes.

The slope and width of the coastal plain[22] determine the size and inland extent of coastal influences on river systems. Coastal regions are periodically inundated by tides, waves, and surges. Therefore, a good working definition of a coastal floodplain, borrowing from the river floodplain definition, is any normally dry land area in coastal regions that is susceptible to being inundated by water from any natural source, including oceans (*e.g.*, tsunami run-up, coastal storm surge, relative sea-level rise) in addition to rivers, streams, and lakes.

Floodplains generally contain unconsolidated sediments, often extending below the bed of the stream or river. These accumulations of sand, gravel, loam, silt, or clay are often important aquifers; the water drawn from them is prefiltered compared to the water in the river or stream. Geologically ancient floodplains are often revealed in the landscape by terrace deposits, which are old floodplain deposits that remain relatively high above the current floodplain and often indicate former courses of rivers and streams.

Floodplains can support particularly rich ecosystems, both in quantity and diversity. These are called riparian zones or systems. Wetting of the floodplain soil releases an immediate surge of nutrients, both those left over from the last flood and those from the rapid decomposition of organic matter that accumulated since the last flood. Microscopic organisms thrive and larger species enter a rapid breeding cycle. Opportunistic feeders (particularly birds) move in to take advantage. The production of nutrients peaks and falls away quickly; however, the surge of new growth endures for some time. This makes

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[22] A coastal plain is an area of flat, low-lying land next to the coast and separated from the interior by other landscape features.

floodplains particularly valuable for agriculture. Markedly different species grow in floodplains than grow outside of floodplains. For instance, riparian trees species (that grow in floodplains) tend to be very tolerant of root disturbance and tend to be very quick-growing, compared to tree species growing some distance from a river.

8.2 WHAT ARE THE POTENTIAL IMPACTS OF SEA-LEVEL RISE ON COASTAL FLOODPLAINS?

Assessing the impacts of sea-level rise on coastal floodplains is an inherently complicated task, because the impacts are coupled with impacts of climate change on other coastal and riverine processes and can be offset by human actions to protect life and property. Impacts may range from extended periods of drought and lack of sediments to extended periods of above-normal freshwater runoff and associated sediment loading. Some seasons may have higher than normal frequency and intensity of coastal storms and flooding events. Impacts will also depend on construction and maintenance of dikes, levees, waterways, and diversions for flood management.

Assuming no human intervention for the moment, the hydrologic and hydraulic characteristics of coastal and river floodplain interactions will change with sea-level rise. Fundamentally, the floodplains will become increasingly subjected to inundation. In tidal areas, the tidal inundation characteristics of the floodplain may change with the range of tide and associated tidal currents increasing with sea-level rise. With this inundation, floodplains would be subjected to increased coastal erosion from waves, river and tidal currents, and storm induced and tidal flooding. Upland floodplain boundaries would be subject to horizontal movement. Coastal marshes could be subject to vertical buildup or inundation.

In a state study for Maine (Slovinsky and Dicksson, 2006), the impacts on coastal floodplains were characterized by marsh habitat changes and flooding implications. The coast of Maine has a significant tidal range (8.6 to 22.0 feet, spring range), so impacts of flooding are coupled with the timing of storms and the highest astronomical tides[23] on top of sea-level rise. The Maine study found increasing susceptibility to inlet and barrier island breaches where existing breach areas were historically found, increased stress on existing flood-prevention infrastructure (levees, dikes, roads), and a gradual incursion of low marsh into high marsh with development of a steeper bank topography. Increased overwash and erosion were the impacts on the outer coast.

In addition, the effects of significant local or regional subsidence[24] of the land will add to the effects of sea-level rise on coastal floodplains. Regional examples with significant subsidence are the Mississippi River Delta region and the area around the entrance to the Chesapeake Bay. Sea-level rise could also increase salt-water intrusion into the existing freshwater or brackish floodplains and could change the extent or reach of the saltwater wedge up into tidal river systems.

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[23] The tides that result from the gravitational influence of the moon and sun on ocean waters; the highest astronomical tide is the highest level expected to occur under average meteorological conditions (*i.e.*, not extreme conditions) and under any combination of astronomical conditions.

[24] Subsidence is the lowering of land-surface elevation as a result of changes that take place underground, including human activities such as pumping of water, oil, and gas from underground reservoirs.

8.3 WHAT ARE THE POTENTIAL EFFECTS OF SEA-LEVEL RISE ON THE IMPACTS OF COASTAL STORMS?

The potential interaction among increased sea levels, storm surges, and upstream rivers is very complex. Storm surge can travel several hundred kilometers up rivers at more than 40 km per hour, as on the Mississippi River, where storm surge generated by land-falling hurricanes in the Gulf of Mexico can be detected on stream gauges upstream of Baton Rouge, Louisiana, more than 480 km from the mouth (Reed and Stucky, 2005).

Both NWS (for flood forecasting) and FEMA (for insurance purposes and land use planning) recognize the complexity of these interactions. In cases like this, the NWS uses both a hurricane storm surge model (the Sea, Lakes, and Overland Surge from Hurricanes (SLOSH) model, Jelesnianski *et al.*, 1992) and a riverine hydraulic model (the Operational Dynamic Wave Model) to forecast effects of storm surge on river stages on the Mississippi River. The two models are coupled together so that the output of the storm surge model is the downstream boundary of the river model. This type of model coupling is needed to determine the effects of sea-level rise and storm surge on riverine systems. Other modeling efforts are starting to take into account river and coastal physical process interactions. The NWS also uses a two-dimensional hydrodynamic model (the Advanced Circulation Model or ADCIRC; Luettich *et al.*, 1992) on the Wacammaw River in South Carolina to predict effects of storm surge on river stages as far inland as Conway, 80 km from the Atlantic Ocean (Hagen *et al.*, 2004). These model coupling routines are becoming increasingly more common and have been identified as future research needs by such agencies as NOAA and the U.S. Geological Survey (USGS), as scientists strive to model the complex interactions between coastal and riverine processes. As sea level rises, these interactions will become ever more important to the way the coastal and riverine floodplains respond (Pietrafesa *et al.*, 2006).

8.3.1 Historical Comparison at Tide Stations

In a post-hurricane NOAA report (Hovis, 2004) on the observed storm tides of Hurricane Isabel, the potential effects of sea-level rise on maximum observed storm tides were assessed for four long -term tide stations in the Chesapeake Bay. The NOAA tide stations examined were Baltimore, MD, Annapolis, MD, Washington, DC, and Sewells Point, VA, which have records beginning in 1902, 1928, 1931, and 1927, respectively. Before Hurricane Isabel, the highest water levels reached at Baltimore, Annapolis, and Sewells Point occurred during the passage of an unnamed hurricane in August, 1933. At Washington, the 1933 hurricane caused the third highest recorded water level, surpassed only by river floods in October 1942 and March 1936. Hurricane Isabel caused water levels to exceed the August 1933 levels at Baltimore, Annapolis and Washington by 0.14 m, 0.31 m, and 0.06 m, respectively. At Sewells Point, the highest water level from Hurricane Isabel was only 0.04 m below the level reached in August 1933. Zervas (2001) obtained sea-level trends for Baltimore, Annapolis, Washington, and Sewells Point of 3.12, 3.53, 3.13, and 4.42 mm/yr, respectively. Using these rates, the time series of monthly highest water level were adjusted for the subsequent sea-level rise up to the year 2003. The resulting time series summarized in the tables below indicate the highest level reached by each storm as if it had taken place in 2003, thus allowing an unbiased comparison of storms. Elevations are relative to the tidal datum of Mean Higher High Water (MHHW).

Table 8.1 Five Highest Water Levels for Baltimore, MD in meters above MHHW.

Absolute water level **Corrected for sea-level rise to 2003**

Hurricane Isabel	Sep 2003	1.98	Hurricane	Aug 1933	2.06
Hurricane	Aug 1933	1.84	Hurricane Isabel	Sep 2003	1.98
Hurricane Connie	Aug 1955	1.44	Hurricane Connie	Aug 1955	1.59
Hurricane Hazel	Oct 1954	1.17	Hurricane	Aug 1915	1.38
Hurricane	Aug 1915	1.11	Hur. Hazel	Oct 1954	1.32

Table 8.2 Five Highest Water Levels for Annapolis, MD in meters above MHHW.

Absolute water level. **Corrected for sea-level rise to 2003**

Hurricane Isabel	Sep 2003	1.76	Hurricane Isabel	Sep 2003	1.76
Hurricane	Aug 1933	1.45	Hurricane	Aug 1933	1.69
Hurricane Connie	Aug 1955	1.08	Hurricane Connie	Aug 1955	1.25
Hurricane Fran	Sep 1996	1.04	Hurricane Hazel	Oct 1954	1.19
Hurricane Hazel	Oct 1954	1.02	Hurricane Fran	Sep 1996	1.06

Table 8.3 Five Highest Water Levels for Washington, DC in meters above MHHW.

Absolute water level **Corrected for sea-level rise to 2003**

Flood	Oct 1942	2.40	Flood	Oct 1942	2.59
Flood	Mar 1936	2.25	Flood	Mar 1936	2.46
Hurricane Isabel	Sep 2003	2.19	Hurricane	Aug 1933	2.35
Hurricane	Aug 1933	2.13	Hurricane Isabel	Sep 2003	2.19
Flood	Apr 1937	1.70	Flood	Apr 1937	1.91

Table 8.4 Five Highest Water Levels for Sewells Point, VA in meters above MHHW.

Absolute water level **Corrected for sea-level rise to 2003**

Hurricane	Aug 1933	1.60	Hurricane	Aug 1933	1.91
Hurricane Isabel	Sep 2003	1.56	Hurricane Isabel	Sep 2003	1.56
Winter Storm	Mar 1962	1.36	Winter Storm	Mar 1962	1.54
Hurricane	Sep 1936	1.21	Hurricane	Sep 1936	1.50
Winter Storm	Feb 1998	1.16	Hurricane	Sep 1933	1.33

8.3.2 Typical 100-Year Storm Surge Elevations Relative to MHHW within the Multi-State Area

A useful application of long-term tide gauge data is a return frequency analysis of the monthly and annual highest and lowest observed water levels. On the east coast and Gulf of Mexico, hurricanes and winter storms interact with the wide, shallow, continental shelf to produce large extreme storm tides. On the west coast, the heights of extreme events, such as those caused by El Niño-related storms, are limited by the narrowness of the continental shelf. A generalized extreme value (GEV) distribution can be derived for each station after correcting the values for the long-term sea-level trend (Zervas 2005). Theoretical exceedance probability statistics give the 99%, 50%, 10%, and 1% annual exceedance probability levels shown in Figures 8.1 and 8.2. These levels correspond to average storm tide return periods of 1, 2, 10, and 100 years. The first figure (Figure 8.1) shows exceedance elevations above local mean sea level (LMSL) at each station relative to the 1983-2001 National Tidal Datum Epoch (NTDE). The second figure (Figure 8.2) is the same except the elevations are relative to Mean Higher High Water (MHHW) computed for the same 1983-2001 NTDE.

In the Figure 8.1, the elevations relative to LMSL are highly correlated with the range of tide at each station (Willets Point has a very high range of tide (2.2m)), except for the 1% level at Washington DC which is susceptible to high flows of the Potomac River. As expected due to their varying locations, the 1% elevation level varies the most among the stations of the mid-Atlantic Region. Figure 8.2 shows a slightly geographically decreasing trend in the elevations from north to south.

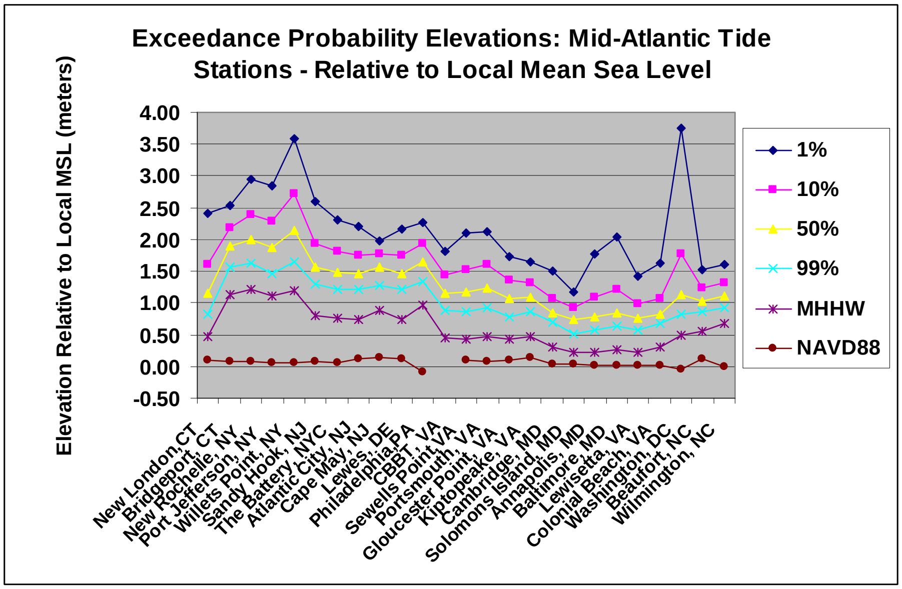


Figure 8.1 Exceedance Probabilities for Mid-Atlantic Tide Stations Relative to Local Mean Sea Level.

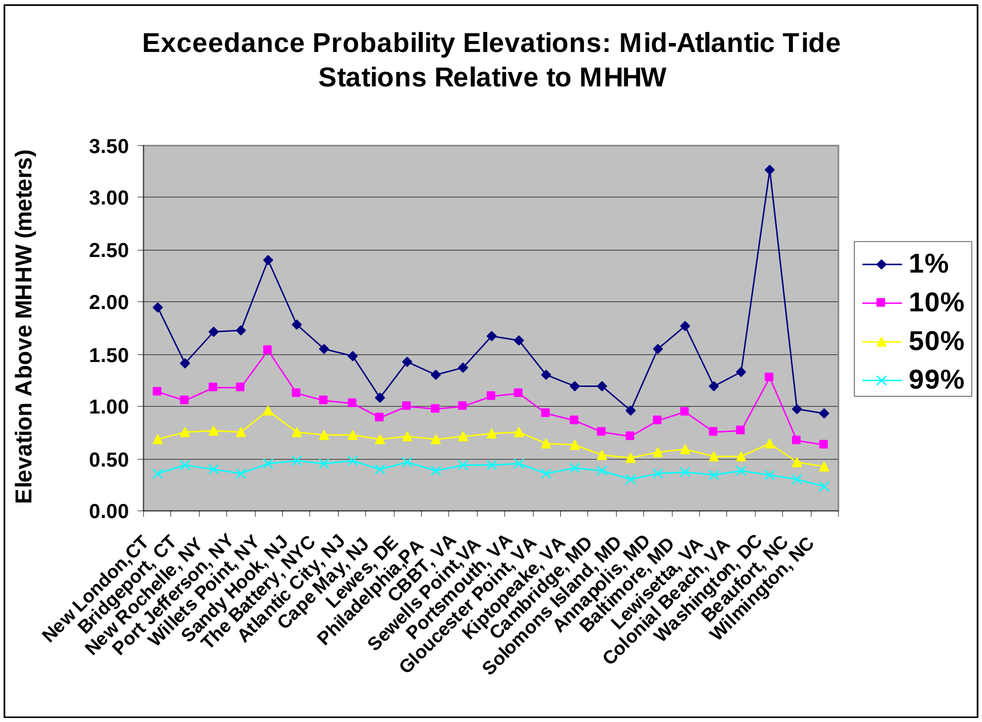


Figure 8.2 Exceedance Probabilities at Mid-Atlantic Tide Stations relative to MHHW.

8.4 FLOODPLAIN MAPPING AND SEA-LEVEL RISE

Given the potential for increased flooding with rising sea levels, there is a need for floodplain maps that take sea-level rise into account. FEMA (1991) performed a study in 1991 (Box 8.1) in which costs for remapping were estimated at $150,000 per county or $1,500 per map panel. With an estimated 283 counties (5,050 map panels) potentially affected, the total cost of restudies and remapping was estimated at $30 million in 1991 dollars. These estimated figures assume that maps and studies are revised on a regular basis and equates to about $46.5 million in 2006 dollars (FEMA, 1991). More current estimates have not been completed to reflect advancements in mapping capabilities."

Tidally and storm surge affected river models require the downstream boundary starting water surface elevation to be the “1 percent annual chance” Base Flood Elevation (BFE) from an adjacent coastal study. If the coastal study BFE is raised by 1 foot or even 3 feet because of sea-level rise, the river study flood profile will be changed as well and this will ultimately affect the resulting Flood Insurance Rate Maps (FIRMs) that are published. This is a complicated issue and points out the fact that simply raising the coastal BFEs to estimate a new 1 percent annual chance floodplain is not taking into account the more complex hydraulics that will have undetermined effects on the upstream 1 percent annual chance floodplains as well. In addition, the 1991 study does not factor in the complexity of different tidal regimes that would be occurring because of an increased sea level and how that would affect the geomorphology of the floodplains.

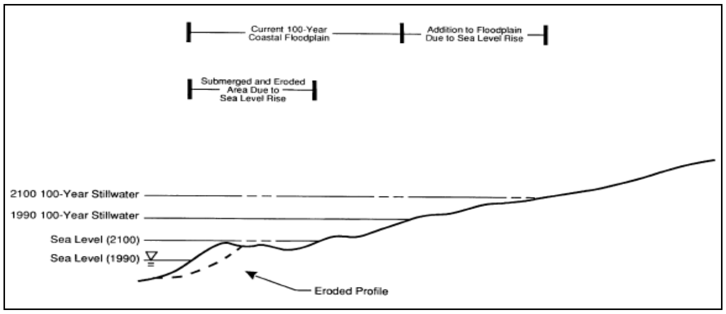
A recent historical overview of FEMA’s Coastal Risk Assessment process is found in Crowell, Hirsch, and Hayes (2007) and includes overviews of the FEMA map modernization program, revised coastal guidelines, and FEMA’s response to recommendations of a Heinz Center report *Evaluation of Erosion Hazards* (Heinz Center, 2000).

Box 8.1 1991 FEMA Study on Projected Impact of Sea-level Rise

In 1989, Congress authorized and signed into law a study of the impact of sea-level rise on the National Flood Insurance Program (NFIP). The legislation directed FEMA to determine the impact of sea-level rise on flood insurance rate maps and project the economic losses, associated with estimated sea-level rise. The final report was delivered to Congress in 1991. The primary objectives of the study were to quantify the impacts of relative sea-level rise on 1) the location and extent of the U.S. coastal floodplain, 2) the relationship between the elevation of insured properties and the 100-year BFE, and 3) the economic structure of the NFIP.

In the 1991 study FEMA used both a 1-foot and 3-foot increase in relative sea level by 2100 based on previous studies (Titus and Green, 1989; IPCC, 1990). For both scenarios it was assumed that the current 100-year floodplain would increase by the exact amount as the change in sea level. This assumption was made to simplify some of the second order dynamic interactions such as the effect of the increased water depth due to sea-level rise on storm surge, and how sea-level rise will propagate up tidally affected rivers to a point where sea-level rise will no longer affect water flood levels. The study did not attempt to model the effects of sea-level rise in upstream river areas, a task that would have required site-specific hydraulic calculations.

For each coastal county a still water flood level (SWFL) was estimated, as were the V-zone flood level, the estimated area covered by the Special Flood Hazard Area (SFHA), and the fraction for which coastal V zones were estimated. The equation divides the amount of sea level rise by the SWFL and multiplies the result by the current floodplain area. Another assumption was that shoreline erosion and inundation due to sea-level rise, causing a net loss in floodplain, would cancel out the net gain in floodplain associated with rising flood levels. Box Figure 8.1 shows this relationship. Coastal areas where shore protection measures such as beach nourishment and construction of groins, levees, bulkheads, and sea walls are used would obviously reduce the amount of land lost to sea-level rise and thus cause some overestimation in the amount of floodplain lost because of rising sea levels using this method (Titus, 1990).



Box Figure 8.1 Schematic diagram of the effect of sea level rise on the 100-year coastal floodplain (FEMA, 1991).

The study notes that these numbers differ slightly from previous sea-level rise studies (Titus and Green, 1989) but supports the conclusion from both studies that the size of the floodplain will not increase as sea level rises because of the balancing of land lost through submergence. Box Tables 8.1a and 8.1b show the breakdown of impacted land areas for 1-foot rise and 3-foot rise by regions in A zones vs. V zones (see Box 8.1 for definitions of A zones and V zones).

Box Table 8.1a Area Affected by a 1-foot Rise in Sea Level by 2100 (square miles)

Area	**Floodplain 1990**			**Additional Area Affected Due to Sea level rise**		
	A-Zone	**V-Zone**	**Total**	**A-Zone**	**V-Zone**	**Total**
Entire U.S.	16160	3335	19495	1806	362	2168
Mid-Atlantic	4163	344	4507	545	44	589

Box Table 8.1b Area Affected by a 3-foot Rise in Sea Level by 2100 (square miles)

Area	**Floodplain 1990**			**Additional Area Affected Due to Sea level rise**		
	A-Zone	**V-Zone**	**Total**	**A-Zone**	**V-Zone**	**Total**
Entire U.S.	16160	3335	19495	5423	1081	6504
Mid-Atlantic	4163	344	4507	1633	134	1767

The total land area nationwide estimated by the study to be in a floodplain was close to 19,500 square miles, with approximately 2,200 square miles added to the floodplain for a 1-foot rise scenario and an additional 6,500 added for a 3-foot rise. These numbers do not account for subsidence rates in the Louisiana region. For the mid-Atlantic region the floodplain was estimated to be about 4,500 square miles, with 590 square miles added to the floodplain for a 1-foot rise and 1,770 added for a 3-foot rise.

The study also estimated the number of households in the coastal floodplain. Based on the 1990 Census, 2.7 million households were currently in the 100-year floodplain, 624,000 of which were in the mid-Atlantic region. For the 1-foot and 3-foot rise scenarios respectively, 5.6 million and 6.6 million households would be in the floodplain, with 1.1 million and 1.3 million in the mid-Atlantic region. Much of this increase is from projected population and development increase in coastal areas and not just from sea level rise, with an estimated increase of 2.4 million households nationally and 382,000 in the mid-Atlantic region.

This projected rise in population and sea-level rise scenarios would increase the expected annual flood damage by 2100 for an average NFIP insured property by 36–58 percent for a 1-foot rise and 102–200 percent for a 3-foot rise. This would lead to actuarial increases in insurance premiums for building subject to sea-level rise of 58 percent for a 1-foot rise and 200 percent for a 3-foot rise. The study estimated that a 1-foot rise would gradually increase the expected annual NFIP flood losses by $150 million by 2100. Similarly, a 3-foot rise would gradually increase expected losses by about $600 million by 2100. Per policy holder, this increase would equate to $60 more than in 1990 for the 1-foot rise and $200 more for the 3-foot rise.

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8.5 STUDIES OF FUTURE COASTAL CONDITIONS AND FLOODPLAIN MAPPING

8.5.1 FEMA Coastal Studies

Currently communities can opt to use future conditions hydrology for mapping per FEMA rules established in December 2001 (Crowell, 2008). Showing future conditions flood boundaries has been accommodated for some communities in Flood Map Modernization, but not routinely provided. As outlined in the December 2001 rules, showing a future condition boundary in addition to the other boundaries normally shown on a DFIRM is acceptable. From the perspective of FEMA, showing a future condition boundary is for informational purposes only and carries with it no additional requirements for floodplain management, nor would insurance be rated using a future condition boundary. The benefits relate to the fact that future increases in flood risk can lead to significant increases in both calculated and experienced flood heights resulting in serious flood losses as well as loss of levee certification and loss of flood protection for compliant post-FIRM structures. Providing this information to communities may lead to them taking coordinated watershed wide actions to manage for or otherwise mitigate these future risks. The current coastal study process is discussed by Honeycutt and Mauriello (2005).

FEMA recognizes that there has been an increase in losses from coastal storms. Hurricane Katrina in 2005 illustrated this all too clearly, racking up the most losses of any U.S. natural disaster. This fact, coupled with the fact that new developments in modeling and mapping technology have allowed for more accurate flood hazard assessment over the past few years and that populations at risk are growing in coastal areas, has caused FEMA to develop a new national coastal strategy. This strategy consists of assessing coastal FISs on a national scope, and developing a nationwide plan for improved coastal flood hazard identification. The assessment will prioritize regional studies, look at funding allocations, and develop timelines for coastal study updates.

Crowell, Hirsch, and Hayes (2007) identify a need for a tide gauge analysis for FEMA Region III, which encompasses the Mid-Atlantic states similar to new studies being done currently on Chesapeake Bay by Maryland. Each coastal region is being evaluated and new guidelines and specifications are being developed by FEMA for future coastal restudies, the first of which is for the Pacific coast region. These guidelines outline new coastal storm surge modeling and mapping procedures that take new modeling technology into account and allow for new flooding and wave models to be used for generating coastal BFEs.

To aid in ongoing recovery and rebuilding efforts, FEMA initiated short-term projects in 2004 and 2005 to produce coastal flood recovery maps for the areas that were most severely affected by Hurricanes Ivan, Katrina, and Rita. The Katrina maps, for example, show high water marks surveyed after the storm, an inundation limit developed from these surveyed points, and FEMA’s Advisory Base Flood Elevations (ABFEs) and estimated zone of wave impacts.

These maps and associated ABFEs (generated for Katrina and Rita only) were based on new flood risk assessments that were done immediately following the storms to assist communities with rebuilding. The recovery maps provided a graphical depiction of ABFEs and coastal inundation associated with the observed storm surge high water mark values, in effect documenting the flood imprint of the event to be used in future studies and policy decisions. Adherence to the ABFEs following Katrina affected eligibility for certain FEMA-funded mitigation and recovery projects. They will be used until the FISs are updated for the Gulf region and are available as advisory information to assist communities in rebuilding efforts.

Future coastal studies may be affected by recent legislation that was submitted to Congress in late spring 2006 as part of the Flood Insurance Reform and Modernization Act of 2006 (109th Congress, 2006). The bill calls for changes to the way FEMA and the NFIP approach coastal studies and make recommendations that FEMA include coastal erosion information on the FIRMs. The Senate version calls for a description of coastal erosion areas to be included in new FISs and that any relevant information from NOAA or USACE on coastal inundation should be included on the maps as well.

FEMA cannot require the use of future conditions data based on planned land-use changes or proposed development for floodplain management or insurance rating purposes unless statutory and regulatory changes to the NFIP are made. In addition, using projected coastal erosion information for land-use management and insurance rating purposes through the NFIP would also require a legislative mandate and regulatory changes.

8.5.2 How Do We Capture or Map Potential Impacts of Sea-level Rise on Coastal Floodplains?

The concept of going above and beyond the current regulations to provide additional hazards information other than BFEs and the 1 percent annual chance flood (coastal erosion, and storm surge inundation potential) is something that the Association of State Floodplain Managers (ASFPM) has been advocating through their No Adverse Impact (NAI) program (Larson and Plasencia, 2002). No adverse impact floodplain management is essentially a “do no harm” policy based on the concept that the actions of any community or property owner should not adversely affect others. This concept was first developed by ASFPM for riverine floodplains and focused on exceeding the minimum requirements of federal programs such as the NFIP to provide vision, principles, and tools through which a community can effectively and permanently manage its land area. NAI helps a community or state achieve disaster resilience, which, in turn, contributes to long-term sustainability. An NAI toolkit was developed that outlines a strategy for communities to implement an NAI approach to floodplain management using these three basic building blocks (ASFPM, 2003).

The Basic Level

The basic level includes what is usually done to meet the minimum requirements of the NFIP or other state or federal requirements for managing floodplains and coastal zones and minimizing flood losses. However, even when rigorously implemented, these basic standards are not effective in all situations and can result in unintended negative consequences.

The Better Level

The better level adds floodplain management activities that are more effective than those of the basic level in protecting flood-prone properties, usually because they are tailored to specific situations, provide protection from larger floods, allow for margins of error, serve multiple purposes, require more diligent enforcement, or provide a combination of these. Even at this level, however, flood loss reduction measures tend not to take into account the effects that may be occurring elsewhere in the watershed or that may accrue after many years.

The NAI Level

The NAI level assumes that the basic activities are implemented and appropriate activities from the better level are used as well. But in addition, tools and techniques are employed that not only are the most effective at reducing flood losses but also prevent direct or indirect negative consequences for the surrounding landscape and watershed, nearby private property, and other communities. Equally important, the NAI techniques keep flood hazards and related problems from worsening in the future. The ASFPM recommends the NAI-level approaches because of their ability to minimize flood losses, preserve the viability of the ecosystem, foster disaster resilience, withstand legal challenges, and forestall increases in the problems in future years.

A coastal version of the NAI toolkit, called the Coastal NAI Handbook, is currently in press. It outlines this process for communities in coastal floodplains. This handbook illustrates how a community in a coastal floodplain can implement NAI concepts using the building blocks for several areas, including hazards identification and mapping, planning, regulation development standards, mitigation, infrastructure, emergency services, public outreach, and education.

8.6 HOW ARE COASTAL RESOURCE MANAGERS COPING WITH SEA-LEVEL RISE AND WHAT KIND OF ISSUES ARE THEY FACING?

8.6.1 Studies by the Association of State Floodplain Managers

The Association of State Floodplain Mangers (ASFPM) recently completed a study *National Flood Programs and Policies in Review–2007* that contains a broad spectrum of recommendations for improving the management of the nation's floodplains (ASFPM, 2007). In a discussion of the significant changes in social, environmental, and political realities and their impact on floodplain management, a changing climate was identified as one of the four major challenges.

> These current and expected (Climate) changes have widespread implications for the flood protection of human populations; their accompanying housing, commerce, and infrastructure; agricultural lands and production; and sensitive ecosystems throughout the planet. Further, climate change is altering the historic record of floods and storms that has formed the basis for the design of various protective measures, creating uncertainty about the adequacy of those measures to protect us from the storms that are expected in the future.

This same ASFPM document makes recommendations for strong federal leadership. Some of these are found in the following Box 8.2

Box 8.2

- USGS and NOAA should support and participate in domestic and international programs for the collection and analysis of data on climate change.
- Joint evaluation of populations centers should be conducted by NOAA's Sectoral Applications Research Program (SARR), the Department of Housing and Urban Development, and FEMA. This should include scenario-based analysis of the fragility of these areas in the face of a changing climate, the expected types and quantity of damage, its impact on the national economy, and responsible modifications to current management strategies.
- When states and communities update their all-hazard plans, FEMA should require that they include an evaluation of the impact of future climate change on their locales, including the potential impacts of sea level rise, extremes in precipitation and runoff, and more severe hurricanes —and include recommendations for adaptation as appropriate.
- The Office of the President should issue an Executive Order directing federal agencies to consider climate change, including adaptations to it, in all their planning, permitting, design, and construction.

Under data and technology for hydrology:

- Future-conditions and cumulative impacts should be incorporated into the identification, mapping, and regulation of flood risk areas under the NFIP
- .The future conditions should account for changes in the watershed, its floodplain, and its hydrology; climate change and variability, including sea level rise; subsidence; and other similar phenomena that alter future flood risk.

And under recommendations for dealing with coastal hazards:

- The closer buildings are sited to the water, the more likely they are to be affected by flooding, wave action, erosion, scour, debris impact, over wash, and high winds, which tend to be stronger along the coast. Repeated exposure to these hazards —even if the buildings are designed to reduce those impacts —leads to increased long-term costs for maintenance and damage repair, as well as to higher insurance rates. Simply siting buildings back a set distance from the water's edge allows for the natural protective systems to do their work and absorb or diminish wave impacts and other coastal energies.
- A national policy for setbacks for erosion, sea level rise, and other coastal hazards is needed. One option is that the NFIP require (or at least provide Community Rating System credit for) construction setbacks that account for the coastal conditions that are expected to exist 100 years into the future

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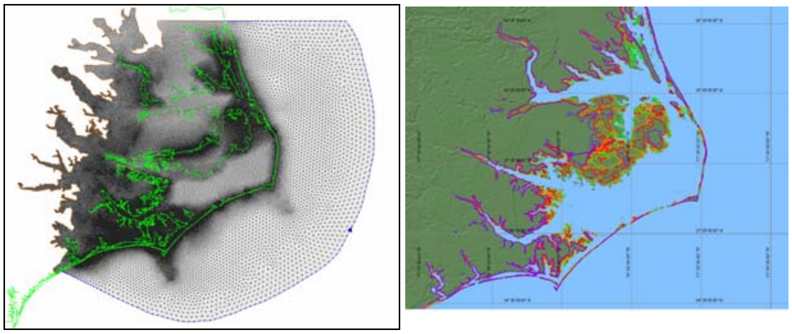
8.6.2 Other Federal Agency Coastal Flooding Studies

Other federal Agencies, such as NOAA, have been sponsoring applied research programs to bring into operations an integrated approach to understanding the effects of sea-level rise. One such study on the ecological effects of sea-level rise is discussed in the Box 8.3 below.

Box 8.3

An ongoing NOAA sponsored study on the ecological effects of sea-level rise is just one example of the type of integrated applied research that will be required to fully describe the effects of sea-level rise in the coming century. It incorporates and integrates features including high resolution data of the littoral zone, geography, ecology, biology and coastal process studies in a region of concern. A complete overview of the NOAA program can be found at:
http://www.cop.noaa.gov/stressors/climatechange/current/sea_level_rise.html
The North Carolina pilot study demonstrates the ability to design meaningful product delivery to the regional coastal manager that integrates capabilities in vertical reference frames, mapping, and modeling with targeted applied research led by the local academic marine science research community. The applied research program is designed to help coastal managers and planners better prepare for changes in coastal ecosystems due to land subsidence and sea level rise. Starting with southern Pamlico Sound, North Carolina, the approach is to simulate projected sea-level rise using a coastal flooding model that combines a hydrodynamic model of water levels with a high resolution digital elevation model (DEM). When completed, the coastal flooding model will be used to simulate long-term rises in water levels. Sub-models will then be developed to forecast ecological changes in coastal wetland and forested areas and these will be integrated with the coastal flooding model. The final goal of the program is to produce mapping and modeling tools that allow managers and planners to see projected shoreline changes and to display predictions of ecosystem impacts. Using these ecological forecasts, proactive mitigation will be possible.



Box Figure 8.3 The Coastal Flooding Model grid and one preliminary result of shoreline change due to various sea-level rise scenarios. **End of text box********

8.6.3 Other Floodplain Manager Activities

In a discussion of effects of sea-level rise on the National Flood Insurance Program, Hudgens (1999) suggested that a community's historical land subsidence and erosion rates as well as the area's projected rate of sea-level rise be incorporated on revised or new flood insurance rate maps. When FEMA remaps an area, they take into account subsidence and erosion as they exist at the time of the study. However, future conditions subsidence and erosion are not considered.

The discussion also recommended that the current mapped 1 percent annual chance floodplains be expanded to encompass the areas of land that would eventually become at risk of flooding after 30 years of sea-level rise, subsidence, or erosion. It called for FEMA to adapt the NFIP and the nation to the risks of sea-level rise and more extreme storms. To decrease the impact of near-future flood risks, FEMA could use the following adaptation techniques:

- Recalculate the 1 percent annual chance floodplains and BFEs to account for relative sea-level rise. Whenever a new study is done FEMA accounts for the relative sea-level rise that has occurred since the last study, however they do not account for future projected sea-level rise.
- Implement new regulations that would require subsidized property owners to flood-proof their homes
- Condition new development on the granting of "rolling easements" (Hudgens, 1999)
- Undertake education campaigns to communicate flood risks to stakeholders more effectively.

Slovinsky and Dickson (2006) recommend that FEMA flood insurance maps may need to be updated in the near future as changes in sea level become more dramatic, causing the 100-year floodplain to migrate upward and inland. Maryland has completed a comprehensive state strategy document in response to sea-level rise (MDDNR, 2000). Their analysis includes the following discussion:

> Issues associated with sea-level rise are significant with respect to the scope of Federal, State, and local management responsibilities under the NFIP. Flood Insurance Rate Maps (FIRMS) developed by FEMA designate areas of special flood risk and hazards, and insurance rates are calculated based on the level of flood risk associated with each designation. FIRMS and storm surge models prepared by FEMA, which guide State and local floodplain management efforts, do not evaluate future sea-level rise factors when establishing base flood elevations or storm surge risk zones. In fact, FEMA maps the 100-year floodplain as it exists at the time of the mapping effort. Future flood conditions, resulting from changes in land use, natural and human changes, or elevated flood levels due to sea-level rise, are not considered. To account for the subsequent uncertainty and degree of error present in the current Flood Insurance Rate Maps, MDDNR requires all communities to adopt standards that call for all structures in the non-tidal floodplain to be elevated one-foot above the 100-year floodplain elevation. However, MDDNR only encourages the adoption of the one-foot freeboard standard in the tidal floodplain. All coastal counties except Worcester, Somerset, and Dorchester, the three most vulnerable to exacerbated flooding due to sea-level rise, have adopted the one-foot freeboard standard. While one-foot of freeboard provides an added cushion of protection to guard against uncertainty in floodplain projections, it may not be enough in the event of two to three feet of sea-level rise. It is unlikely that the federal mapping efforts and floodplain management requirements will be modified to account for future sea-level rise. Therefore, State and local agencies need to take the initiative to address the potential for increased flooding due to sea-level rise.

FEMA does periodically update FIRMs and under the FEMA Map Mod and post-Map Mod, FEMA intends to assess the integrity of the flood hazard data by reviewing the flood map inventory every five years (Crowell, 2008). Where the review indicates the flood data integrity has degraded the flood maps, updates or new studies will be performed. Whenever FEMA updates or remap coastal areas, changes that had occurred in the interim due to sea-level rise will be accounted for.

8.6.4 Coastal Zone Management Act

Dramatic population growth along the coast brings new challenges to managing national coastal resources. Coastal and floodplain managers are challenged to strike the right balance between the growing population's desire to use coastal areas and a naturally changing shoreline. Challenges include protecting life and property from coastal hazards; protecting coastal wetlands and habitats while accommodating needed economic growth; and settling conflicts between competing needs such as dredged material disposal, commercial development, recreational use, national defense, and port development. Coastal land loss caused by chronic erosion has been an ongoing management issue in many coastal states, which have Coastal Zone Management (CZM) programs and legislation to mitigate erosion using a basic retreat policy. With the potential impacts of sea-level rise making current trends worse, coastal managers and lawmakers must now decide how or whether to adapt their current suite of tools and regulations to face prospect of an even greater amount of land loss in the decades to come.

The U.S. Congress recognized the importance of meeting the challenge of continued growth in the coastal zone and responded by passing the Coastal Zone Management Act (CZMA) in 1972. The act, administered by NOAA, provides for management of the nation's coastal resources, including the Great Lakes, and balances economic development with environmental conservation.

As a voluntary federal–state partnership, the CZMA is designed to encourage state tailored coastal management programs. It outlines two national programs, the National Coastal Zone Management Program and the National Estuarine Research Reserve System, and aims to balance competing land and water issues in the coastal zone, while estuarine reserves serve as field laboratories to provide a greater understanding of estuaries and how humans impact them. The overall program objectives of CZMA remain balanced to "preserve, protect, develop, and where possible, to restore or enhance the resources of the nation's coastal zone."

8.6.5 The CZMA and Sea-Level Rise Issues

The following are sections taken directly from the CZMA language and refer specifically to sea-level rise issues:

16 U.S.C. § 1451. Congressional findings (Section 302). The Congress finds that —
(l) Because global warming may result in a substantial sea-level rise with serious adverse effects in the coastal zone, coastal states must anticipate and plan for such an occurrence.

16 U.S.C. § 1452. Congressional declaration of policy (Section 303). The Congress finds and declares that it is the national policy —

(1) to preserve, protect, develop, and where possible, to restore or enhance, the resources of the Nation's coastal zone for this and succeeding generations;

(2) to encourage and assist the states to exercise effectively their responsibilities in the coastal zone through the development and implementation of management programs to achieve wise use of the land and water resources of the coastal zone, giving full consideration to ecological, cultural, historic, and esthetic values as well as the needs for compatible economic development, which programs should at least provide for —

> (B) the management of coastal development to minimize the loss of life and property caused by improper development in flood-prone, storm surge, geological hazard, and erosion-prone areas and in areas likely to be affected by or vulnerable to sea-level rise, land subsidence, and saltwater intrusion, and by the destruction of natural protective features such as beaches, dunes, wetlands, and barrier islands,
>
> (K) the study and development, in any case in which the Secretary considers it to be appropriate, of plans for addressing the adverse effects upon the coastal zone of land subsidence and of sea-level rise; and

(3) to encourage the preparation of special area management plans which provide for increased specificity in protecting significant natural resources, reasonable coastal-dependent economic growth, improved protection of life and property in hazardous areas,

including those areas likely to be affected by land subsidence, sea-level rise, or fluctuating water levels of the Great Lakes, and improved predictability in governmental decision-making.

8.6.6 The Coastal Zone Enhancement Program

The 1990 Reauthorization also established the Coastal Zone Enhancement Program (CZMA §309), which allows states to request additional funding to amend their coastal programs to support attainment of one or more coastal zone enhancement objectives. The program is designed to encourage states and territories to develop program changes in one or more of the following nine coastal zone enhancement areas of national significance: wetlands, coastal hazards, public access, marine debris, cumulative and secondary impacts, special area management plans, ocean/Great Lakes resources, energy and government facility citing, and aquaculture. Specifically from the CZMA 309 language:

6 U.S.C. § 1456b. Coastal Zone Enhancement Grants (Section 309)

(a) “Coastal zone enhancement objective” defined: For purposes of this section; the term “coastal zone enhancement objective” means any of the following objectives:

> (2) Preventing or significantly reducing threats to life and destruction of property by eliminating development and redevelopment in high-hazard areas, managing

development in other hazard areas, and anticipating and managing the effects of potential sea-level rise and Great Lakes level rise.

To help states target Section 309 Coastal Enhancement Program funds to identified program needs, every five years, coastal states and territories conduct an assessment of their coastal management activities within the nine enhancement areas. Through this self-assessment process, state coastal programs identify high-priority enhancement areas. In consultation with NOAA's Office of Ocean and Coastal Resource Management (OCRM), state coastal programs then develop five-year strategies to achieve changes (enhancements) to their coastal management programs within these high-priority areas. Program changes often include developing a new or revising an existing law, regulation or administrative guideline, developing or revising a special area management plan (SAMP), or creating a new program such as a coastal land acquisition or restoration program.

For coastal hazards, states base their evaluation on the following criteria:

1. What is the general level or risk from specific coastal hazards (*i.e.*, hurricanes, storm surge, flooding, shoreline erosion, sea-level rise, Great Lakes level fluctuations, subsidence, and geological hazards) and risk to life and property due to inappropriate development in the state?
2. Have there been significant changes to the state's hazards protection programs (*e.g.*, changes to building setbacks/restrictions, methodologies for determining building setbacks, restriction of hard shoreline protection structures, beach/dune

protection, inlet management plans, local hazard mitigation planning, or local post-disaster redevelopment plans, mapping/GIS/tracking of hazard areas)?

3. Does the state need to direct future public and private development and redevelopment away from hazardous areas, including the high hazard areas delineated as FEMA V-zones and areas vulnerable to inundation from sea and Great Lakes level rise?
4. Does the state need to preserve and restore the protective functions of natural shoreline features such as beaches, dunes, and wetlands?
5. Does the state need to prevent or minimize threats to existing populations and property from both episodic and chronic coastal hazards?

The following table is a summary of the state Coastal Program characterization of coastal hazards for the mid-Atlantic region (NOAA, 2006). Sea-level rise is characterized as a medium or high coastal hazard risk by each of the state coastal managers.

Table 8.5 Coastal Hazard Risk Characterization (H, M, L).

State	Hurricanes/ Typhoons	Flooding	Storm Surge	Episodic Erosion	Chronic Erosion	Sea Level Rise	Subsidence	Geologic Hazards	Nor'easters	Other
North Carolina	H	H	H	H	H	M	M	L		
Virginia	H	H	H	M	M	M	M	L	N/A	Shoreline Hardening — M
Delaware	M	H	H	M	H	M	L	L	N/A	Tsunamis — L
Maryland	M	H	H	H	H	H	M	L	N/A	Extra tropical Storms — H
New Jersey	M	H	H	H	H	H	M	L	H (extra-tropical storms)	

8.6.7 Coastal States Strategies

Organizations such as the Coastal States Organization have recently become more proactive in how coastal zone management programs consider adaptation to climate change, including sea-level rise (Coastal States Organization, 2007) and are actively leveraging each others experiences and approach to how best obtain baseline elevation information and inundation maps, to assess impacts of sea-level rise on social and economic resources and coastal habitats, and to develop public policy.

There have also been several individual state-wide studies on the impact of sea-level rise on local state coastal zones. Most notably see Z. Johnson (2000) for Maryland; Cooper, Beevers and Oppenheimer (2005) for New Jersey. Many states coastal management web-sites show an active public education program with regards to providing information on impacts of sea-level rise:

New Jersey: http://www.nj.gov/dep/njgs/enviroed/infocirc/sealevel.pdf
Delaware: http://www.dnrec.delaware.gov/Climate+change+shoreline+erosion.htm
Maryland: http://www.dnr.state.md.us/Bay/czm/sea_level_rise.html

8.6.7.1 Maryland's Strategy

One of the most progressive state designing strategies for dealing with sea-level rise is Maryland. The evaluation of sea-level rise response planning in Maryland and the resulting strategy document referenced in previous sections constituted the bulk of the States CZMA §309 Coastal Hazard Assessment and Strategy for 2000 – 2005 and again in their 2006 – 2010 Assessment and Strategy. Other mid-Atlantic states mention sea-level rise as a concern in their assessments, but have not developed a comprehensive strategy.

The Maryland strategy development, funded through CZM, included review of technology, data, and research; a comprehensive assessment of Maryland's vulnerability to sea-level rise; and an assessment of existing response capability. It was developed recognizing the need to begin advance planning and the recognition that management measures, programs, and policies were fragmented within the state for response to sea-level rise issues.

The strategy is comprised of four components, listed below, designed to build upon the others to achieve the desired outcome within a five-year time horizon. The cornerstone of the proposed strategy is designation of one or more staff within the Department of Natural Resources with expertise in sea-level rise planning to oversee implementation.

Outreach and Engagement: Engage the general public, State and local planners and elected officials in the process of implementing a sea-level rise response strategy.

Technology, Data and Research Support: Gain a better understanding of the regional impacts of sea-level rise and applicable policy response alternatives.

Critical Applications: Incorporate sea-level rise planning mechanisms into existing State and local management programs and on-going coastal initiatives.

> *Statewide Policy Initiatives*: Enhance, and where necessary, modify key State statues to remedy barriers and advance sea-level rise planning initiatives.

Implementation of the strategy is evolving over time. It is a process that requires a sizeable commitment of time and financial resources. However, this process is crucial to the State's ability to achieve sustainable management of its coastal zone. The State recognizes that a "do nothing" approach will lead to unwise decisions and increased risk over time. Moreover, the strategy states that planners and legislators should realize that the implementation of measures to mitigate impacts associated with erosion, flooding, and wetland inundation will also enhance the State's ability to protect coastal resources and communities whether the sea level rises significantly or not.

The report conclusion lists the concrete steps that the State is undertaking as well as a statement as to what is a stake in successful implementation of a strategy. Maryland is one of the first states to take the first proactive step towards addressing a growing problem by committing to implementation of this strategy by increasing awareness and consideration of sea-level rise issues in both public and governmental arenas. The strategy suggests that Maryland will achieve true success in planning for sea-level rise by establishing effective response mechanisms at the State and local levels. Innumerable social and environmental resources are at stake. Sea-level rise response planning is crucial to ensure future survival of Maryland's diverse and invaluable coastal resources.

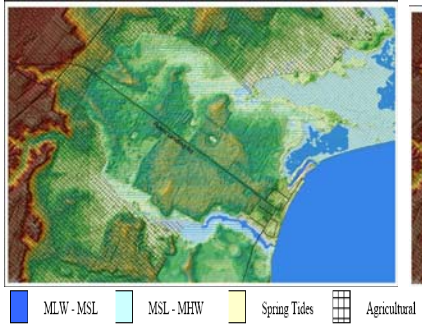
Since the release of Maryland's Sea-level Rise Response Strategy in 2000 (Johnson, 2000), the State has continued to progressively plan for sea-level rise. The strategy is being used to guide the State's current sea-level rise research, data acquisition, and planning and policy development efforts at both the State and local level. The State set forth a design vision for "resilient coastal communities" in its CZMA §309 Coastal Hazard Strategy for 2006 – 2010. The focus of the approach is to integrate the use of recently acquired sea-level rise data and technology based products into both state and local decision-making and planning processes. The State's Coastal Program is currently working one-on-one with local governments and other State agencies to: (1) build the capacity to integrate data and mapping efforts into land-use and comprehensive planning efforts; (2) identify specific opportunities (*i.e.*, statutory changes, code changes, comprehensive plan amendments) for advancing sea-level rise at the local level; and, (3) improve State and local agency coordination of sea-level rise planning and response activities (MDDNR, 2006)

In April 2007, Maryland's Governor, Martin O'Malley signed an Executive Order establishing a Commission on Climate Change (Maryland, 2007). The Commission is charged with advising both the Governor and Maryland's General Assembly on matters related to climate change and is charged with developing a Plan of Action that will address climate change on all fronts, including both the drivers and the consequences. Three working groups, comprised of a broad set of stakeholders and representatives of all levels of government, are working together to develop various components of the Plan of Action. The Adaptation and Response Working Group is responsible for developing a

Comprehensive Strategy for Reducing Maryland’s Climate Change Vulnerability. Efforts of this Working Group will further greatly the implementation of Maryland’s Sea-level Rise Response Strategy. The Adaptation and Response Working Group is developing specific strategies for reducing the vulnerability of the Maryland’s coastal, natural and cultural resources and communities to the impacts of climate change, with a initial focus being given to sea-level rise and coastal hazards (*e.g.*, shore erosion, coastal flooding). Another element of the Comprehensive Strategy will be the development of appropriate guidance to assist local governments with identifying specific measures (*e.g.*, local land use regulations and ordinances) to adapt to sea-level rise and increasing coastal hazards. The Comprehensive Strategy and Plan of Action, including recommendations and draft legislation, will be presented to the Maryland’s Governor and General Assembly in April 2008.

Box 8.4 A Maryland Case Study – Implications for Decision-makers: ***Worcester County Sea Level Rise Inundation Modeling***

The Maryland Department of Natural Resources (MDDNR) and USGS completed the development of a Worcester County Sea Level Rise Inundation Model in November 2006[1] . Taking advantage of recent LIDAR coverage for the county, a Digital Elevation Model(DEM) was produced as the base layer on which to overlay various sea-level rise scenarios modeled for three time periods: 2025, 2050, and 2100. The three scenarios were the historic rate of regional sea-level rise estimated from tide station records (3.1 mm/yr), the average accelerated rate of sea-level rise projected by the 2001 IPCC report, and the worst case scenario using the maximum projection of accelerated sea-level rise by the 2001 IPCC report (85-90 cm by 2100). The scenarios were applied to present day elevations of Mean Sea Level (MSL), Mean High Water (MHW), and Spring tides derived at local tide stations. Box Figures 8.4a and 8.4b below show a typical result for year 2100 using an accelerated rate of sea-level rise scenario from the IPCC 2001 Report. There is an agricultural block overlay that depicts the potential loss of agricultural land to sea level rise for Public Landing, MD.



Box Figure 8.4a Day Public landing.

Box Figure 8.4b Public landing at 2100 with current rate of sea level rise.

Box Figure 8.4c Sea level rise in 2100 using present day sea level trends coupled with a category 2 hurricane storm surge.

Development of the tool was completed in November 2006 and the results of the analyses will not be fully realized until it begins to be used by the Worcester County and Ocean City Planning and Emergency Management offices. Prior to final release of this study, the MDDNR and USGS study team met with Worcester County planners to discuss the model and how it could be applied to understanding of how existing structures and proposed growth areas could be affected by future sea-level rise. The tool is only now being used by county planners to make decisions on development and growth in the implementation of the March 2006 Comprehensive Plan for Worcester County. For Emergency Response Planning, the county is considering next steps and how to best utilize this tool. The county, as part of the Comprehensive Plan[2], already is directing future growth to outside of the category 3 hurricane storm surge zone and the sea level overlays will be used to perform risk assessments for existing and proposed development.

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Part III Overview: Preparing for Sea-Level Rise

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For at least the last four centuries, people have been erecting permanent settlements in the coastal zone of the Mid-Atlantic without regard to the fact that the sea is rising. Because the sea has been rising slowly and only a small part of the coast was developed, the consequences have been relatively isolated and manageable. Part I of this report suggests, however, that a 2 mm/yr acceleration of sea-level rise *could* transform the character of the mid-Atlantic coast, with a large scale loss of tidal wetlands and possible disintegration barrier islands - and a 7 mm/yr acceleration *probably would* cause such a transformation, although shore protection may prevent some developed barrier islands from disintegrating and low-lying communities from being taken over by wetlands.

For the last quarter century, scientific assessments have concluded that regardless of possible policies to reduce emissions of greenhouse gases, people will have to adapt to changing climate and rising sea level (NAS, 1983; Hoffman *et al.*, 1983; IPCC 1990, 1996, 2001, 2007). Adaptation assessments differentiate “reactive adaptation” from “anticipatory adaptation”. (Titus, 1990; Scheraga and Grambsch, 1998; Klein *et al.*, 1999; Frankhauser et al., 1999).

Part III focuses on what might be done to prepare for sea-level rise. Chapter 9 starts by asking whether preparing for sea-level rise is even necessary. In many cases, reacting later is more justifiable than preparing now, both because the rate and timing of future sea-level rise is uncertain and the additional cost of acting now can be high when the impacts are at least several decades in the future. Nevertheless, for several types of impacts, the cost of preparing now is very small compared to the cost of reacting later. Examples where preparing appears to be rationally justified include:

- *Coastal wetland protection*. It may be possible to reserve undeveloped lands for wetland migration, but once developed, it is very difficult to make land available for wetland migration. Therefore, it is far more feasible to aid wetland migration by setting aside land before it is developed, than to require development to be removed as sea level rises.
- *Some long-lived infrastructure*. Whether it is beneficial to design coastal infrastructure to anticipate rising sea level depends on economic analysis of the incremental cost of designing for a higher sea level now, and the retrofit cost of modifying the structure at some point in the future. Most long-lived infrastructure in the threatened areas is sufficiently sensitive to rising sea level to warrant at least an assessment of the costs and benefits of preparing for rising sea level.
- *Floodplain management*. Insurance works best when premiums reflect actual risk. Even without considering the possibility of accelerated sea-level rise, the National Academy of Sciences and a FEMA-supported study by the Heinz Center recommended to Congress that insurance rates should reflect the changing risks resulting from coastal erosion. Rising sea level increases the potential disparity between rates and risk.

Chapter 10 discusses organizations that are preparing for a possible acceleration of sea-level rise. The chapter is short because few organizations responsible for managing coastal resources vulnerable to sea-level rise have modified their activities. Most of the best examples of preparing for the environmental impacts of sea-level rise are in New England, where several states have enacted policies to enable wetlands to migrate inland as sea-level rise. Ocean City (Maryland) is an example of a town considering future sea-level rise in its infrastructure planning.

Chapter 11 examines the institutional barriers that make it difficult to take the potential impacts of future sea-level rise into account for coastal planning. Although few studies (*e.g.*, U.S. Congress, 1993; Barth and Titus, 1984; Titus, 1990, 1998, 2001, 2004) have discussed the challenge of institutional barriers and biases in coastal decision making, their implications for sea-level rise are relatively straightforward:

- *Inertia and short-term thinking*. Most institutions are slow to take on new challenges, especially those that require preparing for the future rather than fixing a current problem.
- *The interdependence of decisions* reinforces institutional inertia. In many cases, preparing for sea-level rise requires a decision as to whether a given area will ultimately be given up to the sea, protected with structures and drainage systems, or elevated as the sea rises. Until communities decide which of those three pathways they will follow in a given area, it is difficult to determine which anticipatory or initial response measures should be taken.

- *Policies favoring protection of what is currently there*. In some cases, longstanding preferences for shore protection (as discussed in Chapter 5) discourage planning measures that foster retreat. Because retreat may require a greater lead time than shore protection, the presumption that an area will be protected may imply that planning in unnecessary. On the other hand, these policies may help accelerate the response to sea-level rise in areas where shore protection is needed.
- *Policies Favoring Coastal Development*. One possible response to sea-level rise is to invest less in the lands likely to be threatened. However, longstanding policies that encourage coastal development are a barrier to such a response. On the other hand, increasingly dense coastal development improves the ability to raise funds required for shore protection. Therefore, policies that encourage coastal development may be an institutional bias favoring shore protection, but they are not necessarily a barrier to responding to sea-level rise.

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Chapter 9. Implications for Decisions

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KEY FINDINGS

- The prospect of accelerated sea-level rise generally justifies examining the costs and benefits of taking adaptive actions. Determining whether and what specific actions are justified is difficult, due to uncertainty in the timing and magnitude of impacts, and difficulties in quantifying projected benefits and costs. Nevertheless, the literature has identified some cases where acting now is justified.
- Key opportunities for preparing for sea-level rise include coastal wetland protection, location and elevation of coastal homes, buildings and infrastructure, and examining whether and how changing risk due to sea-level rise is reflected in flood insurance rates.
- Incorporating sea-level rise into coastal wetlands programs can be justified because it is more effective to plan for the inland migration of tidal wetlands *before* people develop the dry lands onto which those wetlands would migrate, than afterwards. Possible tools include rolling easements, density restrictions, coastal setbacks, and vegetative buffers.
- Long-term shoreline planning is likely to save more than it costs; the more the sea ultimately rises, the greater the value of that planning.

Many decisions of everyday life in the coastal zone have little to do with the fact that the sea is rising. Some day-to-day decisions depend on *today's* water levels: Sailors, surfers, and fishermen all consult tide tables to decide when to go out. And the decision whether to evacuate during a storm may depend on how high the water is expected to rise above the normal level. The fact that the *normal* level of the sea is rising about 0.01 millimeters per day does not affect such short term decisions.

Sea-level rise can have an impact, however, on the outcomes of many decisions with long-term consequences. Even in some of those cases, the impacts of sea-level rise still would not warrant doing things differently today, because the impacts are far enough in the future that people will have ample time to respond in the future. For example, there is no need to anticipate sea-level rise in the construction of port facilities (NRC 1987). In other cases, the adverse impacts of sea-level rise can be substantially reduced by preparing soon.

The previous chapters discuss vulnerable private property and public resources threatened by sea-level rise including real estate, wetlands, and ecosystems, infrastructure (*e.g.*, roads, bridges, parks, playgrounds, industrial plants) and commercial buildings including hotels, casinos, and office buildings. The loss of habitats and ecosystems that support fishing and crabbing may result in the loss of those activities and the communities that depend on them. A continuing theme of previous chapters in this report is that some of these assets will be protected or preserved in their current locations, while others must move inland or be lost. This report examines some of the government policies that are, in effect, the current response to sea-level rise. This chapter discusses responses to sea-level rise that may be justified today.

This chapter describes the categories of decisions that may be sensitive, with a focus on the idea that preparing for sea-level rise is not worthwhile unless the expected present value of the benefits of preparing for sea-level rise is greater than the cost. It then examines five issues in greater detail: wetland protection, shore protection, long-lived structures, elevating homes, and floodplain management. The examples in this chapter focus on activities by governments and homeowners, rather than corporations. Most of the *available* studies have been funded by governments, with a focus either on improving government programs or providing risk communication and technical support to small property owners. Corporations engage in many of the activities discussed in this chapter; but we can not rule out the possibility that privately funded strategic assessments have identified other near-term decisions that are sensitive to sea-level rise.

Much of the discussion in this chapter reflects the basic assumption that decision makers, be they homeowners or corporations, have a well-defined objective for their interest in potentially vulnerable coastal resources. Where a well-defined objective can be stated, the principles of economics and risk management provide an appropriate and useful paradigm for thinking about decision making, and how decisions are affected by sea-level rise. Examples of such well-defined objectives might be maximizing return on an investment (for a homeowner) or maximizing overall social welfare (for a government). Certainly, non-economic factors may also be important in decision making - these could include emotions, perceptions, cultural values, or other difficult to characterize factors - but those factors are beyond what we can evaluate in this chapter. Specifically, in this chapter we use an economic framework to discuss how the prospect of rising sea level might alter certain decisions, such as nourishing a beach or erecting a protective structure, that are consistent with homeowners or governments pursuing a particular objective. See Box 9.1 for further details on the basic economic framework we adopt.

The discussion here is not directly tied to specific sea-level rise scenario, but it does consider a wide range of possible outcomes over time horizons that vary by decision from decades to centuries. As a result, the discussion implicitly acknowledges uncertainty about the future rate of sea-level rise. We also explicitly acknowledge uncertainty about the impacts of sea-level rise. The economic framework applied here, however, does not explicitly identify the extent to which decisions might be affected by sea-level rise. Instead, we reference a wide range of existing quantitative studies that are relevant to this topic.

START BOX HERE

Box 9.1 Conceptual Framework for Decision Making with Sea-Level Rise

Our conceptual framework for decision-making starts with the basic assumption that homeowners or governments with an interest in coastal resources seek to maximize the value of that resource to themselves (homeowners) or to the public as a whole (governments), over a long time horizon (on the order of 50 years or more). In each year, a coastal resource provides some value to its owner. In the case of the homeowner, a coastal property might provide rental income, or it might provide "imputed rent" that the owner derives from owning the home rather than renting a similar home. The market value of a property reflects an expectation that property will generate similar income over many years. Because income today is worth more than income in the future, however, the timing of the income stream associated with a property also matters (see explanation of "discounting" in the text).

The income a property provides over time, however, can be affected by risks to the property, including natural hazards. Even without sea-level rise, there are significant natural hazards that affect coastal resources - these include erosion, hurricane winds, and episodic flooding. All of these risks can cause damage - that damage can reduce the income the property produces, increase the costs of maintaining the property, or both. These "baseline" risks should be taken into account in estimating the value of the property today, to the extent they are known and understood by the owner and the market of potential buyers.

Sea-level rise changes the risks to coastal resources; in almost all cases, it increases existing risks. Investments can be made, however, to respond to and mitigate those changes in the risk of property damage. Decisions about those investments are the main topic of this chapter.

In an economic framework, investing in a response that mitigates coastal hazards will only be worthwhile if the cost of the investment (incurred in the short-term) is less than net expected returns (which accrue over the long-term). It follows logically that these investments are more likely to be judged worthwhile when: 1) there is a large risk of damage that will happen soon (and it can be effectively reduced); 2) there is a small cost to effectively reduce the risk; or 3) the investment shifts the risk to future years.

END BOX

9.1 DECISIONS WHERE PREPARING FOR SEA-LEVEL RISE IS WORTHWHILE

Sea-level rise justifies changing what we do today if the outcome from considering sea-level rise has an expected net benefit greater than the cost. This basic economic framework is expressed in Box 9.1: Conceptual Framework for Decision Making with Sea-Level Rise. Thus, as we consider decisions where sea-level rise justifies doing things differently, we can *exclude* from further consideration those decisions where either (a) the costs are large compared to the impacts we are considering or (b) the net benefits seem small or not necessarily positive. Few if any studies have analyzed the costs of preparing for sea-level rise. But it seems self-evident that preparing for a very small rise in sea level would not be worthwhile. Most of what we know about decisions sensitive to sea-level rise concern decisions whose consequences last decades or longer, during which time significant rise in sea level might occur. Those decisions include long-lived structures, land-use planning, and infrastructure decisions that may influence the location of development for centuries even if the structures themselves do not last a long time.

For what type of decision is there likely to be a net benefit from considering sea-level rise? Most analyses of this question have focused on cases where (1) the more sea level rises, the worse the impact; (2) the impacts are mostly in the future — and uncertain because the precise impact of sea-level rise is uncertain; and (3) if we prepare now, we will reduce the eventual adverse consequences.

The first step is to ask whether preparing now would be better than never preparing. If so, we can then investigate whether preparing now is also better than preparing during some future year. Preparing now to avoid possible effects in the future involves two key economic principles: uncertainty and discounting.

Uncertainty. Because projections of sea-level rise and its precise effects are uncertain, preparing now involves spending today for the sake of uncertain benefits. If sea level rises less than expected, then preparing now may prove — in retrospect — to have been unnecessary. And if sea level rises more than expected, whatever we do today may prove to be too little. This possibility tends to justify waiting to prepare later, if we think that a few years hence (a) we will know more and (b) the opportunity to prepare will be lost as time goes by[25]. To overcome this hurdle, either preparing now has to be fairly

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[25] An extensive economic literature on decision-making and planning under uncertainty, particularly where some effects are irreversible, is applicable here. A good summary of this literature, on the topic of "quasi-option value" can be found in Freeman (2003), page 250-251. Quasi-option value arises from the value of information gained by delaying an irreversible decision (*e.g.*, to retreat). In the sea-level rise context, it applies because in the current state the costs and benefits of choosing to retreat or protect are uncertain, and we can reasonably expect that uncertainty will narrow over time, and yield a value of information, as we observe rates of sea-level rise and develop enhanced technologies for more effectively protecting or retreating. Two of the more influential works in this area include Arrow and Fisher (1974) and Fisher and Hanemann (1987); an application to climate policy decisions is Ha-Duong (1998).

inexpensive, or the preparation has to be fairly "robust" (*i.e.*, work over a wide variety of outcomes). If protecting existing development is important, beach nourishment is an example of a robust way to prepare, because the sand will do some good toward offsetting shore erosion no matter how fast or slowly the sea rises.

Discounting. Discounting is a procedure by which economists determine the "present value" of something given or received at a future date (EPA, 2000, p. 33). A dollar today is preferred over a dollar in the future, even without inflation; so a future dollar must be discounted to make costs and benefits received in different years comparable. Economists agree that the appropriate way to discount is to pick an assumed annual interest rate and compound it year-by-year, just as interest compounds, and use the result to discount future dollars. The precise rate that one should use depends on who is making the decision — and there is ongoing discussion amongst economists regarding what the discount rate should be for the U.S. Government (EPA, 2000, Chapter 6).

Most of the decisions where preparing now has a positive net benefit appear to fall into at least one of three categories: (1) the impact of sea-level rise is large in the near-term relative to value of asset; (2) preparing now costs little compared to the magnitude of the possible impact; or (3) preparing now involves options that reallocate (or clarify) risk, for example, by establishing today that the eventual costs of sea-level rise will be borne by a property owner making a decision sensitive to sea-level rise, rather than by third parties not involved in the decision. We discuss each in turn.

9.1.1 Decisions that Address Large Near-term Impacts

If the near-term impact of sea-level rise is large enough, preparing now may be worthwhile. Such decisions might include:

- Beach nourishment to protect homes that are in danger of being lost if something is not done soon.
- Enhancing vertical accretion (build-up) of wetlands that are otherwise in danger of being lost in the near term.
- Elevating homes that are clearly below the expected flood level due to historic sea-level rise (often after they have been flooded once).
- Fortifying dikes to the elevation necessary to protect from current floods.

9.1.2 Decisions Where Preparing Now Costs Little

These response options can be referred to as “low regrets” and “no regrets,” depending on whether the cost is little or nothing. In such cases, the response measure makes sense even if the sea does not rise. Examples include:

- *Setting a new home back from the sea within a given lot.* Setting a home back from the water can push the eventual damages farther into the future, lowering their expected present value. Unlike the option of not building, this approach retains almost the entire value of using the property — especially if adjacent homes are also set back so that they do not block one’s waterfront view, provided that the lot is large enough to build the same house as one would have built without the setback requirement.
- *Building a new building with a higher floor elevation.* While elevating an existing home can be costly, building it a few feet higher may add little to the cost.

- *Designing new coastal drainage systems with larger pipes to incorporate future sea-level rise*. The retrofit of rebuilding a drainage system can be substantially more expensive than including larger pipes in the initial construction (Titus *et al.*, 1987).
- *Rebuilding roads to a higher elevation during routine reconstruction.* If a road will eventually be elevated, it is easier to do so when it is being rebuilt anyway.
- *Designing bridges and other major facilities.* As sea level rises, clearance under bridges declines, impairing navigation. Building the bridge higher is inexpensive compared with rebuilding it.

9.1.3 Options That Reallocate or Clarify Risks from Sea-Level Rise

Instead of imposing a cost today to avoid problems that may or may not come later, these approaches impose a cost later — but only if and when the problem emerges. The premise for these measures is that policies and practices encourage people to behave in a fashion that increases costs more than necessary. Changing the rules and expectations can avoid those costs. Long-term shoreline planning and rolling easements are two examples.

In some cases, people will logically invest more along eroding shores if they assume that the government will provide subsidized shore protection. (Box 9.2: Erosion, Shore Protection, and Coastal Property Values). The value to to a buyer of that government subsidy is capitalized into higher land prices, which can further encourage increased construction. If the assumption of future government action is wrong (*i.e.*, government does not provide shore protection), then prices can decline; and in extreme cases, people can lose their homes unexpectedly. People’s lives as well as their economic investments can be disrupted if the absence of shore protection does not become widely known until dunes or dikes fail and a community is destroyed. A policy that clearly enunciates that such an area will *not* be protected could lead people to strategically downscale the physical property[26] and avoid developing the strong emotional attachment to the sense of place at that location[27], in favor of those areas that actually will be protected. (Chapter 11 discusses this issue further.)

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Box 9.2 Erosion, Shore Protection Programs, and Property Values

Do government shore protection programs increase property values and encourage coastal development? Heinz Center (2000, p. 131-134) reported that along the Atlantic Coast, a house with a remaining lifetime of 10-20 years before succumbing to erosion is worth 20 percent less than a home expected to survive 200 years. Landry *et al.* (2003) also found that property values tend to be higher with wide beaches and low erosion risk. It would therefore follow that shore protection programs that widen beaches, decrease erosion risk, and lengthen a home's expected lifetime would increase property values. Nevertheless, estimates of the impact on property values are complicated by the fact that proximity to the shore increases the risk of erosion but also improves access and views of the water (Bin *et al.*, in press).

Empirical verification that shore protection increases development is even less. Cordes and Yezer (1998) modeled the impact on new building permit activity in coastal areas of shore protection activity in 42 coastal counties, including all of the counties with developed ocean coasts in New York, New Jersey, Maryland, and Virginia. They did not find a statistically relationship between shore protection and building permits. However they did find fewer building permits in areas where both flood insurance and shore protection are unavailable. The Heinz Center (200 p. 135) estimated that federal flood insurance and other government hazards programs had increased development densities about 30 percent over what it would otherwise be.

END BOX

Rolling easements either reallocate or clarify the risks of sea-level rise, depending on the pre-existing property rights of a given jurisdiction (Titus 1998). A rolling easement is any arrangement under which property owners have no right or expectation of holding back

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[26] Yohe *et al.* (1996) estimates the nationwide value of "foresight" regarding response to sea level rise at $20 billion, based largely on the strategic depreciation that foresight makes possible.

[27] Carol Farbotko (2005) argues that one can view Tuvalu as either a victim losing it's sense of place, or a potentially resilient culture that must adapt to sea level rise.

the sea if their property is threatened. In theory, such easements can be implemented either by regulation or as a special type of conservation easement[28]. In either case, they prevent property owners from holding back the sea but allow any other type of use and activity on the land. As the sea advances, the easement automatically moves or "rolls" landward. Because shoreline stabilization structures cannot be erected, sediment transport remains undisturbed and wetlands and other tidal habitat can migrate naturally. Similarly, there will always be dry or intertidal land for the public to walk along, preserving lateral public access to the shore.

Under a rolling easement, the property owner completely bears all of the risk of sea-level rise. Without a rolling easement, by contrast, along most shores property owners invest as if their real estate is sustainable, and then expend resources — or persuade governments to expend resources — to sustain the property. The overall effect of the rolling easement is that a community clearly decides to pursue retreat instead of shore protection in the future. This could also be done through a large-scale purchase of land now — but in that case there would be a large upfront cost as coastal land becomes unavailable for valuable uses.

Rolling easements, by contrast, do not prevent the land from being used for the next few decades while the land remains dry. (Even if the government purchases the rolling easement, the purchase price is a simple transfer of wealth.) The landward migration from the rolling easement should have lower eventual costs than a government buyout several

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[28] Another mechanism for allowing wetlands and beaches to migrate inland are setbacks, which prohibit development near the shore. Setbacks can often result in "takings" claims if a property is deemed undevelopable due to the setback line. By contrast, rolling easements place no restrictions on development and hence are not a taking. See, *e.g.*, Titus (1998).

decades hence (Titus, 1991). Property owners can strategically depreciate their property and make other decisions consistent with the eventual abandonment of the property, efficiently responding to information on sea-level rise as it becomes available. Figure 9.1 shows how a rolling easement might work over time in an area already developed when rolling easements are obtained.

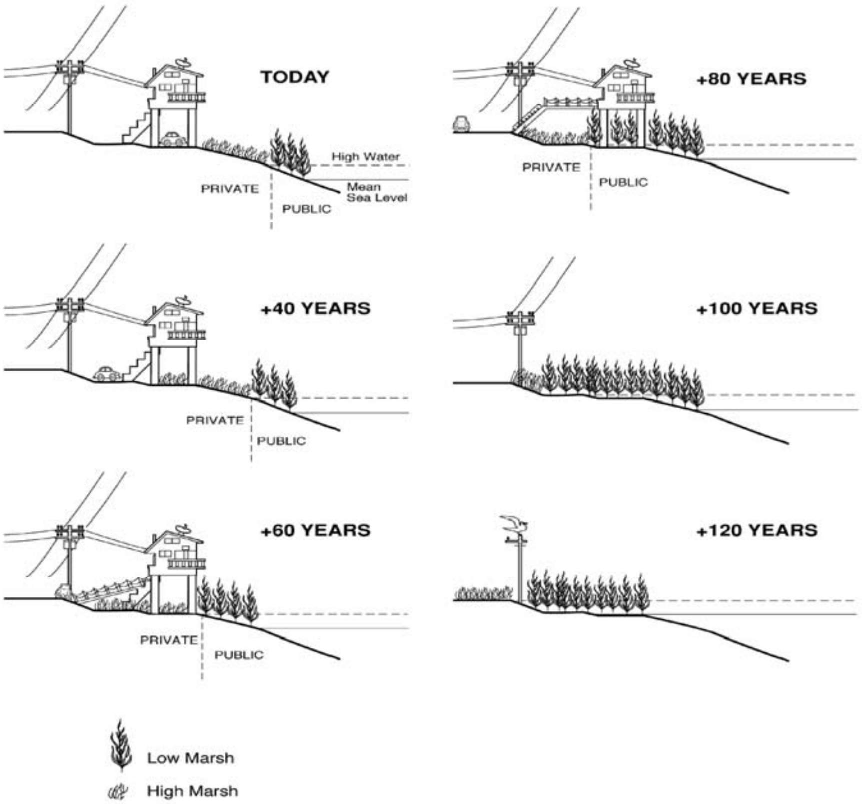

Figure 9.1 The landward migration of wetlands onto property subject to a rolling easement. A rolling easement allows construction near to the shore, but requires the property owner to recognize nature's right-of-way to advance inland as sea level rises. In this case, the high marsh reaches the footprint of the house 40 years hence. Because the house is on pilings, it can still be occupied (assuming that it is hooked to a sewerage treatment plant — a flooded septic system would probably fail). After 60 years, the marsh has advanced enough to require the owner to park the car along the street and construct a catwalk across the front yard. After 80 years, the marsh has taken over the entire yard; moreover, the footprint of the house is now seaward of mean high water and hence on public property. At this point, additional reinvestment in the property is unlikely. Twenty years later, the particular house has been removed, although other houses on the same street may still be occupied. But eventually, the entire area returns to nature (Titus, 1998).

Let us now examine some examples of long-term planning decisions and subsequent reallocation of risk.

9.2 PROTECTING COASTAL WETLANDS

The nation’s wetland programs generally result in the protection of wetlands in their current locations, but they do not explicitly consider retreating shorelines. Most tidal wetlands are likely to keep pace with the current rate of sea-level rise but could become marginal with a 2 mm/yr acceleration, and could be lost if sea-level rise accelerates by 7 mm/yr (Chapter 3). The two key relationships determining future wetland area are the relationship between wetland vertical development and sea-level rise, and between the rates of seaward erosion and inland migration. If wetland vertical development keeps pace with sea-level rise, wetland area will expand if inland migration is greater than seaward erosion, remain unchanged if inland migration and seaward erosion are equal, and decline if seaward erosion is greater than inland migration. If wetland vertical development lags behind sea-level rise (*i.e.*, wetlands do not keep pace), the wetlands will eventually become submerged and deteriorate even as they migrate inland, resulting in a loss of wetland area. Thus although the dry land available for potential inland wetland migration or formation is estimated to be less than 20% of the current area of wetlands (Chapter 1), these lands could potentially become important wetland areas in the future. However, they may not be available for wetland migration and formation given current policies and land use trends (Chapter 5).

A continuation of the current practice of protecting almost all developed estuarine shores could reverse the accomplishments of important environmental programs. Until the middle of the 20th century, tidal wetlands were often converted to dredge-and-fill developments[29]. By the 1970s, the aggregate result of the combination of federal and state regulations had, for all practical purposes, halted that practice. In the Mid-Atlantic, most tidal wetlands are off-limits to development. Coastal states generally prohibit the filling of low marsh, which is publicly owned in most states under the public trust doctrine (See Chapter 7).

A landowner who wants to fill tidal wetlands on private property must obtain a permit from the Army Corps of Engineers. 33 U.S.C. §§ 403, 409, 1344(a). These permits are generally not issued unless the activity is inherently water-related, such as a marina. 40 C.F.R. § 230.10(a)(3). Even then, the owners generally must mitigate the loss of wetlands by creating or enhancing wetlands elsewhere (EPA and USACE 1990). (Activities with very small impacts on wetlands, however, often qualify for a nationwide permit.) The net effect of all these programs has been to sharply reduce the rate of coastal wetland loss (*e.g.*, Stockton and Richardson, 1987; Hardisky and Klemas, 1983) and preserve an almost continuous strip of marshes, beaches, swamps, and mudflats along the U.S. Coast. If sea-level rise accelerates, those wetlands are likely to be lost (Reed *et al.*, 2008) unless either they are able to migrate inland or future generations use technology to ensure that wetland surfaces rise as rapidly as the sea (NRC, 2006).

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[29] See Chapter 5 for an explanation of these developments and their vulnerability to sea level rise.

Current approaches would *not* protect wetlands for future generations if sea level rises beyond the ability of wetlands to accrete — which is likely for most of the Mid-Atlantic with a 7 mm/yr acceleration, and likely for a 2mm/yr acceleration for most of Chesapeake Bay's wetlands.

Existing federal statutes are designed to protect existing wetlands, but the totality of the Nation's wetland protection program is the end result of decisions made by many actors. Federal programs discourage destruction of most *existing* coastal wetlands, but the federal government has not moved towards allowing tidal wetlands to migrate inland (Titus, 2000). The States of North Carolina, Maryland, New Jersey, and New York own the tidal wetlands below mean high water; and Virginia, Delaware, and Pennsylvania have enough of an ownership interest under the Public Trust Doctrine to preserve them even if doing so requires landward migration (Titus, 1998). But most states give property owners a near-universal permit to protect property by preventing wetlands from migrating onto dry land. Farmers rarely erect shore protection structures, but homeowners usually do (Titus, 1998; NRC, 2006). A few coastal counties and states have decided to keep shorefront farms and forests undeveloped, (see Appendices D, E, and F) but most have not. Government agencies that hold land with conservation objectives have not decided to purchase the land or easements necessary to enable wetlands to migrate inland[30]. Thus, in effect, the United States has decided to *save* its existing wetlands. But the net effect of all the decisions made at different levels is very likely to *eliminate*

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[30] But see chapter 10 for discussion of private conservancies.

wetlands by blocking their landward migration as a rising sea erodes their outer boundaries.

Not only is the long-term success of wetland protection sensitive to sea-level rise, it is also sensitive to *when* such decisions are made. The political and economic feasibility of allowing wetlands to take over a given parcel as sea level rises is much greater if appropriate policies are in place before the property is intensely developed. Many coastal lands are undeveloped today, but development continues. Deciding now that wetlands will have land available to migrate inland could protect more wetlands than delaying such a decision. In some places, such policies might discourage development in areas onto which wetlands may be able to migrate. In other areas, development could occur with the understanding that eventually land will revert to nature if sea level rises enough to submerge it. Like beach nourishment, artificial vertical build-up of tidal wetlands would not necessarily require a lead-time of several decades; but developing technologies to do so and determining whether and where they are appropriate could also take decades. To the extent that human activities[31] interfere with natural vertical accretion (build-up), restoring natural processes before the wetlands are lost is more effective than artificially re-creating them (EPA 1995; EPA and USACE 1990; Kruczynski 1990).

Even though the long-term success of the Nation's effort to protect wetlands is sensitive to sea-level rise, most of the individual decisions that ultimately determine whether wetlands can migrate inland depend on factors that are not sensitive to sea-level rise. The

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[31] *E.g.*, water flow management, development that alters drainage patterns, and beach nourishment and inlet modification which thwarts barrier island overwash.

desire of bayfront homeowners to keep their homes is strong; and unlikely to abate even with a significant acceleration of sea-level rise[32]. State governments must balance the public interest in the tidal wetlands against the well-founded expectations of coastal property owners that they will not have to yield their property. Only a handful of states — none of which are in the Mid-Atlantic — have decided in favor of the wetlands (see Chapter 10). Local government decisions regarding land use reflect many interests. Objectives such as near-term tax revenues (often by seasonal residents who make relatively few demands for services) and a reluctance to undermine the economic interests of landowners and commercial establishments are not especially sensitive to rising sea level.

Today's decentralized decision making process seems to protect coastal wetlands reasonably well at the current rate of sea-level rise; but it will not enable wetlands to migrate inland as sea-level rise continues or accelerates. A large-scale landward migration of coastal wetlands is very unlikely to occur in most of the Mid-Atlantic unless a conscious decision is made for such a migration by a level of government with authority to do so.

9.3 SHORE PROTECTION

The case for anticipating sea-level rise as part of activities to prevent erosion and flooding has not been as strong as for wetland protection. The lead time required for shore protection is much less than for a planned retreat and wetland migration. Dikes,

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[32] See, *e.g.*, Weggel *et al.* (1989), Titus *et al.* (1991), and NRC (2006) for an examination of costs and options for estuarine shore protection.

seawalls, bulkheads, and revetments can each be built within a few years. Beach nourishment is an incremental periodic activity; if the sea rises more than expected, one can add more sand.

The U.S. Army Corps of Engineers (Corps) has not evaluated whether sea-level rise will ultimately require fundamental changes in shore protection, but such changes do not appear to be urgent. Since the early 1990s, the Corps' guidance to project managers has urged them to attempt to identify robust strategies: "Feasibility studies should consider which designs are most appropriate for a range of possible future rates of rise. Strategies that would be appropriate for the entire range of uncertainty should receive preference over those that would be optimal for a particular rate of rise but unsuccessful for other possible outcomes." (USACE 2000a, page e-142). So far, this guidance has not significantly altered the Corps' approach to shore protection. Nevertheless, there is some question as to whether beach nourishment would be sustainable in the future if the rate of sea-level rise accelerates. It may be technically possible to double or triple the rate at which we nourish beaches and elevate the land surfaces of barrier islands 50–100 cm to offset rising sea level in the next century. But continuing such a practice indefinitely would eventually leave back barrier bays much deeper than today (see chapter 4), with unknown consequences for the environment and the barrier islands themselves. Similarly, it may be technically possible to build a low bulkhead along mainland shores as sea level rises 50–100 cm, but it could be more challenging to build a tall dike along the same shore—blocking waterfront views, requiring continual pumping, and exposing people behind the dike to the risk of flooding should that dike fail.

9.4 LONG-LIVED STRUCTURES: SHOULD WE PLAN NOW OR LATER?

The fact that eventually we will either hold back the sea or allow it to inundate a particular parcel of land does not, by itself, automatically imply that we must respond today. A community that will not need a dike until the sea rises 2 ft has little reason to build that dike today. Nevertheless, if the land where the dike would eventually be constructed happens to be vacant, the prospect of future sea-level rise might be a good reason to leave the land vacant. A homeowner whose house will be inundated in 30 to 50 years has little reason to move the house back today, but if the opportunity arises, it might be advisable to rebuild the house on a part of the lot that would provide it with a longer life.

Whether we need to be concerned about long-term sea-level rise ultimately depends on the lead time of our response options and on the costs and benefits of acting now versus later. A fundamental premise of benefit-cost analysis is that resources not deployed today can be invested profitably in another activity and yield a return on investment. Most engineering responses to sea-level rise fall into that category. For a given level of protection, dikes, seawalls, beach nourishment, jacking up structures, and elevating roadways are unlikely to cost more a few decades hence than today (USACE 2000b, 2007), and they can be implemented within the course of a few years. To the extent that this is our response to sea-level rise, we may not need to do it today. However, there are two exceptions.

The first exception might be called the “retrofit penalty” for failing to think long-term. If one is building (or rebuilding) a road or a drainage system anyway, then it may be far cheaper to design for a rise in sea level than modify it later, because in the latter case, the project needs to be built twice. For example, in a particular watershed in Charleston, South Carolina, if the sea rises one foot, the planned drainage system would fail and have to be rebuilt, but it would only cost an extra 5% to design the system today for a one-foot rise (Titus *et al.*, 1987, Table 2). The design and location of a house may be another example. If a house is designed to be moved, it can be moved; but a brick house on a slab foundation could be more problematic. Similarly, the cost of building a house 20 ft farther from the shore may be minor if the lot is large enough, whereas moving it back 20 ft could be substantial (EPA, 1989).

The second exception concerns the incidental benefits of doing something sooner. If a dike is not needed until the sea rises 2 ft because at that point a 100-year storm would flood the streets with 4 ft of water, the community is implicitly accepting the 2 ft of water that such a storm would provide today. If a dike is built now, it would stop this smaller flood as well as protect from the larger flood that will eventually occur. This reasoning was instrumental in leading the British to build the Thames River Barrier, which protects London. Some people argued that this expensive structure was too costly given the small risk of London flooding, but rising sea level meant that such a structure would eventually have to be built. Hence, the Greater London Council decided to build it during the 1970s (Gilbert and Horner, 1984).

While most engineering responses can be delayed with little penalty, the same cannot be said about land use decisions. Once an area is developed, the cost of vacating it as the sea rises is much greater than that cost would have been if the area was not developed. This is not to say that eventual inundation should automatically result in placing land off-limits to development. Even if a home has to be torn down 50 to 100 years hence, it might still be worth building. In some coastal areas where demand for beach access is great, rentals may recover the cost of home construction in less than a decade. However, once an area is developed, as a practical matter, it will not be abandoned unless either the eventual abandonment was part of the original construction plan, or the owners could not afford to hold back the sea. Therefore, the only way to preserve natural shores would be to make such a decision before an area is developed. Because the coast is being developed today, a failure to deal with this issue now is, in effect, a decision to allow the loss of wetlands and bay beaches wherever development takes place.

Among those options that have a net benefit compared to the baseline, many can be delayed because the benefits would still accrue. Delaying action can decrease the present value of the cost of acting — and increase the likelihood that the preparation is more closely tailored to what is necessary. But it can also increase the likelihood that one does not prepare until it is too late. One way to address this dilemma is to consider the lead times associated with particular types of adaptation (IPCC, 1992; O’Callahan, 1994).

9.5 DECISIONS BY COASTAL PROPERTY OWNERS ON ELEVATING HOMES

People are increasingly elevating homes to reduce the risk of flooding during severe storms, and in very low areas, people also elevate their yards. The cost of elevating even a small wood-frame cottage on a block foundation is likely to be $15,000–20,000 — and larger houses cost proportionately more. If it is necessary to drill pilings, the cost can be double because one has to move the house to the side and then move it back. If elevating the home prevents its subsequent destruction within a few decades, it will have been worthwhile. At a 5% discount rate, for example, it is worth investing 25% of the value of a structure to avoid a guaranteed loss 28 years hence. In areas where complete destruction of a home is unlikely, people sometimes elevate homes because of the lower insurance rates and to avoid the risk of water damages to walls and furniture. But the decision to elevate involves factors other than flooding as well, including better views of the water, increased storage and/or parking spaces, and greater difficulty for the elderly to enter their homes. Rising sea level can be a motivating factor to elevate a home even when one is uncertain about whether it is worth doing so, because it is likely that it will eventually be necessary (unless there is a good chance that the home will be replaced with a larger structure).

In cases where a new home is being constructed, or an existing home is elevated for reasons unrelated to sea-level rise, (such as a realization of the risk of flooding), rising sea level would justify raising the home to a higher level than would otherwise be the case. Elevating the home to (for example) 30 cm above the base flood elevation as part of the initial construction costs very little. The rising sea level increases the expected flood damages over the lifetime of a home. Thus, for very little marginal cost, future flood damages can be avoided by elevating the home more than would otherwise be the case.

9.6 FLOODPLAIN MANAGEMENT

The decisions that are potentially sensitive to rising sea level include floodplain mapping, floodplain regulations, flood insurance rates, and the various hazard mitigation activities that often take place in the aftermath of a serious storm. Although the outcomes of all these activities are clearly sensitive to sea-level rise, analysis is not available to enable assessment of whether future sea-level rise warrants changing the way things are done today.

9.6.1 Floodplain Regulations

The flood insurance program requires new (or substantially rebuilt) structures in the coastal floodplain to have the first floor above the base flood elevation (100-year flood). The program vests considerable discretion in local officials to tailor specific requirements to local conditions, or to enact regulations that are more stringent than FEMA’s minimum requirements. Several communities have decided to require floor levels to be one foot (or more) above the base flood elevation. In some cases, past or future sea-level rise has been cited as one of the justifications for doing so. There is considerable variation in both the costs and benefits of designing building to accommodate future sea-level rise. If local governments believe that property owners need a nudge to optimally address sea-level rise, they can require more stringent (higher) floor elevations. A possible reason for requiring higher floor elevations is that the current structure of the program does not raise rates for existing structures even if flood risks increase over time.

9.6.2 Floodplain Mapping

Requiring flood elevations above the base flood elevation can create anomalies, unless floodplain mapping also takes sea-level rise in account. Local jurisdictions have pointed this out (see Baltimore box in Appendix F). Otherwise, building in today's floodplain would have to be higher than adjacent buildings on higher ground that is outside of the floodplain today. The ability of local officials to voluntarily prepare for rising sea level is thus somewhat constrained by the lack of floodplain mapping that takes account of sea-level rise. Creation of maps that take account of sea-level rise would thus appear to be a low-regrets activity, because it would enable local officials to modify requirements where appropriate.

9.6.3 Federal Flood Insurance Rates

A 1991 Report to Congress by FEMA concluded that there was little need to change the Flood Insurance Program because rates would be adjusted as sea level rises and flood maps are revised (FEMA, 1991). Other commentators have pointed out, however, that flood insurance rates respond to increased risk for new or rebuilt homes, but not existing homes.

Flood insurance is different than most types of insurance. Unlike automobile insurance, the flood insurance program does not adjust rates as the individual conditions of a property make it riskier. Although shoreline erosion and rising sea level increase the expected flood damages of a given home, they do not cause the rates on a given property to rise. Unless a home is substantially changed, its assumed risk is grandfathered (*e.g.*, NFIP, 2007; Heinz Center, 2000). Thus, not only do insurance rates not anticipate future sea-level rise, they do not react to the past rise. This approach, in effect, prevents property owners from feeling the “market signal” of increased risks.

New homes pay higher rates if new maps show risks to be increasing. And if the house is substantially enlarged, its rates will reflect the new risk. So whether or not a property owner feels the market signal of increased rates depends on the expected frequency of reconstruction compared with the time it will take for a significant increase in the risk. FEMA’s Report to Congress assumed, in effect, that reconstruction occurs rapidly compared to the rate at which risk increases; so relatively few people will have an artificially low insurance rate due to sea-level rise (FEMA, 1991).

Other studies have reached the opposite conclusion. The National Academy of Sciences has recommended that the Flood Insurance Program create mechanisms to ensure that insurance rates reflect the increased risks caused by coastal erosion (NAS 1990, p. 9, 91). NAS pointed out that Congress has explicitly included storm-related erosion as part of the damages covered by flood insurance (42 U.S.C. §4121), and that FEMA’s regulations (44 CFR Part 65.1) already defined special “erosion zones” (NAS 1990, p. 72). A FEMA-supported study by the Heinz Center (2000) and a theme issue in the *Journal of Coastal*

Research (Crowell and Leatherman, 1999) also concluded that, because of existing shore erosion, there can be a substantial disparity between actual risk and insurance rates.

Would sea-level rise justify changing the current approach? Two possible alternatives would be to: (a) shorten the period during which rates are kept fixed so that rates can respond to risk and property owners can respond; or (b) keep the current policy of fixed rates, but instead of basing rates on the risk when the house is built — which tends to systematically underestimate the risk — base the rate on an estimate of the average risk over the lifetime of the structure, using assumed rates of sea-level rise, shore erosion, and structure lifetime. The latter approach received considerable consideration in the FEMA-supported study by the Heinz Center and the theme issue in *Journal of Coastal Research*. That analysis assumed current rates of sea-level rise. FEMA has not investigated whether accelerated sea-level rise would increase the disparity between risks and insurance rates enough to revisit that decision; nor has it investigated the option of adjusting rates to reflect changing risks. Although Congress has not provided FEMA with a mandate to act on the Heinz Center recommendations, the Government Accountability Office (2007) recently recommended that FEMA analyze the potential long-term implications of climate change for the National Flood Insurance Program. FEMA has told Congress that it intends to initiate such an analysis (Buckley 2007).

9.6.4 Post Disaster Hazard Mitigation

If a coastal community is ultimately going to be abandoned to the rising sea level, a major rebuilding effort in the current location may be less useful than expending the same resources rebuilding the community on higher ground. On the other hand, if the community plans to remain in its current location despite the increasing costs of shore protection, then it is important for people to understand that commitment. Unless property owners know which path the community is following, they do not know whether to reinvest. Moreover, if the community is going to stay in its current location, owners need to know whether their land will be protected with a dike or if the street is likely to be elevated a few feet.

9.7 CONCLUSIONS

The need to prepare for rising sea level depends on the length of the period of time over which the decision will continue to have consequences, how sensitive those consequences are to how much the sea rises, how rapidly the sea is expected to rise and the magnitude of uncertainty over that expectation, the decision maker’s risk tolerance, and the implications of deferring a decision to prepare. Someone making a decision with outcomes over a long period of time about an activity that is sensitive to sea level may need to consider sea-level rise — especially if whatever one might do today to prepare would not be feasible later. Decisions with outcomes over a short period of time about activities that are not sensitive to sea level probably need not consider sea-level rise — especially if whatever one might do to prepare today would be just as effective if done later.

Instances where the existing literature provides an economic rationale for preparing for accelerated sea-level rise include:

- *Coastal wetland protection*. Wetlands and the success of wetland-protection efforts are almost certainly sufficiently sensitive to sea-level rise to warrant examination of some changes in coastal wetland protection efforts, assuming that the objective is to ensure that most estuaries that have extensive wetlands today will continue to have tidal wetlands in the future. Coastal wetlands are sensitive to rising sea level, and many of the possible measures needed to ensure their survival as sea level rises have a very long lead time. Changes in management approaches would likely involve consideration of options at various levels of authority.
- *Coastal infrastructure*. Whether it is beneficial to design coastal infrastructure to anticipate rising sea level depends on the ratio of the incremental cost of designing for a higher sea level now, compared with the retrofit cost of modifying the structure later. No general statement is possible, because this ratio varies and relatively few engineering assessments of the question have been published. But because the cost of analyzing this question is very small compared with the retrofit cost, it is likely that most long-lived infrastructure in the coastal zone is sufficiently sensitive to rising sea level so as to warrant an analysis of the comparative cost of designing for higher water levels now and retrofitting later.
- *Building along the coast.* In general, the economics of coastal development alone does not currently appear to be sufficiently sensitive to sea-level rise so as to avoid construction in coastal areas. Land values are so high that development is often economic even if a home is certain to be lost within a few decades. The optimal location and elevation of new homes may be sensitive to prospects for rising sea level.

- *Shoreline planning.* A wide array of measures for adapting to rising sea level depend on whether a given area will be elevated, protected with structures, or abandoned to the rising sea. Several studies have shown that in those cases where the shores will retreat and structures will be removed, the economic cost will be much less if people plan for that retreat. The human toll of an unplanned abandonment may be much greater than if people gradually relocate when it is convenient to do so. Conversely, people may be reluctant to invest in an area without some assurance that lands will not be lost to the sea. Therefore, long-term shoreline planning is generally justified and will save more than it costs; the more the sea ultimately rises, the greater the value of that planning.
- *Rolling easements, density restrictions, and coastal setbacks.* Several studies have shown that in those cases where the shores will retreat and structures will be removed, the economic cost will be much less if people plan for that retreat. Along estuaries, a retreat is rarely forced by events and thus is likely to only occur if land remains lightly developed. It is very likely that options such as rolling easements, density restrictions, coastal setbacks, and vegetative buffers, would increase the ability of wetlands and beaches to migrate inland.
- *Floodplain management: Consideration of reflecting actual risk in flood insurance rates.* Economists and other commentators generally agree that insurance works best when the premiums reflect the actual risk. Even without considering the possibility of accelerated sea-level rise, the National Academy of Sciences (1990) and a FEMA-supported study by the Heinz Center (2000) concluded and recommended to Congress that insurance rates should reflect the

changing risks resulting from coastal erosion. Rising sea level increases the potential disparity between rates and risks of storm-related flooding.

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Chapter 10. Ongoing Adaptation

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KEY FINDINGS

- Most organizations are not yet taking specific measures to prepare for rising sea level. Recently, however, many public and private organizations have begun to assess possible response options.
- Most of the specific measures that have been taken to prepare for accelerated sea level rise have had the purpose of reducing the long-term adverse environmental impacts of sea level rise.

Preparing for the consequences of rising sea level has been the exception rather than the rule in the Mid-Atlantic. Nevertheless, many coastal decision makers are now starting to consider how to respond, and seriously thinking about changing some of the things people do to prepare for a rising sea.

This chapter examines those cases in which organizations are consciously anticipating the effects of sea-level rise. It does not catalogue the activities undertaken for other reasons that might also be justified on the basis for rising sea level, nor does it include all the cases in which an organization has authorized a study but not yet acted upon the study.

10.1 ADAPTATION FOR ENVIRONMENTAL PURPOSES

Many organizations that manage land for environmental purposes are starting to anticipate the effects of sea-level rise. Outside the Mid-Atlantic, some environmental regulators have also begun to address this issue.

10.1.1 Environmental Regulators

Organizations that regulate land use for environmental purposes generally have not implemented adaptation options to address the prospects of accelerated sea-level rise. Congress has given neither the U.S. Army Corps of Engineers (USACE) nor the Environmental Protection Agency (EPA) a mandate to modify existing wetland regulations to address rising sea level; nor have those agencies developed approaches for moving ahead without such a mandate. Outside of the Mid-Atlantic, a number of state and local governments have enacted statutes and regulations to enable wetlands to migrate inland, with the regulations in Maine, Rhode Island, and Cape Cod explicitly addressing rising sea level (Titus, 1998). But none of the eight Mid-Atlantic states have altered land use requirements to help ecosystems adjust to accelerated sea-level rise (NOAA, 2006).

Many restrictions on coastal development promulgated for unrelated reasons can also be justified as a response to sea-level rise. For example, Maryland’s coastal land use statute limits development to one home per 20 acres in most rural areas within 300 m of the shore (see Appendix F). Although the statute was enacted in the 1980s to prevent deterioration of water quality, if a similar statute were enacted today in another state, it could be justified as part of a sea-level rise adaptation strategy. The prospect of losing natural shores as sea level rises has caused Maryland to rethink wetland regulations concerning shore protection. It has a policy preference for “living shorelines”, which is slowly making its way into the wetlands regulations, as the state tries to remove biases that favor hard structures over the soft approaches that enable wetlands and beaches to persist as sea level rises. In the aftermath of Hurricane Isabel, the State of Maryland attempted to move in that direction.

Federal Land Managers

The Department of Interior has a requirement that climate change impacts be taken into account in planning and decision making. The requirement is embodied in Secretarial Order 3226 signed in 2001. Testimony to Congress in 2007 by Lynn Scarlett, Deputy Secretary of Interior, detailed the many ways the Department of Interior is dealing with climate change, from land planning to management practices to scientific studies. The National Park Service has worked with the United States Geological Survey (USGS) to examine coastal vulnerability on all of its coastal parks. The U.S. Fish and Wildlife Service is incorporating studies of climate change impacts, including sea-level rise, in their Comprehensive Conservation Plans where relevant.

The National Park Service and the U.S. Fish and Wildlife Service each have large coastal landholdings that could erode or become submerged as sea level rises. Neither organization has an explicit policy concerning sea-level rise, but both are starting to consider their options. The National Park Service generally favors allowing natural processes to adjust to rising sea level, which led it to move the Hatteras Lighthouse inland some 2,900 ft at a cost of $12 million in 1999. The U.S. Fish and Wildlife Service generally allows dry land to convert to wetlands, but it is not necessarily passive as rising sea level erodes the seaward boundary of tidal wetlands. Blackwater National Wildlife Refuge, for example, has used dredge material to rebuild wetlands on a pilot basis, and has plans to spend approximately $500,000 to recreate 7,000 acres of marsh. Neither agency has made land purchases or easements to enable parks and refuges to migrate inland.

The Nature Conservancy (TNC)

TNC is the largest private holder of conservation lands in the Mid-Atlantic. It has declared as a matter of policy that it is trying to anticipate rising sea level and climate change. Its initial focus has been to preserve ecosystems on the Pamlico-Albemarle Peninsula (TNC, 2007). Options under consideration include plugging canals to prevent subsidence-inducing saltwater intrusion, planting cypress trees where pocosins have been converted to dry land, and planting brackish marsh grasses in areas likely to be inundated. As part of that project, TNC undertook the first attempt by a private conservancy to purchase rolling easements (although none were purchased). TNC owns the majority of barrier islands along the Delmarva Peninsula, but none of the mainland shore. TNC is starting to examine whether preserving the ecosystems as sea level rises would be best facilitated by purchasing land on the mainland side as well, to ensure sediment sources for the extensive mudflats so that they might keep pace with rising sea level.

State conservation managers have not yet started to prepare for rising sea level (NOAA, 2006). But at least one state (Maryland) is starting to refine a plan for conservation that would consider the impact of rising sea level.

10.2 OTHER ADAPTATION OPTIONS BEING CONSIDERED BY FEDERAL, STATE, AND LOCAL GOVERNMENTS

10.2.1 Federal Government

Federal researchers have been examining how best to adapt to sea-level rise for the last few decades, and those charged with implementing programs are also now beginning to consider implications and options. The longstanding assessment programs will enable federal agencies to respond more rapidly and reasonably if and when policy decisions are made to begin preparing for the consequences of rising sea level.

The Coastal Zone Management Act is a typical example. The Act encourages states to protect wetlands, minimize vulnerability to flood and erosion hazards, and improve public access to the coast. Since 1990, the Act has included sea-level rise in the list of hazards that states should address. This Congressional mandate has induced NOAA to fund state-specific studies of the implications of sea-level rise, and encouraged states to periodically designate specific staff to keep track of the issue. But it has not yet altered what people actually do along the coast. One commentator has suggested that for this statutory provision to be carried out, the federal government should consider providing guidance on possible responses to sea-level rise (Titus, 2000). Similarly, the Corps of

Engineers has formally included the prospect of rising sea level for at least a decade in its planning guidance for the last decade (USACE, 2000), and staff has sometimes evaluated the implications for specific decisions (e.g. Knuuti, 2002). But the Corps' overall approach to wetland permits and shore protection has not yet shifted.

10.2.2 State Government

Maryland has considered the implications of sea-level rise in some decisions over the last few decades. Rising sea level was one reason that the state gave for changing its shore protection strategy at Ocean City from groins to beach nourishment. Using NOAA funds, the state developed a preliminary strategy for dealing with sea-level rise. As part of that strategy, the state also recently obtained a complete LIDAR data set of coastal elevations.

Delaware officials have long considered how best to modify infrastructure as sea level rises along Delaware Bay, although they have not put together a comprehensive strategy[33]. Coastal Management staff of the New Jersey Department of Environmental Protection have been guided by a long-term perspective on coastal processes, including the impacts of sea-level rise. So far, neither Delaware nor New Jersey has specifically altered their activities because of projected sea-level rise. Nevertheless, New Jersey is currently undertaking an assessment that may enable it to factor rising sea level into its strategy for preserving the Delaware Estuary[34].

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[33] CCSP 4.1 Stakeholder Report.

[34] CCSP SAP 4.1 Stakeholder Report (summarizing the reaction of the New Jersey Coastal Zone Management Program).

A bill in the New York General Assembly would create a sea-level rise task force (Bill AO9002 2007-2008 Regular Session). Maryland has a climate change adaptation task force that is focusing on sea-level rise.

Outside of the Mid-Atlantic, the California Legislature is considering Bill AB 1066, which would require state agencies to consider sea-level rise in their activities.

10.2.3 Local Government

A few local governments have considered the implications of rising sea level for roads, infrastructure, and floodplain management. (See text boxes in Appendices D and F.). New York City's plan for the year 2030 includes adapting to climate change. (NYC, 2008; pp. 136-40). The New York City Department of Environmental Protection is looking at ways to decrease the impacts of storm surge by building flood walls to protect critical infrastructure such as waste plants, and is also examining ways to prevent the sewer system from backing up more frequently as sea level rises (Rosenzweig et al., 2006). The city has also been investigating the possible construction of a major tidal flood gate across the Verizano Narrows to protect Manhattan. (Velasquez-Manoff, 2006).

Outside of the Mid-Atlantic, Miami-Dade County in Florida has been studying its vulnerability to sea-level rise, including developing maps to indicate which areas are at greatest risk of inundation. The county is hardening facilities to better withstand hurricanes, monitoring the salt front, examining membrane technology for desalinating seawater, and creating a climate advisory task force to advise the county commission (Yoder, 2007).

CHAPTER 10 REFERENCES

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Chapter 11. Institutional Barriers

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KEY FINDINGS

- Most institutions were designed without considering sea-level rise.
- Many institutions were created to respond to a demand for hard shoreline structures to hold the coast in a fixed location, and have generally not shifted to retreat or soft shore protection (*e.g.*, beach nourishment).
- The interdependence of decisions made by property owners and federal, state, and local governments creates an institutional inertia that currently impedes preparing for sea-level rise, as long as no decision has been made regarding whether particular locations will be protected or yielded to the rising sea.

Chapter 9 describes several categories of decisions where the risk of sea-level rise justifies doing things differently today, and Chapter 10 examined the responses people are currently making, which in most cases are very limited.

It takes time to respond to new problems. Most coastal institutions were designed before the 1980s. Land use planning, infrastructure, home building, property lines, wetland protection, and flood insurance all have been designed without considering the dynamic nature of the coast. There is also a general mindset that sea level and shores are stable — or should be. Even when a particular institution has been designed to account for shifting shores, people are reluctant to give up real estate to the sea. Although scientific information can quickly change what people expect, it takes longer to change what people want. Finally, a phenomenon known as “moral hazard” often prevails. Moral hazard refers to a situation in which insurance reduces someone’s incentive to prevent or decrease the risk of a disaster (Pauly 1974). Our political process tends to sympathize with those whose property is threatened, rather than allowing them to suffer the consequences of the risk they assumed when they bought the property. It can be hard to say “no” to someone whose home is threatened (Viscusi and Zeckhauser 2006).

This chapter explores some of the institutional barriers that discourage people and organizations from preparing for the consequences of rising sea level. This discussion has two general themes. First, examination of the institutions and decisions they make regarding sea-level rise reveals that the challenge may more appropriately be how to overcome institutional *biases* rather than *barriers*. Policies that encourage higher densities in the coastal zone, for example, may be barriers to wetland migration, but they improve the economics of shore protection. Such a policy might be viewed as creating a bias in favor of shore protection over wetland migration, but it is not really a barrier to adaptation from the perspective of a community that prefers protection anyway. A bias simply encourages one path over another; a barrier can block a particular path entirely.

Second, interrelationships between various decisions tend to reinforce institutional inertia. Omission of sea-level rise from a land-use plan may discourage infrastructure designers from preparing for it; a federal regulatory preference for hard structures may prevent state officials from encouraging soft structures. Although inertia has slowed current acts to respond to the risk of sea-level rise, it could just as easily help to sustain momentum toward a response once key decision makers decide which path the course of action should follow.

The barriers and biases examined in this chapter mostly concern governmental rather than private sector institutions. Private institutions do not always exhibit foresight—and their limitations have been an important reasons for creating government flood insurance, wetland protection, shore protection, and other government programs. But the published literature does not suggest that rising sea level would change the institutional limitations of the private sector. The duty of corporations to maximize shareholder wealth, for example, may prevent a business from altering development plans to facilitate future environmental preservation as sea level rises. But for purposes of this chapter, the duty to serve shareholders is an essential objective of the corporate institution, not a barrier that keeps corporations from fulfilling their missions. Finally, there is little literature available on private institutional barriers to preparing for sea-level rise. We do not know whether this absence implies that the private barriers are less important, or simply that private organizations keep their affairs private more than public institutions.

11.1 SOME SPECIFIC INSTITUTIONAL BARRIERS AND BIASES

Productive institutions are designed to accomplish a mission, and they design rules and procedures to help accomplish those objectives. These rules and procedures are inherently biased toward achieving the mission, and against anything that thwarts the mission. By coincidence more than design, they may facilitate or thwart the ability of others to achieve other missions.

No one has prepared an exhaustive catalogue of institutional biases in the coastal zone, but three biases have been the subject of substantial commentary: (1) shore protection versus retreat; (2) hard structures versus soft engineering solutions; and (3) coastal development versus preservation.

11.1.1 Shore Protection Versus Retreat

Federal, state, local, and private institutions all have a strong bias *favoring* shore protection over retreat in developed areas. Many institutions also have a bias *against* shore protection in undeveloped areas.

*U.S. Army Corps of Engineers (USACE) Civil Works***.** Congressional appropriations for shore protection in coastal communities generally provide funds for various engineering projects to limit erosion and flooding. The planning guidance documents for the Corps of Engineers appear to provide USACE the discretion to relocate or purchase homes if a policy of retreat is the locally preferred approach and more cost-effective than shore protection. (USACE 2000 p. 2-8). Nevertheless, the general mission of the Corps of Engineers, its history (Lockhart and Morang 2002), staff expertise, and funding preferences combine to make shore protection far more common than a retreat from the shore.

State Shore Protection. North Carolina, Virginia, Maryland, Delaware, and New Jersey all have significant state programs to support beach nourishment along the Atlantic Ocean. (See Appendices C-F). Virginia, Delaware, and New Jersey have also supported beach nourishment in residential areas along estuaries as well. Some agencies in Maryland encourage private shore protection to avoid the environmental effects of shore erosion [35] (see Appendix F) and the state provides interest-free loans for up to 75% of the cost of nonstructural erosion control projects on private property (MD DNR 2008). None of these states has a program to support a retreat in developed areas.

FEMA Programs. Some aspects of the National Flood Insurance Program (NFIP) encourage shore protection, while others encourage retreat. FEMA requires local governments to ensure that new homes along the ocean are built on pilings sunk far enough into the ground so as to remain standing even if the dunes and beach are largely washed out from under the house during a storm. 44 CFR 60.3(e)(4). Although beaches will often recover to some extent after storms, they frequently do not entirely come back. In the past, when homes were built less sturdily, strategic retreat from the shore often occurred after major storms (*i.e.*, people did not rebuild as far seaward as homes had been before the storm). Now, newer homes can withstand storms and instead of retreating the tendency is for emergency beach nourishment operations to protect oceanfront homes. The requirement for construction on pilings also encourages larger homes; after a significant expense for pilings, people rarely build an inexpensive cottage. Therefore, larger homes are better able to justify shore protection. A FEMA emergency assistance

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[35] MD DNR (2006), however, favors the no-action alternative over shore protection structures.

program will often fund such nourishment in areas where the beach was nourished before the storm. (FEMA 2007 p. 86-87; 44 CFR 206.226(j)) In portions of Florida that receive frequent hurricanes, these projects are a significant portion of total beach nourishment. They have not yet been a major source of funding for beach nourishment in the Mid-Atlantic.

Several FEMA programs are neutral or promote retreat. In the wake of Hurricane Floyd, one North Carolina county used FEMA money to elevate structures, while an adjacent county used those funds to help people relocate rather than rebuild (Appendix G.) Repetitively flooded homes have been eligible for relocation assistance under a number of programs. Because of FEMA's rate map grandfathering policy, (see Chapter 9), a statutory cap on annual rate increases, and limitations of the hazard mapping used to set flood insurance rates, some properties have rates that are substantially less than the risk. As a result, these programs assist property owners and save the flood insurance program money by decreasing claims. From 1985 until 1995, the Upton-Jones Act helped fund the relocation of homes in imminent danger from erosion (Crowell *et al.* 2007 p. 22). FEMA's Severe Repetitive Loss Program is authorized to spend $80 million to purchase or elevate homes that have either made four separate claims or at least two claims totaling more than the value of the structure (FEMA 2008a). Several other FEMA programs provide grants for reducing flood damages, which states and communities can use for relocating residents out of the flood plain, erecting flood protection structures, or flood-proofing homes (FEMA 2008b, 2008c, 2008d, 2008e).

Flood insurance rates are adjusted downward to reflect the reduced risk of flood damages, if a dike or seawall decreases flood risks during a 100-year storm. Because rates are ideally based on risk, this adjustment is not necessarily a bias toward shore protection.

Wetland Protection. The combination of federal and state regulatory programs to protect wetlands in the Mid-Atlantic strongly discourages development from advancing into the sea, by prohibiting or strongly discouraging the filling or diking of tidal wetlands for most purposes (See Chapter 9). Within the Mid-Atlantic, New York promotes the landward migration of tidal wetlands in some cases (See Appendix A); Maryland favors shore protection in some cases. The Federal government has no policy on the question of retreat versus shore protection.

Existing regulations do not encourage developers to create buffers that might enable wetlands to migrate inland, nor do they encourage landward migration in developed areas (Titus, 2000). In fact, the Corps of Engineers has issued a nationwide permit for bulkheads and other erosion-control structures.[36] Titus (2000) concluded that this permit which often ensures that wetlands will not be able to migrate inland unless the property owner does not want to control the erosion. For this and other reasons, the State of New York has said that bulkheads and erosion structures otherwise authorized under the nationwide permit will not be allowed in special management areas (which cover a large percentage of the coast) without state concurrence (See Appendix A).

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[36] See 61 Fed. Reg. 65,873, 65,915 (Dec. 13, 1996) (reissuing Nationwide Wetland Permit 13, Bank Stabilization activities necessary for erosion prevention). *See also* Reissuance of Nationwide Permits, 72 Fed. Reg. 11,1108-09, 11183 (March 12, 2007) (reissuing Nationwide Wetland Permit 13 and explaining that construction of erosion control structures along coastal shores is authorized).

Federal statutes appear to discourage possible efforts by regulatory programs to encourage landward migration of wetlands. Section 10 of the Rivers and Harbors Act of 1899 and Section 404 of the Clean Water Act require a permit to dredge or fill any portion of the navigable waters of the United States).[37] Courts have long construed this jurisdiction to include lands within the "ebb and flow of the tides," (Gibbons v. Ogden; Zabel v. Tabb; 40 C.F.R. § 230.3(s)(1) (2000)), but it excludes lands that are dry today but would become wet if the sea rose a meter (Titus, 2000). The absence of a statutory requirement to enable wetlands to migrate inland can be a barrier to possible efforts by Federal wetlands programs to anticipate sea-level rise—especially measures involving preservation of lands that are currently inland of Federal jurisdiction.

In most cases, the absence of a specific policy on sea-level rise appears to have a neutral effect on whether shores are protected or retreat. An important exception concerns the stabilization of barrier islands that might otherwise migrate inland. Under natural conditions, winds and waves tend to cause beaches and marshes on the bay sides of barrier islands to slowly advance into the bay toward the mainland. Rules against filling tidal waters prevent people from artificially doing so. After a storm washes sand from the beach onto the island, local governments bulldoze the sand back onto the beach rather than putting a portion into the bay, even though that is what would happen under natural conditions. Unlike the case of wetlands migrating onto dry land, limits on Federal

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[37] See The Clean Water Act of 1977, § 404, 33 U.S.C. § 1344; The Rivers and Harbors Act of 1899, § 10, 33 U.S.C. §§ 403, 409 (1994).

jurisdiction do not prevent the Federal regulatory program from encouraging the landward migration of barrier islands.

Relationship to Coastal Development. Finally, many policies encourage or discourage coastal development, as discussed below. Even policies that subsidize relocation may indirectly encourage shore protection. Such assistance reduces the risk of an uncompensated loss of one's investment, thereby encouraging coastal construction, which in turn makes shore protection more likely.

11.1.2 Shoreline Armoring Versus Living Shorelines

The combined effect of Federal and state wetland protection programs is a general preference for hard shoreline structures over soft engineering approaches to stop shoreline erosion. (Box 11.1) The Corps of Engineers has issued nationwide permits to expedite the ability of property owners to erect bulkheads and revetments. [38] There is no such permit for soft solutions such as rebuilding an eroded marsh or bay beach.[39] The bias in favor of shoreline armoring results from the fact that the statute focuses on filling navigable waterways, not the environmental impact of the shore protection. Rebuilding a beach of marsh requires more of the land below high water to be filled than building a bulkhead.

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[38] Reissuance of Nationwide Permits, 72 Fed. Reg. 11,1108-09, 11183 ((March 12, 2007) (reissuing Nationwide Wetland Permit 13 and explaining that construction of erosion control structures along coastal shores is authorized)

[39] Reissuance of Nationwide Permits, 72 Fed. Reg. 11, 11183, 11185 ((March 12, 2007) (explaining that permit 13 requires fill to be minimized and that permit 27 does not allow conversion of open to water to another habitat such as beach or tidal wetlands)

Until recently, state regulatory programs shared the preference for hard structures. Maryland now favors “living shorelines” instead (Chapter 10). But Federal rules can be a barrier to these state efforts. After Hurricane Isabel destroyed many shore protection structures, and people were rebuilding them on an emergency basis, Maryland wanted to make it just as easy for someone to get a permit to replace a destroyed bulkhead with a living shoreline, as to rebuild the bulkhead. But the state was unable to obtain Federal approval (Appendix F.).

The regulatory barrier to soft solutions appears to result more from inertia than a conscious bias in factor of hard structures. The nationwide permit program is designed to avoid the unnecessary burden of issuing a large number of specific but nearly-identical permits. For decades, many people have bulkheaded their shores, so Nationwide Permit 13 was issued by the US Army Corps of Engineers in 2007 to cover bulkheads and similar structures. Because few people were rebuilding their eroding tidal wetlands, no nationwide permit for this activity has been issued. Today, as people become increasingly interested in more environmentally sensitive shore protection, they are dealing with institutions that have historically responded to requests for hard shoreline structures to hold the coast in a fixed location, and are just beginning to determine how to manage the development of soft shore protection measures.

BEGIN BOX 11.1:

The Existing Decision-Making Process for Shoreline Protection on Sheltered Coasts

- There is an incentive to install seawalls, bulkheads, and revetments on sheltered coastlines because these structures can be built landward of the Federal jurisdiction and thus avoid the need for Federal permits.

- Existing biases of many decision-makers in favor of bulkheads and revetments with limited footprints limit options that may provide more ecological benefits.

- The regulatory framework affects choices and outcomes. Regulatory factors include the length of time required for permit approval, incentives that the regulatory system creates, [and] general knowledge of the options and their consequences.

- Traditional structural erosion control techniques may appear to be the most cost-effective. However, they do not account for the cumulative impacts that result in environmental costs nor the undervaluation of the environmental benefits of the nonstructural approaches.

- There is a general lack of knowledge and experience among decision makers regarding options for shoreline erosion mitigation on sheltered coasts, especially options that retain more of the shorelines' natural features.

- The regulatory response to shoreline erosion on sheltered coasts is generally reactive rather than proactive. Most states have not developed plans for responding to erosion on sheltered shores.

Source: National Research Council, Ocean Studies Board. 2007. *Mitigating Shore Erosion Along Sheltered Coasts* p. 122-23.

END BOX

11.1.3 Coastal Development

Federal, state, local, and private institutions all have a modest bias favoring increased coastal development in developed areas. The Federal government discourages development in undeveloped areas, while state and local governments have a more neutral effect.

Coastal counties often favor coastal development because expensive homes with seasonal residents can substantially increase property taxes without much demand for government services. The property tax system often encourages coastal development. A small cottage on a lot that has appreciated to $1 million can have an annual property tax bill greater than the annual rental value of the cottage.

Congressional appropriations for shore protection encourage coastal development along shores that are protected, by reducing the risk that the sea will reclaim their land and structures. This reduced risk increases land values and property taxes, which may encourage further development. It may also encourage increased densities in areas that are not eligible for funding. The benefit-cost formulas used to determine eligibility (USACE 2000) find greater benefits in the most densely developed areas, making increased density a possible path toward federal funding for shore protection. Keeping hazardous areas lightly developed, by contrast, is not a path for federal funding. (See *e.g*. Appendix A).

Several commentators have argued that the National Flood Insurance Program (NFIP) encourages coastal development (*e.g.*, Tibbetts 2006; Platt 2007). Without insurance, some people would be reluctant to risk $250,000[40] on a home that could be destroyed in a storm.[41] People would tend to build farther away from the shore, and the homes would be scaled to the level of wealth the owner is willing to place at risk Insurance converts a large risk into a modest annual payment that people are willing to pay. FEMA has analyzed this question, however, and concluded that overall, the owners of coastal property vulnerable to waves and to flooding pay premiums more than enough to pay the flood damage claims; there is no overall subsidy (FEMA 2006a; FEMA 2006b, Hayes *et al*. 2006, Crowell *et al.* 2007). But those analyses exclude the year 2005, when Hurricanes Katrina, Rita, and Wilma required the NFIP to borrow $20 billion from the U.S Treasury (42 USC 4016 modified by PL109-208, 2006). FEMA has not decided whether to raise flood insurance rates to completely account for the risk of another storm like Katrina (Crowell *et al.*, 2007) More broadly, the combination of flood insurance and the various post-disaster and emergency programs providing relocation assistance, mitigation (*e.g.,* home elevation), and emergency beach nourishment provide coastal construction with a federal safety net that makes coastal construction a safe investment.

Flood ordinances have also played a role in the creation of three-story homes where local ordinances once limited homes to two stories. Flood regulations have induced some people to build their first floor more than 8 ft above the ground (FEMA 1984, 1994, 2000, 2007b). Local governments have continued to allow a second floor no matter the

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[40] NFIP only covers the first $250,000 in flood losses. 44 CFR 61.6 For homes with a construction cost greater than $250,000, federal insurance reduces a property owner's risk, but to a lesser extent.

[41] Research quantifying the impact of flood insurance on development is sparse. See Chapter 9.

elevation of the first floor. Property owners often enclose the area below the first floor (*e.g.* FEMA 2002), creating ground-level (albeit illegal[42] and uninsurable[43]) living space.

Currently, FEMA does not adjust rates to reflect new information when flood risks increase, but rather "grandfathers" the assumed risk (NFIP, 2007). Adaptation to climate change means adjusting to the changing nature of risk. But as shore erosion and rising sea level make the property more vulnerable, rates do not rise to reflect the increased risk from erosion until the property is substantially improved (Heinz Center, 2000). Moreover, FEMA is prevented by statute from raising premiums by more than 10% per year (42 USC §4015(e)), even if premiums are substantially below the annual expected damages. Thus, the NFIP probably does provide a subsidized insurance rate for new construction along eroding shores, which would encourage people to build on such shores. Whether the NFIP will also protect policy holders from the risks of sea-level rise is less clear. Under current policy, an increase in total claims would cause an across-the-board increase in rates (Crowell *et al.* 2007). The ability of the NFIP to recover losses from Katrina through a general rate increase would be analogous to the program's ability to adjust rates in response to accelerated sea-level rise or other consequences of changing climate.

The totality of these federal programs — in conjunction with sea-level rise — creates a "moral hazard." Coastal investment is profitable but risky. If government assumes much

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[42] 44 CFR §60.3(c)(2)

[43] 44 CFR §61.5(a)

of this risk, then the investment can be profitable without being risky — an ideal situation for investors (Loucks et al, 2006). The "moral hazard" concern is that when investors make risky decisions whose risk is partly borne by someone else, there is a chance that they will create a dangerous situation by taking on too much risk (Pauly, 1974). The government may then be called upon to take on even the risks that the private investors had supposedly assumed, because the risk of cascading losses could harm the larger economy (Kunreuther and Michel-Kerjant, 2007). Shore protection seems cost-effective and flood insurance rates seem to reflect the risk in most cases. But if sea-level rise accelerates, will taxpayers, coastal property owners, or inland flood insurance policyholders have to pay the increased costs?

The Coastal Barrier Resources Act (16 U.S.C. U.S.C. §3501 *et seq*.) discourages the development of designated undeveloped barrier islands and spits, by denying flood insurance, disaster assistance, federal highway funding, mortgage funding, and most other forms of federal spending to them. The increased demand for coastal property has led many of these areas to become developed anyway (GAO 1992). "Where the economic incentive for development is extremely high, the Act's funding limitations can become irrelevant." (USFWS 2002 p. 29.).

11.2 INTERDEPENDENCE: A BARRIER OR A SUPPORT NETWORK?

Uncertainty can be a hurdle to preparing for sea-level rise. Uncertainty about sea-level rise and its precise effects is one problem, but uncertainty about what others will do can also be a barrier. For environmental stresses, a single Federal agency is charged with developing and coordinating the nation's response. The response to sea-level rise requires coordination among several agencies, including EPA (protecting the environment), USACE (shore protection), Department of Interior (managing conservation lands), and FEMA (flood hazard management). State and local governments generally have comparable agencies that work with their Federal counterparts. No single agency is in charge of developing a response to sea-level rise as it affects the missions of many agencies.

The decisions that these agencies and the private sector make regarding how to respond to level rise are interdependent. From the perspective of one decision maker, the fact that others have not decided on their response is a distinct barrier to preparing their own responses. One of the barriers of this type is the uncertainty whether the response to sea-level rise in a particular area will involve shoreline armoring, elevating the land, or retreat.

11.2.1 Definition of Three Fundamental Pathways: Armor, Elevate, or Retreat

Long-term approaches for managing low coastal lands as the sea rises can be broadly divided into three pathways:

- *Protect* the dry land with seawalls, dikes, and other structures, eliminating wetlands and beaches (also known as *shoreline armoring*)
- *Elevate the land*, and perhaps the wetlands and beaches as well, enabling them to survive
- *Retreat* by allowing the wetlands and beaches to take over land that is dry today.

Combinations of these three approaches are also possible. Each approach will be appropriate in some locations and inappropriate in others. Shore protection costs, property values, the environmental importance of habitat, and the feasibility of protecting shores without harming the habitat all vary by location. Deciding how much of the coast should be protected may require people to consider social priorities not easily included in a cost-benefit analysis of shore protection.

11.2.2 Decisions That Cannot Be Made Until the Pathway Is Decided

Rising sea level has numerous implications for current activities. Nevertheless, in most cases, the appropriate response depends on whether and which of these three courses of action a particular community intends to follow. Six examples are summarized in Table 11.1, discussed below.

Table 11.1 The best way to prepare for sea-level rise depends on whether (and how) a community intends to hold back the sea.

Activity	Pathway for responding to sea-level rise		
	Shoreline armoring (*e.g.*, dike or seawall)	**Elevate land**	**Retreat/wetland migration**
Rebuild drainage systems	Check valves, holding tanks; room for pumps	No change needed	Install larger pipes, larger rights of way for ditches
Replace septics with public sewer	Extending sewer helps improve drainage	Mounds systems; elevate septic system; extending sewer also acceptable	Extending sewer undermines policy; mounds system acceptable
Rebuild roads	Keep roads at same elevation; owners will not have to elevate lots	Rebuild road higher; motivates property owners to elevate lots	Elevate roads to facilitate evacuation
Location of roads	Shore-parallel road needed for dike maintenance	No change needed	Shore parallel road will be lost; all must have access to shore-perpendicular road
Setbacks/subdivisions	Setback from shore to leave room for dike	No change needed	Erosion-based setbacks
Easements	Easement or option to purchase land for dike	No change needed	Rolling easements to ensure that wetlands and beaches migrate

Coastal Drainage Systems. Sea-level rise slows natural drainage and the flow of water through drain pipes that rely on gravity. If an area will not be protected from increased inundation, then larger pipes and pumping may be necessary. If an area will be protected with a dike, then larger pipes are less important than underground storage, check valves, and ensuring that the system can be retrofitted to allow for pumping (Titus *et al.*, 1987). If the land surfaces are going to be elevated, then sea-level rise will not impair drainage.

Septics and Sewer. Rising sea level can elevate the water table to the point where septic systems no longer function properly (U.S. EPA, 2002).[44] If areas will be protected with a

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[44] . "Most current onsite wastewater system codes require minimum separation distances of at least 18 inches from the seasonally high water table or saturated zone irrespective of soil characteristics. Generally, 2- to 4-foot separation distances have proven to be adequate in removing most fecal coliforms in septic tank effluent." U.S. EPA (2002).

dike, then all the land protected must eventually be artificially drained and sewer lines further extended to facilitate drainage. On the other hand, extending sewer lines would be entirely incompatible with allowing wetlands to migrate inland, because the high capital investment tends to encourage coastal protection; a mounds-based septic system is more compatible. If a community's long-term plan is to elevate the area, then either a mounds-based system or extended public sewage will be compatible.

Road Maintenance. As the sea rises, roads flood more frequently. If a community plans to elevate land with the sea, then repaving projects should elevate the roadway accordingly. If a dike is on the horizon, then repaving projects would consciously avoid elevating the street above people's yards, lest the projects prompt people to spend excess resources on elevating their yards when doing so is not necessary in the long run.

As an example, Ocean City, Maryland, currently has policies in place that would be appropriate if the long-term plan was to build a dike and pumping system — but the town intends to elevate instead. Currently, the town has an ordinance that requires property owners to maintain a 2% grade so that yards drain into the street. The town has construed this rule as imposing a reciprocal responsibility on the town itself to not elevate roadways above the level where yards can drain, even if the road is low enough to flood during minor tidal surges. Thus, the lowest lot in a given area dictates how high the street can be. As sea level rises, the town will be unable to elevate its streets, unless it changes this rule. Yet public health reasons require drainage to prevent standing water in which mosquitoes breed. Therefore, the town has an interest in ensuring that all property owners gradually elevate their yards so that the streets can be elevated as the sea rises without causing public health problems. The town has developed draft rules that would require that, during any significant construction, yards be elevated enough to drain during a 10-year storm surge for the life of the project, considering projections of future sea-level rise. The draft rules also state that Ocean City's policy is for all lands to gradually be elevated as the sea rises (See Appendix E).

Locations of Roads. As the shore erodes, any home that is accessed only by a road seaward of the house could lose access before the home itself is threatened, and even homes seaward of the road might lose access if the road were washed out elsewhere. If the shore is expected to erode, it is important to ensure that all homes are accessible by shore-perpendicular roads, a fact that was recognized in the layout of early beach resorts along the New Jersey and other shores. But if a dike is likely, then a road along the shore would be useful for dike construction and maintenance. If all land is likely to be elevated, then sea-level rise may not have any significant impacts on the location of new roads.

Subdivision and Setbacks. If a dike is likely, then houses need to be set back enough from the shore to allow room for the dike and associated drainage systems. Setbacks and larger coastal lot sizes are also desirable in areas where a retreat policy is preferred, for two reasons. First, the setback provides open lands onto which wetlands and beaches can migrate inland without immediately threatening property. Second, larger lots mean lower density and hence fewer structures that would have to be moved — as well as less justification for investments in central water and sewer. By contrast, in areas where the plan is to elevate the land, sea-level rise does not alter the property available to the homeowner, and hence would have minor implication for setbacks and lot sizes.

Covenants and Easements Accompanying Subdivision. Although setbacks are the most common way to anticipate eventual dike construction and the landward migration of wetlands and beaches, a less expensive method would often be the purchase of (or regulatory conditions requiring) rolling easements, which allow development but prohibit hard structures that stop the landward migration of ecosystems. The primary advantage is that society makes the decision to allow wetlands to migrate inland long before the property is threatened, so people can plan around the assumption of migrating wetlands, whether that means leaving an area undeveloped or building structures that can be moved.

Local governments can also obtain easements for future dike construction. Both of these types of easements would have very low market prices in most areas, because the fair market value is equal to today’s land value discounted by the rate of interest compounded over the many decades that will pass before the easement would have any effect. As with setbacks, a large area would have to be covered if wetlands are going to migrate inland, a narrow area would be required along the shore for a dike, and no easements are needed if the land will be elevated in place.

11.2.3 Opportunities for Deciding on the Pathway

Chapters 5 briefly mentions an ongoing effort to create present maps that distinguish areas where shore protection is likely from those areas where a retreat is more likely, given current policies and land use trends (See *e.g.* Titus 2004). At the local level, one must make an assumption about which land will be protected to truly understand which lands will truly become inundated (chapter 1) and how shorelines will actually change (chapter 2), which existing wetlands will be lost (chapter 3), whether wetlands will be able to migrate inland (chapter 5), and the environmental consequences (chapter 4); the population whose homes would be threatened (chapter 6) and the implications of sea-level rise for public access (chapter 7) and floodplain management. Assumptions about future shore protection are also necessary to estimate the level of resources that would be needed to fulfill people's current expectations for shore protection.

Improving our ability to project the impacts of sea-level rise is not the only reason for mapping expectations for future shore protection. Another use of such studies has been to initiate a dialogue about what *should* be protected, so that state and local governments can decide upon a plan of what will actually be protected. Just as the lack of a plan is a barrier to preparing for sea-level rise, the adoption of a plan would remove an important barrier and signal to many decision makers that the time has come for them to plan for sea-level rise as well.

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Part IV. Sensitivity to Sea-Level Rise at the Local Scale

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Previous chapters have provided region-wide perspectives on different effects, social impacts, and components of society's response to sea-level rise. The issue-by-issue presentation closely matches the separate professions involved in studying the effects and developing options for adapting to sea-level rise.

Many decisions, however, concern a specific location and require local andregional perspectives and information. Fortunately, much of the information that the previous chapters presented at the regional scale is also available at the state and local scale. Moreover, some information that is not available region-wide is available for some locations: For example, previous chapters did not look at the impacts of increased salinity on drinking water, but such information is available for the Philadelphia and New York metropolitan areas, which appear to be the primary areas where sea-level rise could harm water supplies.

This report does not recommend specific policies or actions in response to sea-level rise. Instead, it summarizes information on the options that are available. Impacts of sea-level rise on any specific community or local area will depend upon many factors and need to be carefully assessed as policy options and mitigation alternatives are examined.
Part IV is an overview of Appendices A-G, which provide state and local information similar to chapters 1-5 and 7, as well as information on some aspects of the effects of sea-

level rise that chapters 1-11 did not address but that may be important for specific locations.

IV.1 INFORMATION IN THE APPENDICES

There are separate appendices for each of seven sub-regions: Long Island, Greater New York City, New Jersey Shore, Delaware Estuary, Atlantic Coast of the Delmarva Peninsula, Chesapeake Bay, and North Carolina. These sub-regions generally track the sub-regional classifications of the results presented in the Chapters of this report. The data used in the discussion for these sub-regions are the same as those used in the thematic chapters and are explained there. The sub-regional presentation provides a more fine-grained analysis on certain themes (such as elevation and population), but for certain topics (such as wetland accretion) the data do not permit more site-specific conclusions for most locations.

The presentation of local-scale information in the appendices represents the best data available as this report was being prepared. Limited resolution and/or availability of data create some uncertainty in estimating land and population that could be vulnerable to sea-level rise. In addition, some data are several years old, leading to uncertainties regarding policies and expectations for land use.

IV.1.1 Effects of Sea-Level Rise

Depending on the size of the region discussed, each appendix includes one or more elevation maps similar to the elevation maps in Chapter 1. These maps generally have a contour interval of 50 centimeters, but in cases where the underlying data was less accurate, a 1-meter contour was used following the recommendations of the underlying study from which the map data was obtained. Tables are also included with county-specific uncertainty ranges for the amount of land below a particular elevation. As in Chapter 1, all elevations are measured relative to spring high water.

The Appendices discuss coastal erosion and the potential for the vertical buildup of wetlands. Those discussions serve as background for discussions of vulnerable ecosystems and species.

IV.1.2 Social Impacts

Discussions of wetland vertical buildup provide essential background for considering the environmental impacts of sea-level rise, but identifying specific areas where wetlands are likely and unlikely to migrate inland is a complex undertaking. Most appendices describe state and local policies on coastal development and response to a shifting shoreline, and illustrate examples of how these policies might affect wetland migration as well as estuarine ecosystems.

Finally, the appendices discuss unique aspects of each region’s vulnerability to sea-level rise, including population data on developed lands close to sea level, policy context, and — where applicable —responses. Some of these aspects do not fit neatly within the structure of the issues presented in Parts I-III, such as the vulnerability of the Path trains in the New York area to flooding from sea-level rise, the dikes along Delaware Bay dating back to the 17th century, or the vulnerability of areas in Washington, D.C. created by filling the Potomac River.

IV.2 EXAMPLES

The following excerpts come from the appendices of this report and provide examples of the analytical insights possible within the regions:

IV.2.1 Long Island (Appendix A)

Long Island has almost 1,350 miles of coastline along Long Island Sound, the Peconic bays, the south shore bays, and the Atlantic Ocean. On the north shore of the island, coastal bluffs presently protect structures from possible inundation by rising seas; however, measures may be taken in the future to protect structures at the top of the bluffs from erosion at the bottom. Along the Atlantic shore, most of the shoreline, especially along the mainland and areas of the south shore, particularly within Nassau County, is highly developed and, as a result, has already been hardened by bulkheads.

There has already been a significant loss of the historical area of vegetated tidal wetlands in Long Island Sound (Holst *et al.*, 2003), which some scientists partially attribute to sea-level rise (Mushacke, 2003). Beaches are far more common than tidal wetlands in the Long Island Sound study area, however; and if the shoreline is hardened by armoring then the potential for beach loss is increased.

Because the eastern part of Long Island is not as densely populated as the western part, some coastal lands in eastern Long Island are designated for preservation, conservation, or recreation and therefore for the foreseeable future will most likely be left in a natural state in the face of rising sea level.

IV.2.2 New York Metropolitan Area (Appendix B)

Although people generally think of the Southeast as the coastal area vulnerable to natural disasters, the New York metropolitan area is also susceptible. For example, in December 1992 a powerful nor'easter submerged parts of uptown Manhattan in 4 feet of water, shut down significant portions of the city's transportation system, and caused coastal flooding that damaged as many as 20,000 homes. Given New York's large population, the effects of hurricanes and other major storms combined with higher sea levels could be particularly severe. With much of the metropolitan area's transportation infrastructure at low elevation (most at 3 meters or less), even slight increases in the height of flooding could cause extensive damage and bring the thriving city to a relative standstill until the flood waters recede (Gornitz, 2002).

Although the New York metropolitan area is among the most densely populated and highly developed in the nation, there are local ecosystems being affected by sea-level rise as well. For example, the wetlands of Staten Island may not be able to migrate inland as sea level rises because of the relatively steep slopes that have formed near the shore. Jamaica Bay's wetlands may be able to respond naturally to sea-level rise, but wetlands in some parts of the bay already show substantial losses (Hartig, 2002).

IV.2.3 New Jersey Shore (Appendix C)

As far back as the 1800's, the dense development of the New Jersey shore led many people to take the view that people should not simply retreat in response to storm erosion, but instead hold back the sea. In 1898 the U.S. Army built a seawall between Sandy Hook and Sea Bright to protect the operations at Fort Hancock (NPS, 2007). Over time, the seawall was extended south as far as Long Branch, and as a result there was little or no beach along most portions of the New Jersey shore between Long Branch and Sandy Hook. During the 1970s, oceanographer Orrin Pilkey and coastal geologists began to warn people around the nation about the disadvantages of what they called "New Jerseyization", by which they meant replacing beaches with seawalls (Pilkey, *et al.*, 1978). The state has since reversed that trend and restored the beaches, although the seawalls remain.

The New Jersey shore continues to be vulnerable to storm erosion and rising seas. In several neighborhoods in the southern half of Long Beach Island, streets and yards are flooded by spring high tides whenever the bay is elevated by either strong winds from the East or a rainy period.

Though New Jersey has a well-established policy against shore armoring along the developed ocean shores, today beach nourishment is the preferred method for reversing beach erosion and protecting oceanfront land from coastal storms. In fact, the primary debate in New Jersey tends to be the level of public access required before a community is eligible to receive beach nourishment, not the need for nourishment itself.

IV.2.4 Delaware Estuary (Appendix D)

From the 17th through 20th centuries, more marsh was converted to dry land along the Delaware River and Delaware Bay than anywhere else in the United States. Today, however, efforts are under way to restore the wetlands to areas that were formerly diked (DDFW, 2007). Therefore, wetlands may be able to migrate inland along New Jersey sections of the Delaware Bay shores as sea level rises. In Delaware, the combination of floodplain regulations, preservation easements, and land purchases has created a major conservation buffer that will almost certainly be available for wetlands to potentially migrate inland as sea level rises.

Pennsylvania is the only state in the nation along tidal water without an ocean coast. The resulting lack of barrier islands and communities vulnerable to coastal erosion and life-threatening hurricanes has often led observers to ignore the impact of sea-level rise on Pennsylvania (USGS, not dated). Pennsylvania's sensitivity to sea-level rise is in fact different than other states. The Delaware River is usually fresh along almost all of the Pennsylvania shore. Because Philadelphia relies on freshwater intakes in the tidal river, the most important impact may be the impact of salinity increases from rising sea level on the city's water supply. Areas of Philadelphia (mostly near Philadelphia International Airport) are already below spring high water because of the long history of dike construction and may be prone to flooding (see Figure IV.1).

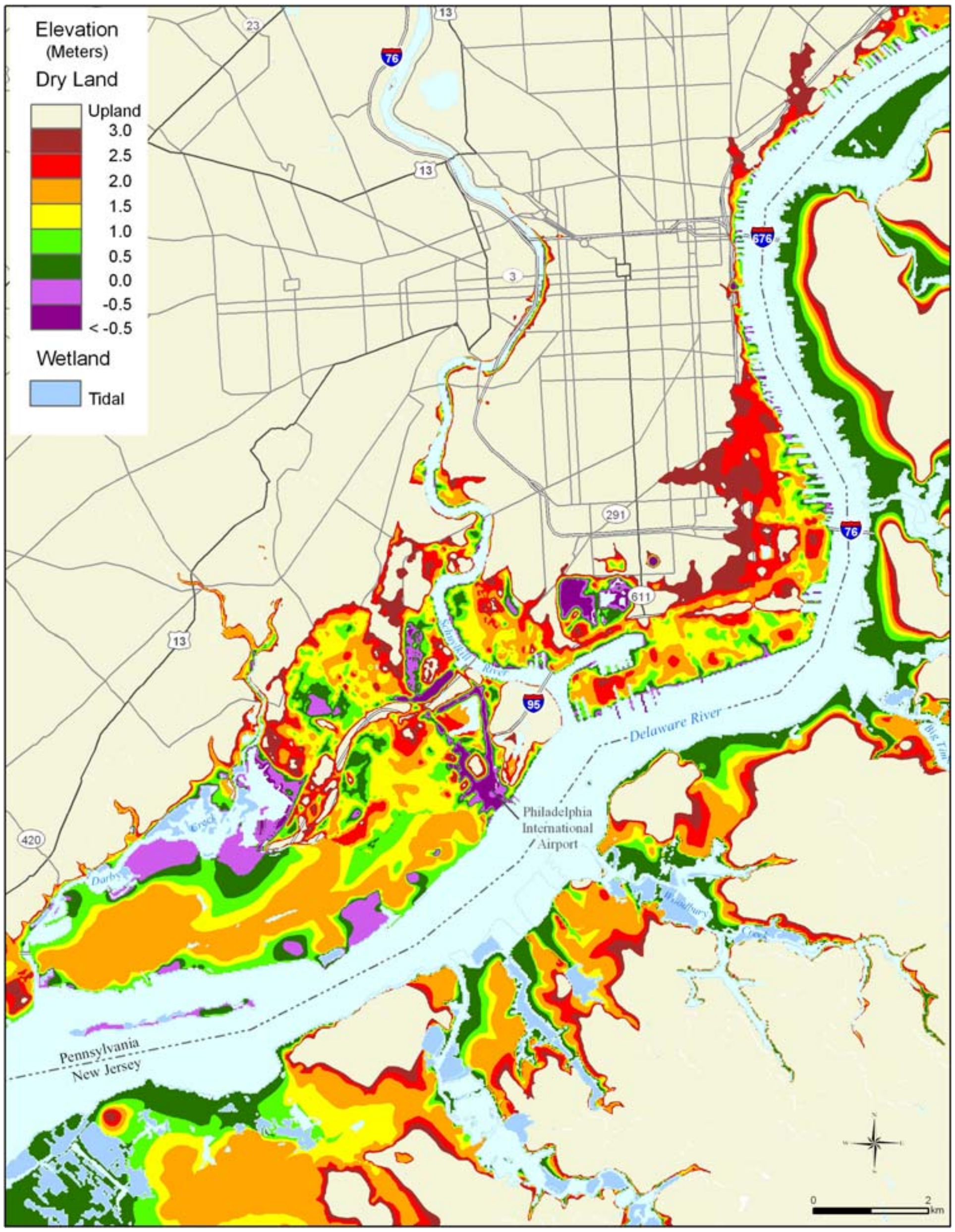


Figure IV.1 Philadelphia: Elevation relative to spring high water.

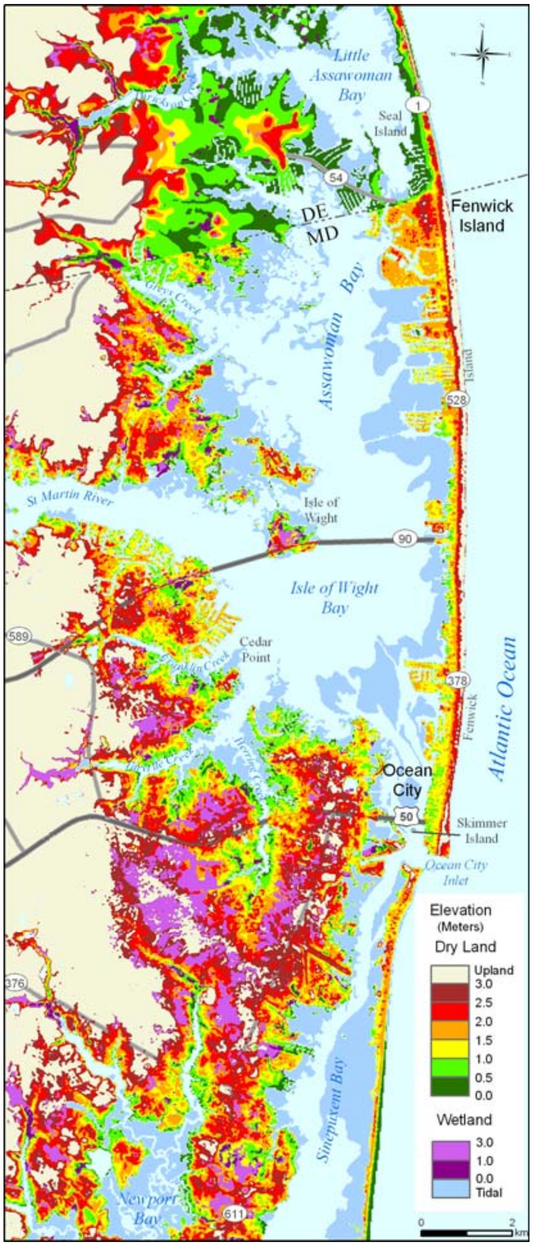
In addition, sea-level rise poses the risk of inundating dry land and reducing habitat for wildlife species along the bay. A sea-level rise modeling study estimated that a 2 foot rise in relative sea level over the next century could reduce shorebird foraging areas in Delaware Bay by 57 percent or more by 2100 (Galbraith *et al.*, 2002). If these foraging habitats are lost and prey species such as horseshoe crab decline, there are likely to be substantial reductions in the numbers of shorebirds supported by the bay (Galbraith *et al.*, 2002).

IV.2.5 DelMarVa (Appendix E)

Along the Atlantic Ocean between the mouths of the Chesapeake and Delaware bays lie approximately 200 kilometers of ocean beaches, only 30 kilometers of which have been developed. Unless conservation policies are reversed or conservation organizations change their priorities, the portion that is now developed is likely all that ever will be developed. All of the Virginia Eastern Shore’s 124-kilometer ocean coast is owned by the U.S. Fish and Wildlife Service, The Nature Conservancy, or NASA. Of Maryland’s 51 kilometers of ocean coast, 36 kilometers are Assateague Island National Seashore, and densely populated Ocean City occupies the other 15 kilometers. More than three-quarters of the barrier islands and spits in Delaware are part of Delaware Seashore State Park, while the mainland coast is about evenly divided between Cape Henlopen State Park and resort towns such as Rehoboth, Dewey Beach, and Bethany Beach.

With development accounting for a smaller portion of land area compared to other regions of the mid-Atlantic coast, the natural shoreline processes may dominate along much of the ocean shores. Counteracting shoreline erosion in developed areas with beach nourishment may continue as the primary shore preservation activity in the near term, but preventing the inundation of low-lying lands will eventually be necessary as well.

Maryland's Coastal Bays National Estuary Program has long included sea-level rise as a factor to be addressed in plans to protect the bays (MCBP, 1999), and the state of Maryland has the most stringent policies governing development along these coastal bays. The Virginia counties of the DelMarVa have shores along both the Atlantic Ocean and Chesapeake Bay, and setback rules that apply to both. Similarly, the Delaware Department of Natural Resources has proposed a 100-foot setback along their coastal bays (DNREC, 2007).



BOX IV.2: Elevating Ocean City as Sea Level Rises

Logistically, the easiest time to elevate low land is when it is still vacant, or during a coordinated rebuilding. Low parts of Ocean City's bay side were elevated during the initial construction. As sea level rises, the town of Ocean City has started thinking about how it might ultimately elevate.

Ocean City's relatively high bay sides make it much less vulnerable to inundation by spring tides than other barrier islands. Still, some streets are below the 10-year flood plain, and as sea level rises, flooding will become increasingly frequent.

However, the town cannot elevate the lowest streets without considering the implications for adjacent properties. A town ordinance requires property owners to maintain a 2% grade so that yards drain into the street. The town construes this rule as imposing a reciprocal responsibility on the town itself to not elevate roadways above the level where yards can drain, even if the road is low enough to flood during minor tidal surges. Thus, the lowest lot in a given area dictates how high the street can be.

As sea level rises, failure by a single property owner to elevate could prevent the town from elevating its streets, unless it changes this rule. Yet public health reasons require drainage, to prevent standing water in which mosquitoes breed. Therefore, the town has an interest in ensuring that all property owners gradually elevate their yards so that the streets can be elevated as the sea rises without causing public health problems.

Ocean City has developed draft rules that would require that, during any significant construction, yards be elevated enough to drain during a 10-year storm surge for the life of the project, considering projections of future sea-level rise. The draft rules also state that Ocean City's policy is for all lands to gradually be elevated as the sea rises.

Note: 1. This discussion is based on the presentation by Terry McGean, city engineer, Town of Ocean

Box Figure IV.2-1

IV.2.6 Chesapeake Bay (Appendix F)

Rising sea level has been altering the Jamestown peninsula in Virginia since at least colonial days. Two hundred years ago, the narrow strip of land that connected the peninsula to the mainland eroded, creating Jamestown Island (Johnson and Hobbs, 1994). Shore erosion also threatened the location of the historic town itself, until a stone revetment was constructed (Johnson and Hobbs, 1994). As the sea rose, the shallow valleys between the ridges on the island became freshwater marsh, and then tidal marsh (Johnson and Hobbs, 1994). Maps from the 17th century show agriculture on lands that today are salt marsh. The National Park Service may eventually have to decide whether to allow the rising sea to convert the island to open water or to continue to armor the shoreline.

Other shorelines along Chesapeake Bay have also been retreating over the last four centuries. Several bay island fishing villages have had to relocate to the mainland as the islands on which they were located eroded away (Leatherman, 1992). Low-lying farms on the eastern shores are converting to marsh, while the marshes in wildlife refuges convert to open water. As sea level rises, the risk of flooding is increasing from Poquoson, Virginia, to Fells Point in Baltimore, Maryland.

Coastal elevations and sensitivity to sea-level rise vary at a local scale along the Chesapeake Bay. Each area confronts unique issues and must design site-specific responses.

For example, between the Choptank River and Ocohannock Creek along the Eastern Shore of Chesapeake Bay lies that nation's fifth largest concentration of land close to sea level (see Figure IV.3). Water levels in roadside ditches rise and fall with the tides in some sections of Dorchester and Somerset Counties in Maryland. Tidal wetlands are gradually encroaching onto many farms. Narrow sandy beaches with gradual sloping shoreline throughout the area could accommodate moderate sea-level rise, assuming no armoring or other barriers exist. Many of the beaches provide critical nesting habitat for the diamondback terrapin (*Malaclemys terrapin*), and proximity of these nesting beaches to nearby marshes provides habitat for new hatchlings. Erosion control and shoreline stabilizing practices block access to the beach, forcing females to travel around the obstructions, or to deposit their eggs below the high tide line.

On the other hand, Lewisetta, Virginia, appears to be the only community along the Potomac River vulnerable to tidal inundation with a 50–100 cm rise in sea level. With a fairly modest rise in sea level, wetlands may begin to take over portions of Lewisetta's homeowners' yards and flooding will be more frequent. But outside a small number of other communities in this area, shore erosion–not inundation–will almost certainly be the primary factor forcing people to choose between shore protection and land loss.

Although each state has conducted assessments, neither Maryland nor Virginia has adopted an explicit policy to address the consequences of rising sea level. Nevertheless, both states have policies designed to protect wetlands, beaches, and private shorefront property and collectively create an implicit policy.

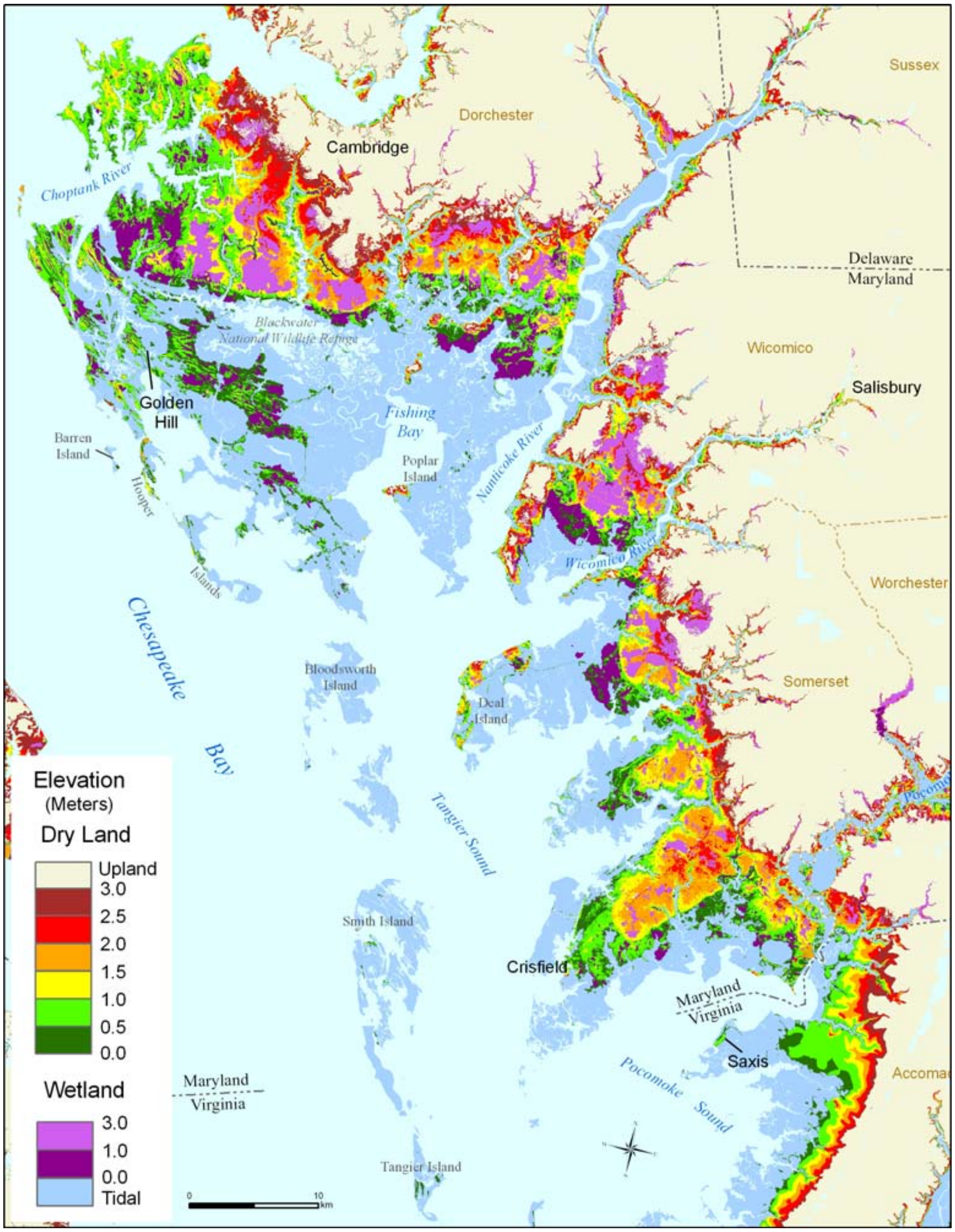


Figure IV.2 Lower Eastern Shore: Lands Close to Sea Level.

IV.2.7 North Carolina (Appendix G)

The third largest area of land vulnerable to rising sea level in the United States lies between Cape Lookout and the mouth of Chesapeake Bay (Figure IV.4). In North Carolina alone, between 1300 and 1800 square kilometers of dry land is within one meter above the tides (Titus and Cacela, 2008) —approximately half the total for the entire Mid-Atlantic. Another 3000 to 3400 square kilometers of non-tidal wetlands are within one meter above the tides —again approximately half the total for the entire Mid-Atlantic. The state of North Carolina alone has as much vulnerable ocean shore as all of the shores from Virginia to New York combined.

Many ocean shores in the state are gradually eroding, claiming shorefront homes and prompting officials to relocate the coastal highway (NC 12) and the Cape Hatteras lighthouse inland. Several studies have estimated increases in future shoreline erosion as sea level rises, and some researchers also believe that the islands off the coast of North Carolina may be in jeopardy if sea-level rise accelerates.

Some wetland systems in North Carolina are already at the limit of their ability to keep pace with rising sea level. Altered drainage patterns appear to be limiting their ability to build upward—and saltwater intrusion could cause subsidence and conversion to open water. Rather than helping the ecosystem respond to rising sea level, human activities appear to be disabling the processes that could otherwise allow these wetlands to stay ahead of the rising sea.

However, several North Carolina laws and regulations have an impact on response to sea-level rise: Buildings being constructed or reconstructed are required to be set back a certain distance from the shoreline, and property owners are not allowed to build seawalls, bulkheads, or dikes to hold back the sea.

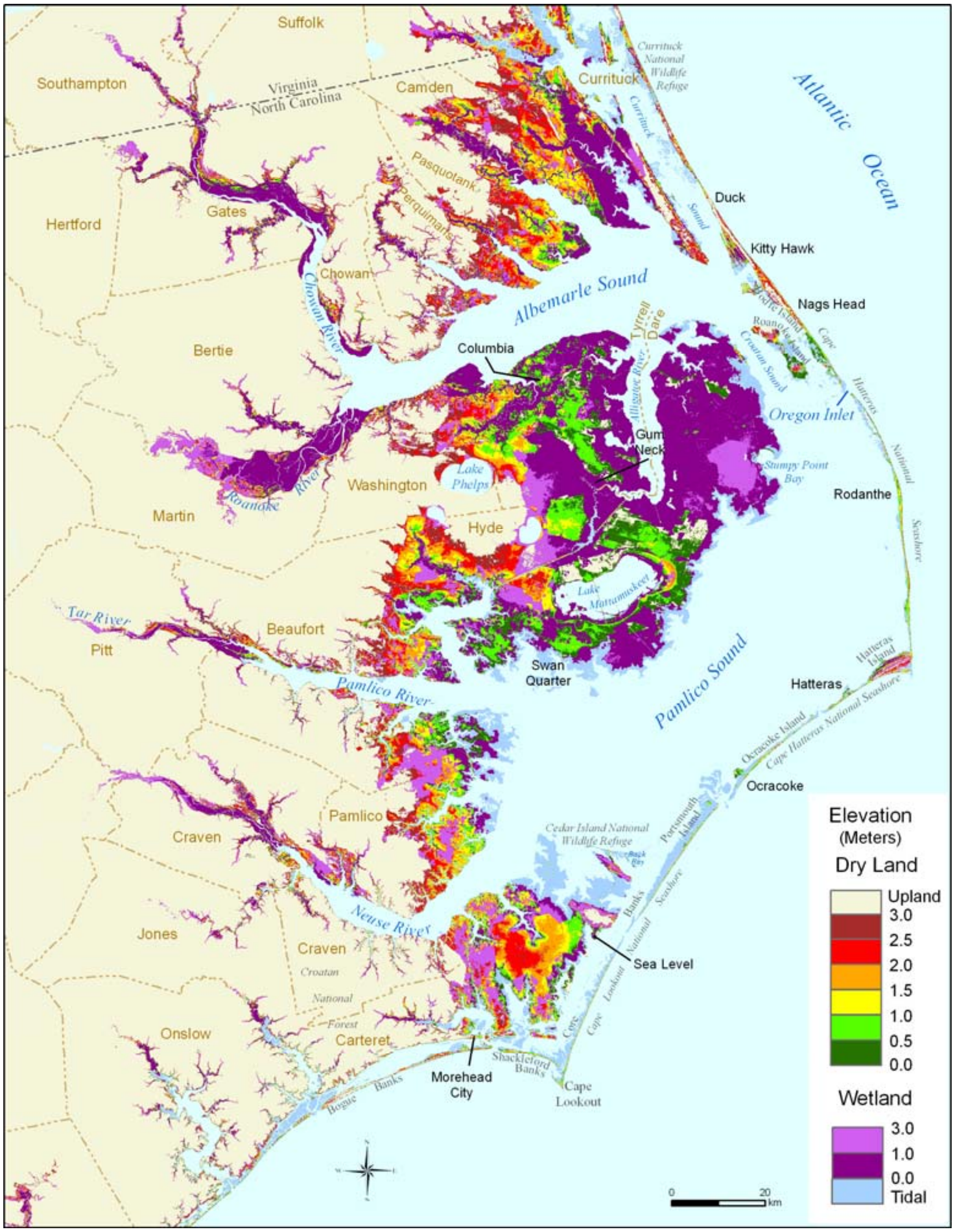


Figure IV.3 Elevation of lands close to sea level: Cape Lookout to Virginia Beach.

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Part V. Implications of Sea-Level Rise to the Nation

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A large and expanding proportion of the United States population and related urban development are located along the Atlantic, Gulf of Mexico, and Pacific coasts and increasingly come into conflict with the natural processes associated with coastal change from extreme storms and sea-level rise. Currently the majority of the population lives in the coastal zone and movement to the coast and development continues in spite of the growing vulnerability. Fourteen of the Nation's 20 largest urban centers are located along the coast, most of which were historically sited on or near the coast to serve as commercial ports and for defense. Coastal populations have increased dramatically over the past 60 years as these urban centers have expanded. In addition, these economic and population pressures have transformed sparsely developed coastal areas into high-density year-round urban complexes. The growth in coastal development has been spurred too by purchase of vacation homes for recreation and retirement. With the very likely accelerated rise in sea level and increased storminess, the conflicts between people and development at the coast and the natural processes will increase dramatically. Sea-level rise associated with climate change will increase erosion and the frequency of flooding and many more coastal areas will become vulnerable. For some regions, mitigation and adaptation may be successful, but for other coastal areas, relocation landward to higher ground may be the only economic means to ensure long term sustainability.

Coastal landforms reflect a complex interaction between the natural physical processes that act on the coast, the geological characteristics of the coast, and human activities that alter coastal landforms and processes. Spatial and temporal variations in these physical processes and the geology along the coast are responsible for the wide variety of landforms around the United States (Williams, 2003). With future sea-level rise, it is **very likely** that the majority of the U.S. ocean coast will undergo long-term net erosion, probably at rates higher than those that have been observed over the past century (Figure V.1). The exact manner and the rates at which these changes are likely to occur depend on the character of coastal landforms and the physical processes, as discussed here and in earlier chapters of this report. Regions of low relief, undergoing land subsidence, and subject to frequent storm landfalls, such as the south-central Gulf of Mexico, Florida, and the Mid-Atlantic are particularly vulnerable.

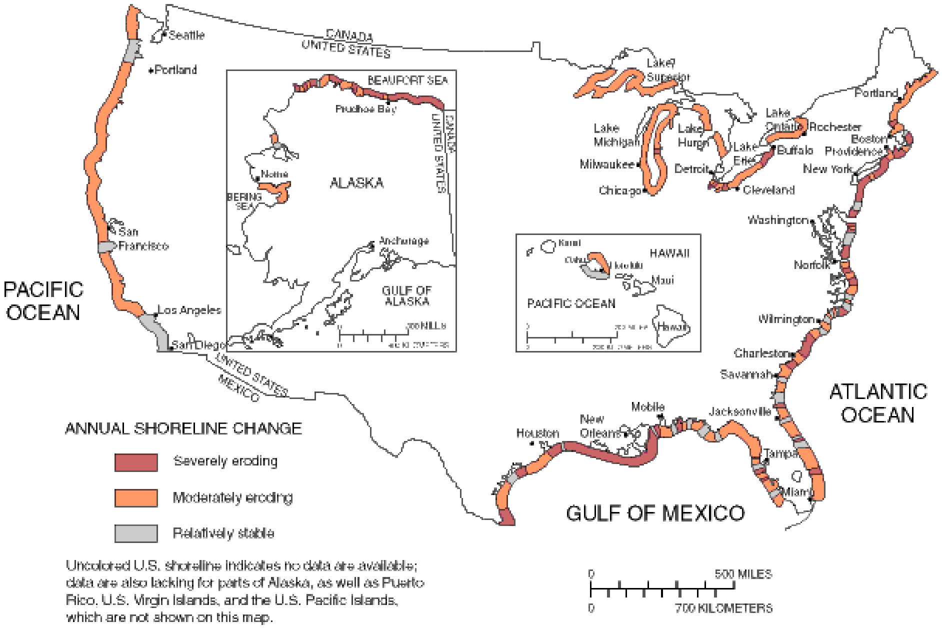

Figure V.1 Map of historic annual ocean shoreline change around the U.S. All 30 coastal states are undergoing erosion at highly variable rates due to natural and human factors (USGS National Atlas, 1985).

V.1 TYPES OF COASTS

Coasts are dynamic junctions of water and land. Winds and waves, tides and currents, migrating sand dunes and mud flats combine to form ever-changing shorelines. The main coastal types found in the mid-Atlantic region as well as the rest of the U.S. are described below. With future sea-level rise, all of these landforms will become more dynamic, but predicting and quantifying change with high confidence will be scientifically challenging.

V.1.1 Cliff and Bluff Shorelines

A portion of the U.S. coast is comprised of coastal cliffs and bluffs (see Chapter 2). These occur predominantly along the Pacific coast, northern New England, and the Alaskan coast where rock intersects the shore and cliffs have formed in ancient marine terraces that have been uplifted (Hampton and Griggs, 2004; Hapke *et al.*, 2006). Active tectonic environments, such as the Pacific coast, produce rocky coasts as a result of mountain-building processes, faulting, and earthquakes. Rocky coasts, such as parts of Massachusetts, New Hampshire, and Maine, form where glacial ice has scoured the land surface and strong waves and currents have winnowed and reworked the glacial sediment. In Alaska, glaciers continue to scour and transport sediment from the land to the shore. Because rocky coasts are composed of resistant rock, erosion is slow and inundation will be a primary response to sea-level rise.

V.1.2 Sandy Shores and Barrier Beaches, Spits, and Dunes

As described in Chapter 2, sandy beaches can be categorized into three types: mainland, pocket, and barrier beaches. Mainland beaches stretch unbroken for many miles along the edges of major landmasses. Some are low relief and prone to flooding; others are backed by steep headlands. They receive sediment from nearby rivers and eroding bluffs. Examples of mainland beaches include northern New Jersey, parts of Delaware and Maryland, and southern California. Pocket beaches form in small bays and are often surrounded by rocky cliffs or headlands. Pocket beaches are common in New England, the Pacific Northwest, and Hawaii. Barrier beaches and spits are the most abundant coastal landform along the Atlantic and Gulf of Mexico coasts. Sandy shores are particularly vulnerable to storms and sea-level rise due to their low elevations and sandy composition and their sensitivity to these processes are **very likely** to increase in the future.

V.1.3 Coastal Wetlands

Coastal wetlands include swamps and tidal flats, coastal marshes, and bayous. They form in low-relief, low-energy sheltered coastal environments, often in conjunction with river deltas, landward of barrier islands, and along the flanks of estuaries (*e.g.*, Delaware Bay, Chesapeake Bay, Everglades, San Francisco Bay). Most coastal wetlands of the U.S. are in Louisiana, North and South Carolinas, Florida, and Alaska. Wetlands are extremely vulnerable to sea-level rise and can maintain their elevation and viability only if sufficient sediment (both mineral and organic) is available and if terrestrial accommodation space is available for migration landward (see Chapter 3, Wetlands Accretion). Under the highest projected rates of future sea-level rise, most wetlands are **likely** to drown and convert to estuarine and open-water environments.

V.1.4 Coral Reef Coasts

Coral reefs in the U.S. are most common along the southeastern coast of Florida, the Keys and around the Hawaiian Islands, Puerto Rico, and the Virgin Islands. In tropical isles, living coral organisms build reefs that provide important wildlife habitats and buffer coasts from waves and storms. Healthy coral reefs are also an important source of carbonate sandy sediment for tropical beaches. Most corals are able to accommodate low to moderate rates of sea-level rise, but warming of the oceans and increased sediment turbidity from storms may have detrimental effects on many coral reef ecosystems.

V.1.5 Mudflat Shores

Mudflat shorelines are in the minority for U.S. coasts, are frequently associated with wetlands, and occur predominately in low-energy regions with high inputs of fine-grained sediments and organic materials. These shoreline types are common to the western Louisiana and along the northeastern part of the Gulf Coast of Florida.

V.2 SHORELINE SETTINGS AROUND THE UNITED STATES

Very marked differences in geological character and processes and climatic settings produce a diverse array of coastal landforms described above occur in the U.S. The three major regions- the Atlantic coast, Gulf of Mexico coast, and Pacific coast exhibit all of these landforms.

V.2.1 Atlantic Coast

The Atlantic coast is a low-relief passive margin comprised of river deposits derived from the erosion of the Appalachian Mountains (Walker and Coleman, 1987). From Long Island and Cape Cod northward, glaciations scoured the landscape leaving glacial deposits that give the coastal landscape its unusual character. From New York to southern Florida, the coast consists almost exclusively of barrier islands, spits and dunes. Along the New England coast, barriers are also present but are shorter, often extending between headlands composed of glacial sand and gravel deposits (FitzGerald *et al.*, 1994). Pocket beaches, coastal cliffs, and bluff coasts occur in a number of places, but these are found mostly in the northeast as a result of the glacial landscape.

V.2.2 Gulf of Mexico Coast

The Gulf coast, like the Atlantic, is classified as a passive margin consisting of a gently sloping coastal plain that has been built by the deltas of large river systems. Eroding mainland shores and the continental shelf are the main sources of sand that maintain the Gulf coast barriers and beaches since the region’s rivers contribute minor amounts of sediment to the coast (Morton *et al.*, 2004). Barrier islands are the dominant coastal landform of this region. Mainland beaches and Chenier plain coasts also occur along minor portions of the coast. Along the shores of southwestern Florida rarer shoreline types can be found, which include mangrove swamps, irregular drowned karst features, and marshes.

V.2.3 Pacific Coast

The tectonic activity from the collision of tectonic plates on the west coast of the U.S. has influenced the development of the coastal landforms (Komar, 2004; Hapke *et al.*, 2006). Because of the active tectonic environment, some portions of the coast are being uplifted at different rates. Uplifting of the crust contributes to the development of steep gradients in the landscape as well as variations in rates of relative sea-level rise along the coast. This is evident from the marine terraces, rock outcrops, and mountain ranges that comprise the coastal landscape. The steep slopes close to the coast contribute to high sediment supplies to coastal rivers. High amounts of sediment in coastal rivers on the Pacific margin provide some of the material that sustains the sandy shores. In addition, erosion of coastal cliffs also contributes a significant amount of sandy material to Pacific coast beaches (Hampton and Griggs, 2004; Hapke *et al.*, 2006). The majority of the ocean coast consists of beaches which front coastal cliffs. Pocket beaches, barrier spits, and barrier islands, which extend between coastal headlands or bays, are also found along the Pacific coast (Komar, 2004; Hapke *et al.*, 2006).

V.3 PREDICTING FUTURE SHORELINE CHANGE

During the last century that scientists have studied shoreline changes, sea-level changes have been relatively small. During this time variations in shoreline position that have occurred reflect perturbations due to storms and sediment supply, as well as changes in sea level (Morton *et al.*, 1994; Douglas *et al.*, 1998; Honeycutt *et al.*, 2001; Zhang *et al.*, 2004). While it is well accepted that sea-level changes can also contribute to this change, the extent has been subject to debate. Because of this complexity, it has been difficult for researchers to reach consensus on a more exact importance and role of sea-level rise in driving shoreline change.

While the factors that influence coastal change in response to sea-level rise are well known, our ability to incorporate this understanding into quantitative models that can be used to predict shoreline change over long time periods is limited. Part of the reason for this is the complexity of quantifying the effect of these factors on shoreline change. The most easily applied models incorporate relatively few factors that influence shoreline change and rely on assumptions that do not always apply to real-world settings. In addition, these assumptions apply best to present conditions, not necessarily those that may exist in the future. Those that do incorporate many of the key factors (*e.g.*, the geological framework and sediment budget) require a precise knowledge on a local scale.

To apply over larger coastal regions, information regarding the model boundary conditions is not readily available.

V.3.1 Coastal Vulnerability to Sea-Level Rise

One approach applied to assess the sea-level rise risks and vulnerability of the Nation's ocean coasts involves the use of a Coastal Vulnerability Index (CVI) (Gornitz *et al.*, 1989; Thieler and Hammar-Klose, 1999). This technique was first applied by Gornitz *et al*. (1989; 1990; 1994) to evaluate coastal hazards along portions of the U.S. open coast. The USGS application of this method relies upon a quantitative ranking scheme to categorize risks due to sea-level rise for the U.S. Atlantic, Pacific, and Gulf of Mexico coasts (Figure V.2, Thieler and Hammar-Klose, 1999). The CVI does not apply to wetlands, but a full discussion of the vulnerability of wetlands to sea-level rise is included in Chapter 3. A total of six geologic and oceanographic variables are used to calculate the CVI for each coastal region: tidal range, wave height, coastal slope, shoreline change, geomorphology, and historical rate of relative sea-level rise. Initially, CVI was applied on a national scale. More recently, the USGS has applied CVI assessments to 25 coastal National Park units to serve as a tool for planning for mitigating or adapting to accelerated sea-level rise (Pendleton *et al.*, 2004).

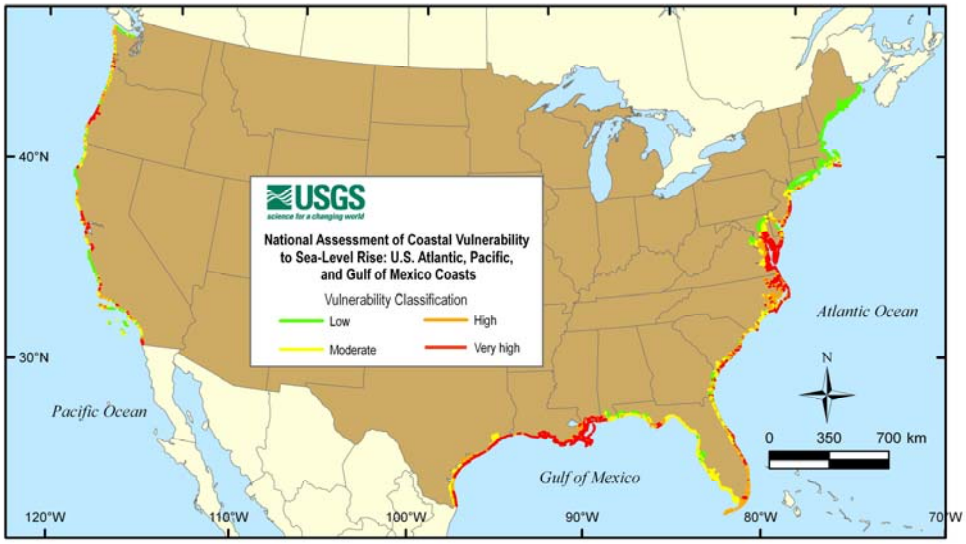

Figure V.2 Map of the Coastal Vulnerability Index (CVI) for the U.S. showing the relative vulnerability of the ocean coast to changes due to future rises in sea level. Segments of the coast are assigned a ranking from low to very high based on the analysis of geologic and oceanographic variables that contribute to coastal change. From Thieler and Hammar-Klose (2000).

In the national assessment, CVI estimates indicated regions of high vulnerability along each coast, particularly the Atlantic and Gulf coasts. On the Atlantic coast, the high-vulnerability areas are typically barrier islands with small tidal ranges, large waves, a low coastal slope and high historical rates of sea-level rise. In contrast, rocky, cliff coasts, such as most of the Maine shoreline, with large tidal ranges, steep coastal slopes, and lower historical rates of sea-level rise are represented as the least vulnerable. On the Gulf coast, high vulnerabilities are also associated with low energy, beach and barrier island settings where the tidal range is low and erosion rates are relatively high. But this vulnerability is enhanced by the highest rates of relative sea-level rise along the U.S. coasts. Along the Pacific coast, there are also many areas of high vulnerability, but these are less extensive than the other coasts. Here, the high-vulnerability areas occur typically along the high energy coast, where pocket beaches are sandwiched between rocky headlands.

V.3.2 Potential for Future Shoreline Change

Space does not permit detailed discussion of the national implications for all of the key questions, but the following addresses potential implications for the physical environment and society as framed by the five main questions:

- Which lands are currently at an elevation that could lead them to be inundated by the tides without shore protection measures?
- How does sea-level rise change the coastline? Among those lands with sufficient elevation to avoid inundation, which land could potentially erode in the next century? Which lands could be transformed by related coastal processes?
- What is a plausible range for the ability of wetlands to vertically accrete, and how does this range depend on whether shores are developed and protected, if at all? That is, will sea-level rise cause the area of wetlands to increase or decrease?
- Which lands have been set aside for conservation uses so that wetlands will have the opportunity to migrate inland; which lands have been designated for uses requiring shore protection; and which lands could realistically be available for either wetland migration or coastal development requiring shore protection?
- What are the potential impacts of sea-level rise on coastal floodplains? What issues would FEMA, coastal floodplain managers, and coastal communities face as sea level rises?

Over the next century, with an acceleration in sea-level rise, the potential for coastal change is **very likely** to increase and be much more variable than has been observed in historic past. The potential changes include increased coastal erosion, more frequent tidal and storm surge flooding of low-relief areas, and wetland deterioration and losses. Many of these changes will occur in all of the 30 coastal states. These changes to the coastal zone will have especially large impacts to developed areas. Relatively minor portions of the U.S. coast, however, will be subject solely to inundation from sea-level rise over the next century. Inundation will be limited to the bedrock coasts such as those in New England and along the Pacific which are resistant to erosion; and, low-energy/low-relief coasts such as upper reaches of bays and estuaries (*e.g.*, Chesapeake and Delaware Bays, Tampa Bay, Lake Pontchatrain, San Francisco Bay). The presence of sandy barrier islands and beaches along the majority of the U.S. coastline indicates that erosion, sand transport and deposition are active processes and will modify coastal environments in response to future sea-level rise.

It is **very likely** that coastal landforms will become even more dynamic and that erosion will dominate changes in shoreline position over the next century and beyond. Wetlands with sufficient sediment supply and available land for inland migration may be able to maintain elevation keeping pace with sea-level rise, but sediment starved wetlands and those constrained by engineering structures or steep uplands are likely to deteriorate or convert to open water. On barrier island shores, erosion will **very likely** occur on both the ocean front and the back-barrier shorelines due to a combination of storm activity, sediment starvation, more frequent tidal flooding, and rising water levels.

It is **very likely** that many coastal areas in the U.S. will experience an increased frequency and magnitude of storm-surge flooding and erosion due to storms over this time period as part of the response to sea-level rise. It is **likely** that the impacts from these storm events will extend farther inland than those that would be affected by sea-level rise alone.

It is **likely** that significant portions of the U.S. will undergo large changes to the coastal system such increased rates of erosion, landward migration, and potential barrier island collapse (see Chapter 2 for discussion of thresholds). The likelihood of crossing thresholds leading to barrier collapse will increase with higher rates of sea-level rise. The barrier coasts of Virginia, North Carolina, and Louisiana are more **likely** to experience evidence of collapse prior to other regions of the U.S. Use of “soft” coastal engineering mitigation activities, such as beach nourishment on large scales using sand dredged from offshore, may reduce the risk of significant erosion or barrier disintegration temporarily, however, a major challenge that must be addressed is whether or not these practices can be maintained for the long-term to provide sustainable erosion protection in the face of high costs and limited offshore sand resources. There are regions now where high quality offshore sand is so limited that continued beach nourishment is in question (*e.g.*, Miami Beach, Outer Banks, NC). The use of “hard” engineering structures (*e.g.*, seawalls, breakwaters) to mitigate erosion and flooding may be economically justified for urban coasts, but their use on sandy shores can further exacerbate erosion over time due to disruption of sediment transport processes. More aggressive alternatives, such as relocation landward, strategic removal of development or limiting redevelopment following storm disasters from highly vulnerable parts of the coast may be considered, especially if the higher, more rapid predicted rates of sea-level rise are realized. If coastal development is removed or not replaced along the shore, those areas could be converted to open-space conservation lands that would buffer sea-level rise effects and also provide recreation and wildlife habitat values.

V.4 PREVIOUS SEA-LEVEL RISE IMPACT ASSESSMENTS

Over the past 25 years, several studies have examined the potential nation-wide impacts and costs of sea-level rise (*e.g.*, EPA, 1989). This report does not fundamentally change our understanding; nevertheless, this report quantifies several impacts using new data for the mid-Atlantic region. If this revised assessment of the Mid-Atlantic is any indication of what a revised nationwide assessment would yield, then the impacts of sea-level rise on the U. S. are more sensitive to the *rate* of sea-level rise than previously assumed.

Previous national assessments estimated that the impact of sea-level rise on the Mid-Atlantic is roughly proportional to how much the sea rises, with some impacts increasing more than proportionately and others less than proportionately. This assessment implies that impacts of sea-level rise on the Mid-Atlantic generally increase proportionately or more than proportionately with the rate of sea-level rise:

- *Inundation:* The area of dry land vulnerable to a 1 meter rise now appears to be 2 times the area vulnerable to a 50 cm rise (see Chapter 1), rather than 1.5 times as previously estimated in EPA's 1989 Report to Congress.
- *Ocean Coast: Cost of Shore Protection:* Previous assessments assumed that shoreline retreat resulting from sea-level rise is proportional to how much the sea rises, and thus the nationwide cost of protecting the ocean coast would be proportional to sea-level rise. This assessment concludes that shoreline retreat may be a nonlinear function of sea-level rise (see Chapter 2), and therefore it may follow that the costs associated with shoreline protection and replenishment may also increase nonlinearly.
- *Loss of Existing Wetlands:* This assessment suggests that tidal wetlands may be better able to keep pace with rising sea level than assumed by previous national assessments. The previous nationwide assessments assumed that most mid-Atlantic wetlands are unable to keep pace with the current rate and none of the wetlands would be able to keep pace with a 2 mm/yr acceleration. This assessment concludes that most mid-Atlantic tidal wetlands can keep pace with today's rate of sea-level rise, and that they would be marginal (but not necessarily lost) with a 2 mm/yr acceleration (see Chapter 3). Like previous assessments, we conclude that a 7 mm/yr acceleration would cause the loss of most existing tidal wetlands in the Mid-Atlantic.
- *Creation of New Wetlands:* This assessment shows that previous nationwide assessments over-estimated the potential for the inland migration of coastal wetlands in the Mid-Atlantic, for two reasons. First: this assessment finds that the amount of land low enough to convert to sea-level rise is about 15-25 percent of the current area of tidal wetlands, while past assessments found that the area was comparable to the

current area of tidal wetlands. Second, it is now better understood that, due to human activities (*e.g.*, shore protection, land use), substantially less land may become submerged than previously estimated.

V.5 AREA OF LAND VULNERABLE TO TIDAL INUNDATION

The EPA (1989) Report to Congress remains the sole *nationwide* estimate of the dry land that could be inundated by the tides with a 50 or 100 cm rise in sea level[45]. The report estimated that a one meter rise in sea level would inundate approximately 20,000 km^2 of dry land. This report grouped the sites into seven regions, one of which was New York to Virginia, which the report defined as “mid-Atlantic.” Our new estimate of the land vulnerable to a 2 m rise is about 30 percent less than the estimate from the 1989 report. Our estimates of the land vulnerable to a 50 or 100 cm rise, however, are 50-60 percent less than those of the 1989 study. The key difference is that our newer data suggest that that dry land is uniformly distributed by elevation below 5 m, although Park *et al.* (1989) found the dry land to be disproportionately close to sea level. The Report to Congress, in effect, estimated land to be 30-40 cm lower on average than this study.

V.5.1 Early Cost Estimates of Shore Protection

EPA’s 1989 Report to Congress and associated studies estimated the nationwide cost of shore protection as sea level rises. More recent studies by Yohe *et al*. (1996) prepared refined estimates more consistent with economic and decision theory, but relied mostly on the same data. A 1 m rise, EPA estimated, would entail shore protection costs of

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[45] The study excluded Alaska and Hawaii.

$143-305 billion, mostly for beach nourishment and elevating the land and structures on coastal barrier islands. Based on an analysis by Weggel *et al.*, the study estimates that the cost of protecting estuarine shores with dikes and bulkheads would be about $11-33 billion, with a cost of $5 billion for the Mid-Atlantic (1985).

Weggel *et al.* (1989) calculated that approximately 9,300 km of shoreline would require new or rebuilt shore protection. This number, however, only considers existing development—consideration of recent and future development would likely increase estimates of total cost of shore protection.

The possibility that more shore protection will be undertaken than was estimated in 1989 is not the only possible source of error in the cost estimates of that study. Other factors that could lead to higher costs than previously estimated include:

- The cost of preserving Louisiana's wetlands and the development behind them were not explicitly addressed.
- The assumption that a dike is designed for the 100-year storm may underestimate the cost of dike construction if communities decide that a greater degree of protection is needed.
- The possibility of increased storm intensity may require larger dikes, and dikes in areas where bulkheads might have otherwise been sufficient.
- The trend has been away from bulkheads and toward other types of shore structures that are more expensive.

- The estimated costs of shore protection were much greater along estuarine shores because EPA (1989) assumed that developed barrier islands would be elevated but that mainland communities would be protected with bulkheads or dikes, which are less expensive. Some mainland communities where dikes are infeasible or aesthetically unacceptable might be elevated as well.

EPA (1989) assumed a gradual increase in sand costs as nearshore supplies were depleted and it became necessary to add booster pumps to the dredging projects to move sand increasing distances. The study assumed that all of the required sand would be available within 10 km of the shore (or available from land sources) at a cost of $20 per cubic meter. That assumption may have been too optimistic. Recent offshore mapping studies and assessments of marine aggregates by USGS suggest that many regions of the U.S., including much of the Mid-Atlantic, have limited usable marine sand resources and sand volumes might not be sufficient to sustain long-term beach nourishment (S.J. Williams, USGS, personal communication).

V.5.2 Coastal Wetlands

The change in the area of coastal wetlands would be the net result of the loss of existing wetlands and the creation of new wetlands as previously dry areas are inundated by the tides. EPA’s 1989 Report to Congress quantified the nationwide loss of coastal wetlands as sea level rises. That report estimated that if developed areas are protected, then a 50 and 100 cm rise in global sea level would cause the nationwide area of coastal wetlands to decline by 20-45 and 29-69%, respectively. For the Mid-Atlantic, the corresponding estimates were 27 and 46%.

Our findings on the loss of existing wetlands imply that if sea-level rise accelerates 2 mm/yr, our uncertainty about the net loss of wetlands is much greater than previously estimated. But with a 7 mm/yr acceleration, the net loss of coastal wetlands is likely to be more than previously estimated.

V.6 CONCLUSIONS

The scientific evidence observed over the past several decades demonstrates with little doubt that the global climate is changing, largely due to carbon emissions from human activities (IPPC, 2007). Sea-level rise is one of the impacts of climate change that will have profound effects on coastal regions of the United States over the next century and beyond. The scientific tools and techniques for predicting the effects of future sea-level rise on coastal systems are superior to what was available just a decade ago, but much remains to be done in order to make reliable predictions. Improved data collection, monitoring of coastal change, and improvements in computer modeling will lead to better understanding and prediction of environmental conditions that are likely to impact the U.S. in the decades ahead. Planning for near future impacts of sea-level rise and increased storminess should include evaluation of a number of alternatives, such as shore protection and strategic relocation of development and population centers. Those decisions should be based careful consideration of long-term benefits for a sustainable future and the total economic and environmental costs of various methods of shore protection and adaptation.

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Part VI: A Science Strategy for Improving Our Understanding of Sea-Level Rise and its Impacts on U.S. Coasts

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VI.1 INTRODUCTION

This section of the report identifies several major themes that present opportunities to improve our scientific understanding of future sea-level rise and its impacts on U.S. coastal regions. Advances in scientific understanding will enable the development of higher quality and more reliable information for planners and decision makers at all levels of government, as well as the public. An integrated scientific program of sea level studies that seeks to learn from the historic and geologic past, and monitor ongoing physical and environmental changes will improve our knowledge and reduce the uncertainty about potential responses of coasts, estuaries and wetlands to sea-level rise. Outcomes of scientific research will support decision making and adaptive management in the coastal zone. The main elements of a potential science strategy, and their interrelationships, are shown in Figure VI-1.

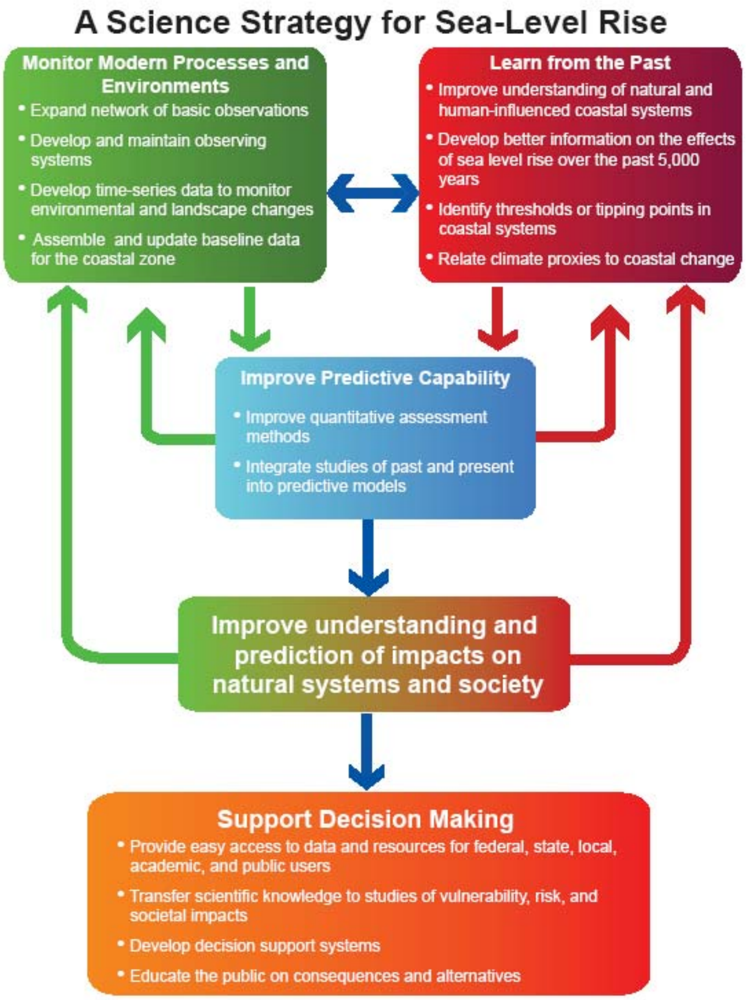

Figure VI.1 Schematic flow diagram summarizing a science strategy for improvement of scientific knowledge and decision making capability needed to address the impacts of future sea level rise.

Building on and complementing ongoing efforts at federal agencies and universities, a research and observation program should incorporate new technologies to address the complex scientific and societal issues highlighted in this report. These studies should include further development of a robust monitoring program for all coastal regions, leveraging the existing network of site observations, as well as the growing array of coastal observing systems. Research should also include studies of the historic and recent geologic past to understand how coastal systems evolved in response to past changes in sea level. The availability of higher resolution data collected over sufficient time spans, coupled with conceptual and numerical models of coastal evolution should provide the basis for improved quantitative assessments and the development of predictive models useful for decision making. Providing ready access to interpretations from scientific research – as well as the underlying data – by means of publications, data portals, and decision support systems will allow coastal managers to evaluate alternative strategies for mitigation, develop appropriate responses to sea-level rise, and practice adaptive management as new information becomes available.

A number of recent studies have focused specifically on research needs in coastal areas. Two National Research Council (NRC) studies, *Science for Decision-making* (NRC, 1999) and *A Geospatial Framework for the Coastal Zone* (NRC, 2004) contain numerous recommendations for science activities that can be applied to sea-level rise studies. Other relevant NRC reports include *Responding to Changes in Sea Level* (NRC, 1987), *Sea Level Change* (NRC, 1990) and *Abrupt Climate Change* (NRC, 2002). The Marine Board of the European Science Foundation's Impacts of Climate Change on the European Marine and Coastal Environment (Philippart, *et al.*, 2007) identified numerous research needs, many of which have application to the U.S. Recent Pew Trust studies (Panetta, 2003, Kennedy, *et al.*, 2002) on global climate change included the coastal zone. Other recent studies by the NRC (1990a, 1990b, 1990c, 2001, 2006a, 2006b) and the Heinz

Center (2000, 2002a, 2002b, 2006) have addressed issues relevant to the impacts of sea-level rise on the coastal zone. These reports and related publications have helped guide the development of the potential research and decision support activities described below.

VI.1.1 Learn From the Historic and Recent Geologic Past

Studies of the recent geologic and historical record of sea-level rise and coastal and environmental change are needed to improve our understanding of the key physical and biological processes involved in coastal change. As described throughout this report, and particularly in Chapters 2 and 3, significant knowledge gaps exist that inhibit useful prediction of future changes.

- Improve understanding of natural and human-influenced coastal systems

Significant opportunities exist to improve predictions of coastal response to sea-level rise. For example, our understanding of the processes controlling and rates of sediment flux in both natural and especially in human-modified coastal systems is still evolving. This is particularly true at the regional (littoral cell) scale, which is often the same scale at which management decisions are made. The human impact on coastal processes at management scales is not well understood. Shoreline engineering such as bulkheads, revetments, seawalls, groins, jetties and beach nourishment can alter fundamentally the way a coastal system behaves by changing the transport, storage, and dispersal of sediment. The same is true of development and infrastructure on mobile landforms such as the barrier islands that comprise much of the mid-Atlantic coast.

- Develop better information on the effects of sea-level rise over the past 5,000 years

Broadly speaking, the foundation of modern coastal barrier island and wetland systems has evolved over the past 5,000 years as the rate of sea-level rise slowed significantly. More detailed investigation of coastal sedimentary deposits is needed to understand the rates and patterns of change during this part of the recent geologic past. Advances in stratigraphic sampling and analytical techniques over the past 15 years have improved significantly the centennial to millennial scale record of sea-level rise and coastal environmental change (*e.g.*, Gehrels, 1994; Gehrels *et al.*, 1995; van de Plassche, 1997; Donnelly *et al.*, 2001; Horton *et al.*, 2006) and provide a basis for future work.

- Understand thresholds in coastal systems that, if crossed, could lead to rapid changes to coastal and wetland systems

Several aspects of climate change studies, such as atmosphere-ocean interactions, vegetation change, sea-ice extent, and glaciers and ice cap responses to temperature and precipitation, involve understanding the potential for abrupt climate change or 'climate surprises' (Meehl *et al.*, 2007). Coastal systems may also respond abruptly to changes in sea-level rise or other physical and biological processes (see Box 2.1 in Chapter 2). Coastal regions that may respond rapidly to even modest changes in future external forcing need to be identified, as well as the important variables driving the changes.

For example, limited sediment supply, and/or permanent sand removal from the barrier system, in combination with an acceleration in the rate of sea-level rise, could result in the development of an unstable state for some barrier island systems (*i.e*., a behavioral threshold or tipping point). Coastal responses could result in: a) landward migration or roll-over, b) barrier segmentation, or c) barrier disintegration. If the barrier were to disintegrate, portions of the ocean shoreline could migrate or back-step toward and/or merge with the mainland.

The future evolution of low-elevation, narrow barriers will likely 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 back-barrier systems, altering local sediment budgets and leading to a reduction in sandy materials available to sustain barrier systems (FitzGerald *et al.*, 2003, 2006).

- Relate climate proxies to coastal change

Links between paleoclimate proxies (*e.g.*, atmospheric gases in ice cores, isotopic composition of marine microfossils, tree rings), sea-level rise, and coastal change should be explored. Previous periods of high sea level, such as those during the last several interglacial periods, provide tangible evidence of higher-than present sea levels that are broadly illustrative of the potential for future shoreline changes. For example, sea level high-stands approximately 420,000 and 125,000 years ago left distinct shoreline and other coastal features on the U.S. Atlantic coastal plain (Colquhoun *et al.*, 1991; Baldwin *et al.*, 2006). While the sedimentary record of these high-stands is fragmentary, opportunities exist to relate past shoreline positions with climate proxies to improve our understanding of the relationships between the atmosphere, sea level, and coastal evolution. Future studies may also provide insight into how coastal systems respond to prolonged periods of high sea level (MIS 11), and rapid sea level fluctuations during a high-stand (MIS 5) (Neumann and Hearty, 1996).

VI.1.2 Monitor Modern Coastal Conditions

The status and trends of sea level change and changes in coastal environments should be better monitored by expanding the existing network of observation sites, as well as through the continued development of coastal and ocean observing systems. There are numerous ongoing efforts that could be leveraged to contribute to understanding spatial and temporal patterns of sea level rise and the response of coastal environments.

- Expand the network of basic observations

The coverage and quality of the U.S. network of basic observations of sea level should be improved. Tide gauges are a primary source of information for sea-level rise data at a wide range of temporal scales, from minutes to centuries. These data contribute to a multitude of studies on local to global sea level trends. U.S. tide gauge data include some of the longest such data sets in the world and have been especially valuable for monitoring long-term trends.

A denser network of high-resolution gauges is needed to rigorously assess regional trends and effects. The addition of tide gauges along the open ocean coast of the U.S. would be valuable in some regions. These data can be used in concert with satellite altimetry observations. Tide gauge observations also provide records of terrestrial elevation change that contributes to relative sea level change and can be coupled with field- or model-based measurements or estimates of land elevation changes. Existing and new gauges should also be connected to GPS-based Continuously Operating Reference Systems (CORS) to enable the coupling of the geodetic and oceanographic vertical reference frames at the land-sea interface. Long time series data from CORS can provide precise local vertical land movement information (*e.g.*, Snay et al, 2007; Woppelmann *et al*, 2007) that contribute to the delineation of eustatic and non-eustatic sea level change.

- Develop and maintain coastal observing systems

Observing systems have become an important tool for examining environmental change. They can be place-based (*e.g.*, specific estuaries or ocean locations), or consist of regional aggregations of data and scientific resources (*e.g.*, the developing network of coastal observing systems, such as that for the Gulf of Maine) that cover an entire region. Oceanographic observations also need to be integrated with observations of habitats biological processes.

An example of place-based observing systems is the National Estuarine Research Reserve System (NERRS: http://www.ners.noaa.gov/, accessed 21 September 2007), a network of 27 reserves for long-term research, monitoring, education, and resource stewardship. Targeted experiments in such settings can potentially elucidate impacts of sea-level rise on the physical environment, such as shoreline change or impacts to groundwater systems, or biological processes, such as species changes or ecosystem impacts. Important contributions are also made by the Long Term Ecological Research sites (http://www.lternet.edu/, accessed 21 September 2007) such as the Virginia Coast Reserve. The sites combine long-term data with current research to closely examine ecosystem change over time. Integration of these ecological monitoring networks with the geodetic and tide gauge networks mentioned previously would also be an important enhancement.

The Integrated Ocean Observing System (IOOS) (http://www.ocean.us/, accessed 21 September 2007) will bring together observing systems and data collection efforts to understand and predict changes in the marine environment. Many of these efforts can contribute to understanding spatial and temporal changes in sea-level rise. These observing systems bring together a wide range of data types and sources, and provide an integrated approach to ocean studies. Such an approach should enable sea-level rise-induced changes to be distinguished from the diverse processes that drive changes in the coastal and marine environment.

A major new initiative began in 2005 with a worldwide effort to build a Global Earth Observation System of Systems (GEOSS) (http://www.earthobservations.org/, accessed 21 September 2007) over the next 10 years. GEOSS will work with and build upon existing national, regional, and international systems to provide comprehensive, coordinated Earth observations from thousands of instruments worldwide, and should have broad application to sea-level rise studies.

- Develop time series data to monitor environmental and landscape changes

Observations of sea level using satellite altimetry (*e.g.*, TOPEX/Poseidon) have provided new and important insights into the temporal and spatial patterns of sea level change. Such observations have allowed scientists to examine sea level trends and compare them to the instrumental record (Church *et al.*, 2001; 2004), as well as predictions made by previous climate change assessments (Rahmstorf *et al.*, 2007). The satellite data provide spatial coverage not available with ground-based methods such as tide gauges, and provide an efficient means for making global observations. Plans for future research should include a robust satellite observation program.

Studies of environmental and landscape change also need to be expanded across larger spatial scales and longer time scales. Examples include systematic mapping of shoreline changes and coastal barrier and dunes around the U.S. (*e.g.*, Morton and Miller, 2005), and other national mapping efforts to document land use and land cover changes (*e.g.*, the NOAA Coastal Change Analysis Program: http://www.csc.noaa.gov/crs/lca/ccap.html, accessed 21 September 2007). It is also important to undertake a rigorous study of land movements beyond the point scale of tide gauges and Global Positioning System networks. A good example is the application of an emerging technology—Interferometric Synthetic Aperture Radar (InSAR)—which enables the development of spatially-detailed maps of land-surface displacement over broad areas (Brooks *et al.*, 2007).

Determining wetland sustainability to current and future sea-level rise requires a broader foundation of observations if they are to be applied with high confidence at regional and national scales. In addition, there is a significant knowledge gap concerning the viability or sustainability of human-impacted and restored wetlands in a time of accelerating sea-level rise. The maintenance of the network of sites that utilize surface elevation tables and soil marker horizons for measuring marsh accretion or loss will be essential in understanding the impacts on areas of critical wetland habitat. The addition of sites to the network would aid in delineating regional variations (Cahoon, *et al.*, 2006). Similar long term studies for coastal erosion, habitat change, and water quality are essential.

Coastal process studies require a long time series of data to evaluate changes in beach and barrier profiles to track morphological changes over a period where there has been a significant rise in sea level. These data will also reflect the effects of storms and the sediment budget that frequently make it difficult to extract the coastal response to sea level change. For example, routine lidar mapping updates to track morphological changes and changes in barrier island area above mean high water (*e.g.* Morton and Sallenger, 2003), as well as dune degradation and recovery, and shore-face profile and near-shore bathymetry evolution may provide insight into how to distinguish various time and space scales of coastal change and their relationship to sea-level rise.

Time series observations can also be distributed across the landscape and need not be tied to specific observing systems or data networks. They do, however, need a means to have their data assimilated into a larger context. For example, new remote sensing and *in-situ* technologies and techniques should be developed to help fill critical data gaps at the land-water interface.

- Assemble and update baseline data for the coastal zone

Baseline data for the coastal zone, including elevation, bathymetry, shoreline position, and geologic composition of the coast, as well as biologic and ecologic parameters such as vegetation and species distribution, ecosystem and habitat boundaries, should be collected at high spatial resolution. Existing 30-meter digital elevation models are generally inadequate for meaningful mapping and analyses in the coastal zone. The use of lidar data, with much closer data spacing and better vertical resolution, is essential. While some of these mapping data are being collected now, there are significant areas around the U.S. that need higher quality data. More accurate bathymetric data, especially in the near-shore, is required for site specific analyses and to develop a complete topographic-bathymetric model of the coastal zone to be able to predict with confidence wave and current actions, inundation, shoreline erosion, sediment transport, and storm effects.

To improve confidence in model predictions of wetland vulnerability to sea-level rise, more information is needed on: 1) maximum accretion rates (*i.e.*, thresholds) regionally and among vegetative communities, 2) wetland dynamics across larger landscape scales, 3) the interaction of feedback controls on flooding with other accretion drivers (*e.g.*, nutrient supply and soil organic matter accumulation), 4) fine-grained, cohesive sediment supplies, and 5) changing land use in the watershed (*i.e.*, altered river flows and accommodation space for landward migration of wetlands). In addition, population data on different species in near shore areas are needed to accurately judge the effects of habitat loss or transformation. More extensive and detailed areas of habitat mapping will enable preservation efforts to be focused on the most important areas.

VI.1.3 Predict Future Coastal Conditions

Studies of the past history of sea-level rise and coastal response, combined with extensive monitoring of present conditions, will enable more robust predictions of future sea-level rise impacts.

- Develop quantitative assessment methods that identify high-priority areas (geographic or topical) needing useful predictions

Assessment methods are needed to identify both geographic and topical areas most in need of useful predictions of sea-level rise impacts. For example, an assessment technique for objectively assessing potential effects of sea-level rise on open coasts, the Coastal Vulnerability Index (CVI), has been employed in the U.S. and elsewhere (*e.g.*, Gornitz and White, 1992; Shaw *et al.*, 1998; Thieler and Hammar-Klose, 1999; 2000a; 200b). Although the CVI is a fairly simplistic technique, it offers useful insights and has found application as a coastal planning and management tool (Thieler *et al.*, 2002).

Projecting long-term wetland sustainability to future sea-level rise requires data on accretionary events over sufficiently long time scales that encompass return frequencies of major storms, floods, and droughts, as well as information on the effects of wetland elevation feedback on inundation and sedimentation processes that affect wetland vertical accretion. Numerical models can be applied to predict wetland sustainability at the local scale, but there is not sufficient data to populate these models at the regional or national scale (see Chapter 3). Given this data constraint, current numerical modeling approaches will need to improve or adapt such that they can be applied at broader spatial scales with more confidence.

- Integrate studies of past and present coastal behavior into predictive models

As summarized by Gutierrez *et al.* (2007), existing shoreline-change prediction techniques are typically based on assumptions that are either difficult to validate or too simplistic to be reliable for many real-world applications. As a result, the usefulness of these modeling approaches has been debated in the coastal science community (see Chapter 2). Newer models that include better representations of real-world settings and processes (*e.g.*, Cowell and Roy, 1992; Stolper *et al.*, 2005; Pietrafesa *et al.*, 2007) have shown promise in predicting coastal evolution. Informing these models with improved data on past coastal changes should result in better predictions of future changes.

Although the process of marine transgression across the continental shelf has left an incomplete record of sea level and environmental change, an improved understanding of the rate and timing of coastal evolution is needed to improve models of coastal change. Using a range of techniques such as high-resolution seafloor and geologic framework mapping coupled with geochronologic and paleoenvironmental studies, the record of Late Pleistocene to Holocene coastal evolution should be explored to identify the position and timing of former shorelines and coastal environments.

VI.1.4 Develop Coastal Decision Support Systems for Planning and Policy Making

For coastal zone managers in all levels of government, there is a pressing need for more scientific information, a reduction in the ranges of uncertainty for processes and impacts, and new methods of assessing options and alternatives for management strategies. Geospatial information on a wide range of themes that is maintained on regular cycle will be a key component of planning for mitigation and adaptation strategies. For example, specialized themes of data such as hydric soils may be critical to understanding the potential for wetland survival in specific areas. Developing and maintaining high resolution maps that incorporate changes in hazard type and distribution, coastal development, and societal risk will be critical. A regular process of undertaking vulnerability assessments and reviews will be necessary to adapt to changing conditions.

- Provide easy access to data and information resources for federal, state, local, academic, and public users

Understanding and acting on scientific information about sea-level rise and its impacts will depend upon common, consistent, shared databases for integrating knowledge and providing a basis for decision making. Thematic data and other value-added products should adhere to predetermined standards to make them universally accessible and transferable through internet portals. All data should be accompanied by appropriate metadata (NRC, 2004).

In order to combine terrestrial and marine data in a seamless geospatial framework, a national project to develop and apply data integration tools should be initiated. This will involve the collection of real-time tide data and the development of more sophisticated hydrodynamic models for the entire U.S. coastline, as well as the establishment of protocols and tools for merging bathymetric and topographic datasets (NRC, 2004). Modern and updated digital flood insurance rate maps (DFIRM) that incorporate future sea-level rise are needed in the coastal zone.

- Transfer scientific knowledge to studies of vulnerability, risk, and societal impacts

In addition to basic scientific research and environmental monitoring, a significant need exists to integrate the results of these efforts into comprehensive vulnerability and risk assessments. Tools are needed for mapping, modeling, and communicating risk to help public agencies and communities understand and reduce their vulnerability to, and risk of, sea-level rise hazards. Social science research activities are also needed that examine societal consequences and economic impacts of sea-level rise, as well as identify institutional frameworks needed to adapt to changes in the coastal zone.

For example, analyses of the economic costs of armoring shores at risk of erosion and the expected lifespan of such efforts will be required, as will studies on the durability of armored shorefronts under different sea-level rise scenarios. The physical and biological consequences of armoring shores will need to be quantified and the tradeoffs communicated. Effective planning for sea-level rise will also require integrated economic assessments on the impact to fisheries, tourism, and commerce.

Applied research in the development of coastal flooding models for the subsequent study of ecosystem response to sea-level rise is underway coastal states such as North Carolina (Feyen *et al.*, 2006). There is also a need for focused study on the ecological impacts of sea-level rise and in how the transfer of this knowledge can be made to coastal managers for decision-making.

- Develop decision support systems

Feedback from stakeholder meetings during the preparation of this report made it clear that county and state planners need tools to analyze vulnerabilities, explore the implications of alternative response measures, assess the costs and benefits of options, and provide decision making support. These might take the form of guidelines, checklists, or software tools. In addition, stakeholders recognize the need to examine issues in a landscape or ecosystem context rather than only administrative boundaries.

In addition to new and maintained data, models, and research, detailed site studies will be required to assess potential impacts on a site-specific basis and provide information that allows informed decision making. Appropriate methodologies need to be developed and made available. These will have to look at a full range of possible impacts including aquifer loss by saltwater intrusion, wetland loss, coastal erosion, and infrastructure implications, as well as the impact of adaptation measures themselves. Alternative strategies of adaptive management will be required. Each locality may need a slightly different mix of responses to provide a balanced policy of preserving ecosystems, protecting critical infrastructure, and adjusting to property loss or protection. Providing a science-based set of decision support tools will provide a sound basis for making these important decisions.

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Appendix A. Long Island

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Long Island has almost 1,350 miles of coastline along Long Island Sound, the Peconic bays, the south shore bays, and the Atlantic Ocean. Its northern coast is characterized by high bluffs, while the south coast includes low-lying inner bays and a long stretch of barrier islands that provide recreational beach access for many New Yorkers (such as Jones Beach State Park). Long Island consists of Nassau County, Suffolk County, and the New York City boroughs of Brooklyn and Queens (discussed in Appendix B). Nassau County is primarily suburban and very densely developed, with less than 2% of the land area vacant. Suffolk County to the east is comparatively less developed. Although not part of Long Island, this chapter includes some discussion of the areas of Westchester County, NY, and the Bronx, which have shorelines on the Long Island Sound.

A.1 LANDS VULNERABLE TO INUNDATION

The north shore of Long Island is generally characterized by high bluffs of glacial origin, making this area less susceptible to problems associated with increased sea level. This can be observed in Figure A.1. The south shore has comparatively much more land under 3 meters. Almost all areas in the barrier islands along the south shore of Long Island and the tidal wetlands south of Nassau County in Great South Bay are low-lying. Between 81 and 193 square kilometers of lands are within 1 meter above the tides (see Table A.1); as the map shows, almost all of this land lies along the south shore of Long Island. As a result, there are already enormous planning efforts under way in the region to preserve the dry lands under threat of inundation. A brief discussion of these efforts, especially on the south shore, is provided in the policy discussion at the end of this chapter.

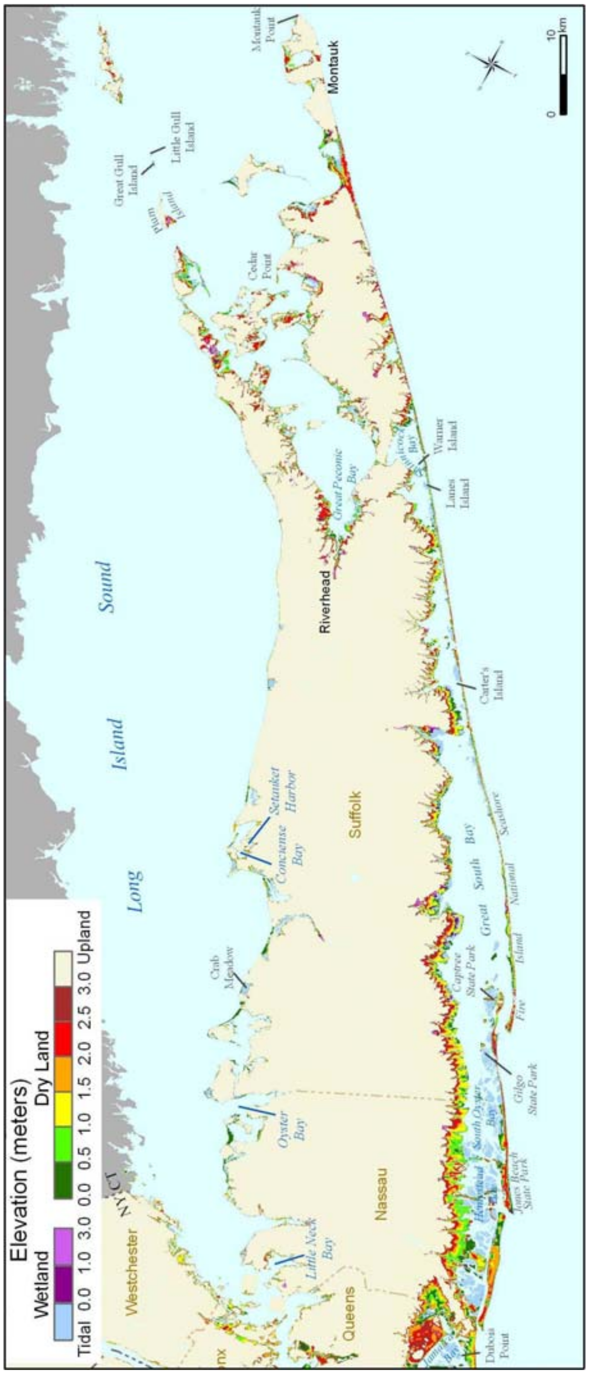

Figure A.1 Long Island: Elevations relative to spring high water (Source: Titus and Wang, 2008).

Table A.1 Low and high estimates for the area of dry and wet land close to sea level.

Long Island Sound, New York
(square kilometers)

		50 cm		1 meter		2 meters		3 meters		5 meters	
	Tidal	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Locality	**Cumulative (total) amount of dry land below a given elevation**										
Westchester		0.2	1.5	1.1	3.0	2.8	5.8	5.1	8.6	10.0	12.4
Bronx		0.4	2.6	1.8	5.1	4.8	9.8	8.7	14.6	16.9	19.6
Queens		6.2	17.0	14.6	28.1	31.7	48.6	50.7	66.6	76.5	80.8
Brooklyn		3.1	9.1	8.0	15.6	18.8	30.5	34.0	47.4	58.9	62.8
Nassau		2.2	19.2	12.9	44.5	50.9	85.4	85.4	104.1	119.3	132.1
Suffolk		13.7	51.5	43.1	96.8	114.9	181.3	188.6	251.3	318.8	371.4
Total		**25.8**	**100.9**	**81.4**	**193.1**	**223.9**	**361.4**	**372.4**	**492.6**	**600.4**	**679.1**
	Cumulative (total) amount of wetlands below a given elevation										
Westchester	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
Bronx	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
Queens	11.9	0.0	0.2	0.1	0.3	0.4	0.5	0.5	0.6	0.7	0.7
Brooklyn	10.1	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2
Nassau	43.7	0.1	0.4	0.3	0.7	0.8	1.5	1.4	2.1	2.6	3.2
Suffolk	72.1	1.5	5.7	4.9	9.8	10.8	15.2	15.1	18.3	20.8	23.8
Total	**140.0**	**1.7**	**6.4**	**5.4**	**11.0**	**12.1**	**17.4**	**17.2**	**21.3**	**24.3**	**28.1**
Dry and nontidal wetland		27	107	87	204	236	379	390	514	625	707
All land	140	167	247	227	344	376	519	530	654	765	847

Source: Titus J.G., and D. Cacela, 2008: Uncertainty Ranges Associated with EPA's Estimates of the Area of Land Close to Sea Level. Section 1.3 in: *Background Documents Supporting Climate Change Science Program Synthesis and Assessment Product 4.1: Coastal Elevations and Sensitivity to Sea Level Rise*, J.G. Titus and E.M. Strange (eds.). EPA 430R07004. U.S. EPA, Washington, DC. The low and high estimates are based on the contour interval and/or stated root mean square error (RMSE) of the data used to calculate elevations and an assumed standard error of 30 cm in the estimation of spring high water.

A.2 ENVIRONMENTAL IMPACTS

North Shore and Peconic Bay. Sea-level rise may threaten habitats along the Long Island Sound including the North Shore, Westchester, and the Bronx, as well as the Peconic Estuary at the far eastern end of Long Island. Habitats of interest include tidal marsh, estuarine beaches, tidal flats, nearshore shallows, sea-level fens, and marsh and bay islands.

Of the 8,425.6 hectares (20,820 acres) of tidal wetlands in the Sound, about 15% are found in New York, primarily along the shores of Westchester and Bronx counties (Holst, 2003). There are some notable areas of marsh in and around Stony Brook Harbor and West Meadow, bordering the Nissequogue River and along the Peconic Estuary (NYS DOS, 2004), In general, tidal wetlands along the north shore are limited due to the steep uplands and bluffs[46]. Wetland loss may be expected if the shorelines of Long Island Sound are structurally protected (see Chapter 5)[47]. Indeed, there has already been a significant loss of the historical area of vegetated tidal wetlands in Long Island Sound (Holst, 2003; Hartig and Gornitz, 2004), which some scientists partially attribute to sea-level rise (Mushacke, 2003).

The loss of vegetated low marsh reduces habitat for several rare bird species that nest only or primarily in low marsh (*e.g.*, seaside sparrow)[48]. Low marsh also provides safe foraging areas for small resident and transient fishes (*e.g.*, weakfish, winter flounder). Diamondback terrapin live in the creeks of the low marsh, where they feed on plants, molluscs, and crustaceans (LISF, 2008).

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[46] Ron Rosza, coastal ecologist with the Connecticut Office of the Long Island Sound Program, written communication to EPA, 5/14/07.

[47] Map 1, “Study Results for Coastal Region of New York State,” in Tanski, J. In review. Assessment of Sea Level Rise Response Scenarios in New York. U.S. Environmental Protection Agency, Washington, DC.

[48] See section on marshes, and references therein, in Chapter 4.

Some wetlands along Long Island Sound may be allowed to respond naturally to sea-level rise, including some in the Peconic Estuary. Where migration is possible, preservation of local biodiversity as well as some regionally rare species is possible. Several rare bird species are found in the Flanders Bay wetlands, including least tern, common tern, piping plover, black skimmer, osprey, and common loon (NYS DOS, 2004) (see text box on piping plover). Waterfowl also feed in and around the wetlands.

Beaches are far more common than tidal wetlands in the Long Island Sound study area. Several notable barrier beaches exist. For example, the sandy barrier-beach system fronting Hempstead Harbor supports a typical community progression from the foreshore to the bay side, or backshore (LISHRI, 2003). The abundant invertebrate fauna provide forage for sanderling, semipalmated plovers, and other migrating shorebirds (LISHRI, 2003). The maritime beach community between the mean high tide and the primary dune provides nesting sites for several rare bird species, including piping plover, American oystercatcher, black skimmer, least tern, common tern, roseate tern, the Northeastern beach tiger beetle, and horseshoe crab (LISHRI, 2003). Diamondback terrapin use dunes and the upper limit of the backshore beach for nesting (LISHRI, 2003).

Since nearly all of the Long Island shoreline of the Sound is densely populated and highly developed, the land may be armored in response to sea-level rise, raising the potential for beach loss. The Long Island Sound Habitat Restoration Initiative cautions, “Attempts to alter the natural cycle of deposition and erosion of sand by

> construction of bulkheads, sea walls, groins, and jetties interrupt the formation of new beaches" (LISHRI, 2003).

Shallow water habitats are a major ecological feature in and around the Peconic Estuary. Here eelgrass beds provide food, shelter, and nursery habitats to diverse species, including worms, shrimp, scallops and other bivalves, crabs, and fish (PEP, 2001). Horseshoe crabs reportedly forage in the eelgrass beds of Cedar Point/Hedges Bank, where they are prey for loggerhead turtles (federally listed as threatened), crabs, whelks, and sharks (NYS DOS, 2004). Atlantic silverside spawn here; silverside eggs provide an important food source for seabirds, waterfowl, and blue crab, while adults are prey for bluefish, summer flounder, rainbow smelt, white perch, Atlantic bonito, and striped bass (NYS DOS, 2004). The Cedar Point/Hedges Bank Shallows eelgrass beds are known for supporting a bay scallop fishery of statewide importance (NYS DOS, 2004). The consequences of sea-level rise for submerged aquatic vegetation (SAV) are unknown, although studies suggest that deepening water, which may limit sunlight penetration, could reduce eelgrass growth and undermine the productivity and services the beds provide (Short, 1999). Increased salinity from sea-level rise may also negatively impact SAV. Furthermore, shoreward movement of eelgrass beds could be impeded by steep shores or water turbidity in front of shoreline protection structures.

Other noteworthy habitats that could be affected by sea-level rise include the following:

- A sea-level fen vegetation community grows along Flanders Bay (NYS DOS, 2004). Because sea-level fen vegetation needs nutrient-poor waters, the Flanders Bay fen may not survive inundation by sea-level rise.
- On Long Island's north shore, longshore drift carries material that erodes from bluffs and later deposits it to form tidal flats and barrier spits or shoals (LISHRI, 2003). For instance, one of the largest areas of tidal mudflats on the north shore is near Conscience Bay, Little Bay, and Setaucket Harbor west of Port Jefferson (NYS DOS, 2004). Large beds of hard clams, soft clams, American oysters, and ribbed mussels are found in this area (NYS DOS, 2004). As seas continue to rise and the flats become inundated, the invertebrates of tidal flats could become less accessible for feeding by the many wading birds, dabbling ducks, and shorebirds whose growth and survival depend on such invertebrate food supplies (Erwin, 2006).

South Shore. Species and habitats along the south shore of Long Island are also potentially at risk because of sea-level rise. Key habitats include back-barrier salt marshes, back-barrier beaches, tidal flats, marsh and bay islands, and shallow nearshore environments.

Extensive back-barrier salt marshes exist to the west of Great South Bay in southern Nassau County (USFWS, 1997). These marshes are particularly notable given widespread marsh loss on the mainland shoreline of southern Nassau County (NYS DOS and USFWS, 1998; USFWS, 1997). Accretion experts indicate that most back-barrier marshes adjacent to Jones Inlet may survive modest sea-level rise rate increases, but that they will be lost under higher sea-level rise scenarios (Reed, 2008). To the east of Jones Inlet, the extensive back-barrier and fringing salt marshes are keeping pace with current rates of sea-level rise, but experts predict that the marshes' ability to keep pace will be marginal if the rate of sea-level rise increases moderately, and that the marshes would be lost under higher sea-level rise scenarios (Reed, 2008). Furthermore, opportunities for marsh migration along Long Island's south shore will be limited. Much of the mainland shoreline in southern Nassau County is already bulkheaded. Outside of New York City, the state requires a minimum 75-foot buffer around tidal wetlands to allow marsh migration, but outside of this buffer, additional development and shoreline protection are permitted[49]. Numerous wildlife species could be affected by salt marsh loss:

- Under higher sea-level rise scenarios, many commercially and recreationally important fish species may move elsewhere in search of suitable nursery and foraging areas.
- The recovery of a number of at-risk bird species could be impeded if additional marsh loss occurs. For example, the Dune Road Marsh west of Shinnecock Inlet provides nesting sites for several species that are already showing significant declines, including clapper rail, sharp-tailed sparrow, seaside sparrow, willet, and marsh wren (USFWS, 1997). The salt marshes of Gilgo State Park provide nesting sites for northern harrier, a species listed by the state as threatened (NYS DOS, 2004).

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[49] The state has jurisdiction up to 300 feet beyond the tidal wetland boundary (150 feet in NYC). See NYDEC, Undated.

- The northern diamondback terrapin, a federal species of concern, feeds and grows along marsh edges and the nearshore bays of the south shore. A local terrapin expert believes that additional marsh loss could lead to a "very serious reduction" in the terrapin's already low abundance (Feinberg and Burke, 2003)[50].

Of the extensive tidal flats along Long Island's southern shoreline, most are found west of Great South Bay and east of Fire Island Inlet, along the bay side of the barrier islands, (USFWS, 1997) in the Hempstead Bay–South Oyster Bay complex, (USFWS, 1997) and around the Moriches and Shinnecock inlets (USFWS, 1997; NYS DOS and USFWS, 1998). These flats provide habitat for several edible shellfish species, including soft clam, northern quahog (hard clam), bay scallop, and blue mussel. Tidal flats and shallow water habitats are heavily used by shorebirds, raptors, and colonial waterbirds in spring and summer and by waterfowl during fall and winter (Erwin, 1996). The tidal flats around Moriches and Shinnecock inlets are particularly important foraging areas for migrating shorebirds. If shoreline waters become too deep for foraging on these flats, migrating shorebirds may lack forage for their long-distance migrations. Scientists writing on behalf of the South Shore Estuary Reserve program have asserted that "because shorebirds concentrate in just a few areas during migration, loss or degradation of key sites could devastate these populations" (NYS DOS and USFWS, 1998).

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[50] Written communication from Dr. Russell Burke, Department of Biology, Hofstra University, as cited in Section 3.4 of Background Documents Supporting Climate Change Science Program Synthesis and Assessment Product 4.1: Coastal Elevations and Sensitivity to Sea Level Rise, J.G. Titus and E.M Strange (eds.), EPA430R07004, Washington, DC: U.S. EPA. Russell Burke has operated an annual diamondback terrapin conservation project at the Jamaica Bay Wildlife Refuge in the Gateway National Recreational Area since 1998.

Several other habitat types merit consideration when characterizing sea-level rise impacts on Long Island's south shore:

- As sea levels rise, back-barrier beaches will erode in front of shoreline protection structures, and will be lost without continual beach nourishment. The back-barrier beaches of the south shore provide nesting sites for the northern diamondback terrapin, the endangered roseate tern, and horseshoe crabs (NYS DOS, 2004; USFWS, 1997; USFWS, 1998). Shorebirds (*e.g.*, red knot) feed preferentially on horseshoe crab eggs during their spring migrations.

Increased flooding and erosion of marsh and dredge spoil islands will reduce habitat for many bird species that forage and nest there, including breeding colonial waterbirds, migratory shorebirds, and wintering waterfowl. For example, erosion on Warner Island is reducing nesting habitat for the federally endangered roseate tern and increasing flooding risk during nesting (NYS DOS and USFWS, 1998). The Hempstead Bay–South Oyster Bay complex includes a network of salt marsh and dredge spoil islands that are important for nesting by herons, egrets, and ibises. Likewise, Lanes Island and Warner Island in Shinnecock Bay support colonies of the state-listed common tern and the roseate tern (USFWS, 1997).

- Seagrass beds occur along much of the southern shoreline of Long Island[51].

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[51] See SAV mapping information available at: http://www.csc.noaa.gov/benthic/data/northeast/longisl.htm. Accessed 1/11/08.
SW: NOAA Coastal Services Center, Northeast Region. Long Island South Shore SAV Data Set 2002

- The consequences of sea-level rise for SAV are unknown, although studies suggest that deepening water could reduce eelgrass growth and undermine the productivity and services the beds provide (Short, 1999).

BOX A.1: Effects on the Piping Plover

Piping Plover *Charadrius melodus*

Adult and juvenile piping plover foraging on a sandy beach near the water's edge.

Habitat: The piping plover, federally listed as threatened, is a small migratory shorebird that primarily inhabits open sandy barrier island beaches on Atlantic coasts (USFWS, 1996). Major contributing factors to the plover's status as threatened are beach recreation by pedestrians and vehicles that disturb or destroy plover nests and habitat, as well as shoreline development that inhibits the natural renewal of barrier beach and overwash habitats (USFWS, 1996). In some locations, dune maintenance for protection of access roads associated with development appears to be correlated with absence of piping plover nests from former nesting sites (USFWS, 1996).

Piping plover nest

Locations: Piping plovers winter on beaches from the Yucatan Peninsula to North Carolina. In the summer, they migrate north, and breed on beaches from North Carolina to Newfoundland.[52] In the mid-Atlantic region, breeding pairs of plovers have been observed at numerous coastal beaches and barrier islands, although suitable habitat is limited in some areas. For example, Virginia and Delaware have one site each where piping plovers breed.[53] (USFWS, 2000) In contrast, piping plovers breed more frequently on Long Island's sandy beaches, from Queens to the Hamptons, in the eastern bays and in the harbors of northern Suffolk County. New York's Breezy Point barrier beach, at the mouth of Jamaica Bay, consistently supports one of the largest piping plover nesting sites in the entire New York Bight coastal region (USFWS, 1997). New York has seen an increase in piping plover breeding pairs in the last decade from less than 200 in 1989 to near 375 in recent years (2003-2005), representing nearly a quarter of the Atlantic coast's total breeding population (USFWS, 2004). Despite this improvement, piping plovers are still state listed as endangered in New York (TNC, No Date).

Impact of Sea-Level Rise: Where beaches are prevented from migrating inland by shoreline armoring, sea-level rise will negatively impact Atlantic coast piping plover populations. As described, continuous linear dunes, hardened shorelines, and established vegetation are all avoided by plovers for breeding, indicating that any armoring or stabilizing structures such as jetties and groins already in place, or built in response to sea-level rise, will have a negative impact on their reproduction and populations.

To the degree that developed shorelines result in erosion of ocean beaches, and to the degree that stabilization is undertaken as a response to sea-level rise, piping plover habitat will be lost. In contrast, where beaches are able to migrate landward, plovers may find newly available habitat. For example, on Assateague Island, piping plover populations increased after a storm event that created an overwash area on

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[52] Cornell Lab of Ornithology Piping Plover bird guide available online here: http://www.birds.cornell.edu/AllAboutBirds/BirdGuide/Piping_Plover.html. Access September 28, 2007.
[53] Audubon IBA Barrier Island/Lagoon System IBA Northampton and Accomack Counties.

the north of the island.[54] This suggests that if barrier beaches are allowed to migrate in response to sea-level rise, piping plovers might adapt to occupy new inlets and beaches created by overwash events.

Beach nourishment, the anticipated protection response for much of New York's barrier beaches such as Breezy Point, can benefit piping plovers and other shorebirds by increasing available nesting habitat in the short-term, offsetting losses at eroded beaches, but may also be detrimental depending on timing and implementation (USFWS, 1996). For instance, a study in Massachusetts found that plovers foraged on sandflats created by beach nourishment.[55] However, once a beach is built and people spread out to enjoy it, many areas become restricted during nesting season. Overall, throughout the Mid-Atlantic, coastal development and shoreline stabilization projects constitute the most serious threats to the continuing viability of storm-maintained beach habitats and their dependent species, including the piping plover (USFWS, 1996).

Photograph credit: USFWS, New Jersey Field Office /Gene Nieminen 2006. Accessed at http://www.fws.gov/northeast/njfieldoffice/Endangered/Plover_public_domain/P_P_index.html on March 1, 2007.

-- END TEXT BOX --

A.3 POPULATION OF LANDS CLOSE TO SEA LEVEL

Based upon a spatial analysis of elevation data and U.S. Census data on the number of residents, Table A.4 shows that more than 300,000 Long Island residents live within 2 meters of spring high water. Nassau County has the larger population within the low lands, up to 223,000 people.

Table A.2 Long Island block level population of the lands close to sea level by various scenarios of sea-level rise — low and high estimates.

	Population (count)					
	50 centimeters		1 meter		2 meters	
County	Low	High	Low	High	Low	High
Nassau County	2,863	146,134	2,863	174,237	97,208	223,039
Suffolk County	25	41,210	25	52,618	37,587	95,577

A.4 EXISTING SHORE PROTECTION AND POLICY CONTEXT

For information on New York's statewide policies relevant to coastal management and sea-level rise, readers should refer to Appendix B. Similar to the New York metropolitan area, the relevant policies for Long Island reflect the fact that the region is intensely developed in the west and developing fast in the east. Much of south shore, particularly within Nassau County, is already developed and has already been protected, primarily by bulkheads. For example, the Nassau County GIS database shows 528 miles of bulkheads[56].

Some of the south shore's densely developed communities facing flooding problems, such as Freeport and Hempstead, have already implemented programs calling for elevating buildings and infrastructure in place and installing bulkheads for flood protection. The Town of Hempstead has adopted the provisions of the state's Coastal

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[56] Based upon an analysis by Jay Tanski of GIS data provided by Nassau County (Nassau County, 2002).

Erosion Hazards Area Act, described in Appendix B, because erosion and flooding along Nassau County's ocean coast have been a major concern. The Town of Hempstead has also been actively working with the U.S. Army Corps of Engineers to develop a long-term storm damage reduction plan for the heavily developed Long Beach barrier island (USACE, 2003).

Suffolk County has an aggressive open space preservation and land acquisition effort. Several programs focus on acquiring or preserving the open space remaining in the county, and hundreds of millions of dollars are spent to acquire lands that are open but still developable. In general, Suffolk County is interested in acquiring lands that are in floodplains, near streams, or near creeks because they do not want development in these areas. In the Shirley/Mastic area, Suffolk County initiated a land exchange program in which owners can exchange property in the floodplain for county-owned land outside of the floodplain, and 30 to 40 owners are participating in the program(Gaffney, 1996). Similar efforts by state, county, and local governments to buy development rights to agricultural lands would prevent them from being developed in the future.

Beach nourishment and the construction of flood and erosion protection structures are also common on the island. For example, in the early 1990s the U.S. Army Corps of Engineers constructed a substantial revetment around the Montauk Lighthouse at the eastern tip of Long Island and after a new feasibility study has proposed construction of a larger revetment (Bleyer, 2007). The Corps is also reformulating a plan for the development of long-term storm damage prevention projects along the 83 mile portion of the south shore of Suffolk County. As part of this effort, the Corps is assessing at-risk properties within the 71 square mile floodplain, present and future sea-level rise, restoration and preservation of important coastal landforms and processes, and important public uses of the area (USACE, undated).

Existing regulations do not prevent shoreline property owners from attempting to protect their land against flooding or erosion as long as they apply for the permits at the right time (i.e., before the land becomes wetlands). However, state policy requires individual property owners first evaluate non-structural approaches and only if such methods can be shown to be ineffective can they graduate to armoring strategies (New York State, 2002). Because emergency permits may be issued in extreme cases, in some cases, individuals will wait until their house is in imminent danger before applying for a permit, which will almost always be granted in emergency cases. In extreme cases, individuals may even wait for damage to occur, at which time the federal government may step in to relieve the burden of reconstruction in severely damaged areas. After major disasters, emergency permits may be issued, allowing applicants to receive approvals without going through a long and often costly permit process.

According to state policy, non-structural methods of shore protection are preferred whenever possible. Local governments try to discourage using bulkheads and other shore-hardening structures. Shoreline structure, which by definition includes beach nourishment in New York State, are permitted only when it can be shown that the structure can prevent erosion for at least thirty years and will not cause an increase in erosion or flooding at the local site or nearby locations (New York State, 2002). Setbacks, relocation, and elevated walkways are also encouraged before hardening.

The Comprehensive Coastal Management Plan (CCMP) of the Peconic Bay National Estuary Program Management Plan calls for “no net increase of hardened shoreline in the Peconic Estuary.” The intent of this recommendation is to discourage individuals from armoring their coastline, but this document is only a management plan and does not have any legal authority. However, towns such as East Hampton are trying to incorporate the plan into their own programs. In 2006, the town of East Hampton has adopted and now enforcing a zoning overlay district that prevents shore armoring along much of the town’s coastline (Town of East Hampton, 2006). Despite such regulations, authorities in East Hampton and elsewhere recognize that there are some areas where structures will have to be allowed to protect existing development.

The NY Department of State (DOS) is also examining options for managing erosion and flood risks through only land use measures, such as further land exchanges. For example, there is currently an attempt to revise the proposed Fire Island to Montauk Point Storm Damage Reduction project to in favor of combination of nourishment and land use measures. The intent is to then phase out the use of beach nourishment over the 50-year period. Over the 50-year project life, DOS staff would seek to promote measures to relocate out of hazardous locations[57]. Non-conforming development will eventually be

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[57] Comment from Fred Anders, New York State Department of State, Division of Coastal Resources and Waterfront Revitalization, in response to expert review draft of this appendix.

brought into conformance as it is reconstructed, moved, damaged by storms or flooding or other land use management plans are brought into effect[58].

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Appendix B. New York Metropolitan Area

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Contributing Authors: E. M. Strange, Stratus Consulting Inc.; J. Tanski, New York Sea Grant; G. Sinha, Industrial Economics Inc.

In December 1992, a powerful nor'easter submerged parts of downtown Manhattan in 4 feet of water, shut down significant portions of the city's transportation system, and resulted in coastal flooding that damaged as many as 20,000 homes (NYC OEM, 2007; Gornitz *et al.*, 2002). Given its large population, the effects of hurricanes and other major storms combined with higher sea levels could be particularly severe in the New York Metropolitan Area. With much of the area's transportation infrastructure at low elevation (most at 3 meters or less), even slight increases in the height of flooding could cause extensive damage and bring the thriving city to a relative standstill until the flood waters recede (Gornitz *et al.*, 2002).

B.1 LAND VULNERABLE TO INUNDATION

The New York metropolitan area has a mixture of elevated and low-lying coastlines (Figure B.1). New York's two major airports, LaGuardia and John F. Kennedy International Airport, are located along Queens' northern and southeastern shore, respectively, and both are within 3 meters of spring high water. Much of the recreational lands along Jamaica Bay’s Gateway National Recreation Area (*e.g.*, Floyd Bennett Field, Jamaica Bay Wildlife Refuge, Fort Tilden, Riis Park) have significant low-lying lands. Similarly, on Staten Island, the communities of South Beach and Oakwood Beach have substantial land under 2 meters in elevation. The New York City Department of Environmental Protection is planning "bluebelts" in repeatedly flooded residential neighborhoods; the Bluebelt Program would use remaining open space for stormwater management.

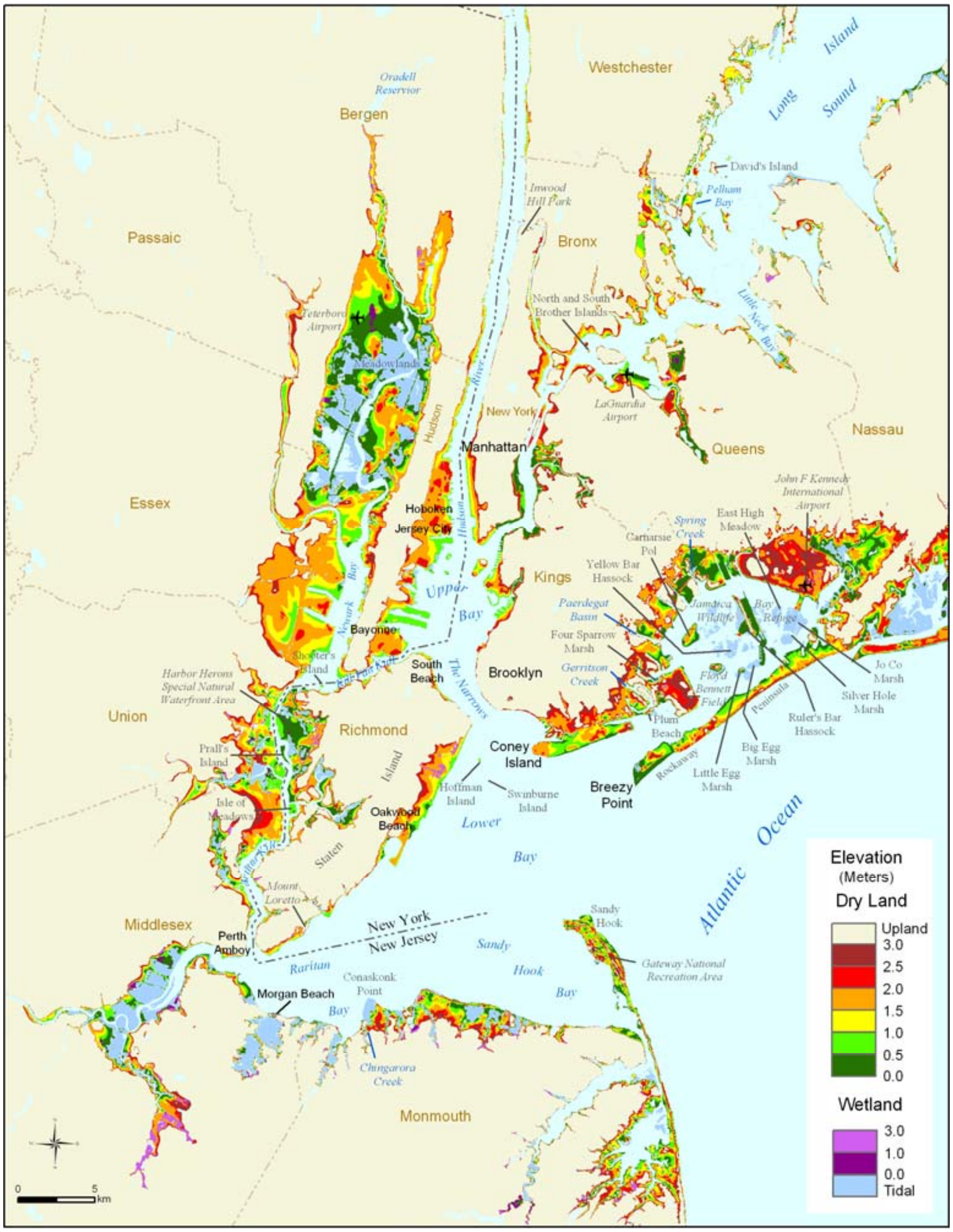

Figure B.1 Greater New York area: Elevations relative to spring high water (Source: Titus and Wang, 2008).

In New Jersey, the heavily developed coast of Hudson County (including Hoboken, Jersey City, and Bayonne) is also within 3 meters of spring high water. More than half the low land of North Jersey is in an area known as the Meadowlands. The New Jersey Meadowlands Commission (formerly the Hackensack Meadowlands Development Commission) regulates the portion of the Meadowlands west of US-1/US-9 and east of the NJ Transit Kingland and Pascack lines, south of the Teterboro Airport and north of the Lower Hackensack drawbridge. At the northern end, however, the area between Redneck Road and Moonachie Road south to Moonachie Avenue is excluded from the commission's jurisdiction. This area includes some of the lowest developed lands in North Jersey, with the intersection of Moonachie Avenue and Road at an elevation of 5 feet above NGVD, according to the USGS 1:24,000 scale map. As a result, the area floods regularly.

Table B.1 shows the area of land under specified elevations for the portion of the New York City metropolitan area draining into New York Harbor and Raritan Bay. As shown, between 139 and 230 square kilometers of land are located within 2 meters of spring high water. Staten Island has between 15 and 25 square kilometers of land within 2 meters elevation. The New Jersey counties also have significant quantities of low land, with a range of 115 to 186 square kilometers below 2 meters. Similar data for Queens and the portion of Brooklyn that drain into Long Island Sound and the Atlantic are available in Appendix A.

Table B.1 Low and high estimates for the area of dry and wet land close to sea level New York harbor[1] (square kilometers).

Locality	State	Tidal	50 cm		1 meter		2 meters		3 meters		5 meters	
			Low	High	Low	High	Low	High	Low	High	Low	High
		Cumulative (total) amount of dry land below a given elevation										
Monmouth	NJ		2.0	5.4	5.9	10.5	15.8	18.7	22.4	24.7	31.2	32.5
Middlesex	NJ		0.4	8.8	4.3	17.4	14.7	31.2	25.4	43.5	45.6	62.0
Somerset	NJ		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
Union	NJ		0.4	6.9	4.2	13.7	12.6	22.7	20.2	29.3	31.7	40.9
Hudson	NJ		0.6	16.2	10.4	32.2	30.6	49.0	46.4	56.9	60.4	67.5
Essex	NJ		0.4	6.1	3.9	12.0	11.3	19.6	17.8	25.3	27.8	32.2
Bergen	NJ		0.9	15.6	10.2	31.0	29.4	44.2	42.5	49.0	51.1	58.2
Passaic	NJ		0.0	0.2	0.1	0.3	0.3	0.7	0.6	1.1	1.3	1.9
Ellis Island	NJ		0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Staten Island	NY		0.3	7.8	5.1	15.5	14.9	24.9	23.3	30.8	33.9	39.0
Brooklyn	NY		0.0	0.8	0.5	1.6	1.6	3.1	2.7	4.5	5.3	6.4
Manhattan	NY		0.0	2.2	1.4	4.3	4.2	8.3	7.2	12.1	14.1	17.5
Bronx	NY		0.0	0.6	0.4	1.2	1.2	2.7	2.2	4.4	5.3	6.9
Westchester	NY		0.0	1.3	0.7	2.6	2.3	4.7	4.1	6.1	6.4	8.3
Total			**5.1**	**71.9**	**47.1**	**142.6**	**138.9**	**230.0**	**214.9**	**288.0**	**314.1**	**373.7**
		Cumulative (total) amount of wetlands below a given elevation										
Monmouth	NJ	7.7	0.1	0.3	0.4	0.6	0.8	0.9	1.1	1.2	1.7	1.8
Middlesex	NJ	21.7	0.1	1.2	0.7	2.3	2.1	3.9	3.5	5.3	5.7	7.8
Union	NJ	2.3	0.0	0.2	0.1	0.3	0.3	0.5	0.4	0.6	0.6	0.8
Hudson	NJ	12.0	0.0	0.2	0.1	0.3	0.3	0.4	0.4	0.5	0.5	0.5
Essex	NJ	0.3	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Bergen	NJ	15.0	0.0	0.6	0.4	1.2	1.1	1.5	1.5	1.5	1.6	2.1
Passaic	NJ	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Staten Island	NY	4.0	0.0	0.5	0.3	0.9	0.9	1.4	1.3	1.6	1.7	1.9
Bronx	NY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
Westchester	NY	0.7	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Rockland	NY	2.3	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.2
Orange	NY	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Putnam	NY	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Dutchess	NY	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total[2]		**67.6**	**0.2**	**3.0**	**2.0**	**5.8**	**5.6**	**9.0**	**8.6**	**11.1**	**12.2**	**15.5**
Dry and nontidal wetland			5	75	49	148	145	239	223	299	326	389
All land		68	73	142	117	216	212	307	291	367	394	457

Source: Titus J.G., and D. Cacela, 2008: Uncertainty Ranges Associated with EPA's Estimates of the Area of Land Close to Sea Level. Section 1.3 in: *Background Documents Supporting Climate Change Science Program Synthesis and Assessment Product 4.1: Coastal Elevations and Sensitivity to Sea Level Rise*, J.G. Titus and E.M. Strange (eds.). EPA 430R07004. U.S. EPA, Washington, DC.

[1] Does not include portions of Queens and Brooklyn that flow into Jamaica Bay. See Table A.1 at Appendix A.

[2] Brooklyn does not contain a substantial amount of wetlands that flow into New York harbor.

B.2 ENVIRONMENTAL IMPLICATIONS

Species and habitats in the region encompassing New York City, the lower Hudson River, the East River, and Jamaica Bay are potentially at risk because of sea-level rise. Although the area is heavily urbanized, it also has regionally significant habitats for fish, shellfish, and birds. These include tidal wetlands, estuarine beaches, tidal flats, marsh and bay islands, and shallow nearshore environments.

Tidal wetlands are distributed throughout the region:

- **Staten Island:** The Northwest Staten Island/Harbor Herons Special Natural Waterfront Area (SNWA) is an important nesting and foraging area for herons, ibises, egrets, gulls, and waterfowl (USFWS, 1997). Several marshes, such as Arlington Marsh and Saw Mill Creek Park, Staten Island, provide foraging areas for the birds of the island heronries, and loss of these marshes could have a significant negative impact on these species because of a lack of alternative foraging sites nearby. Hoffman Island and Swinburne Island provide important nesting habitat for herons and cormorants, respectively[59].
- **Manhattan:** Most of the Manhattan shoreline, including Lower Manhattan and the Battery, has been bulkheaded and filled. An exception is the marsh and mudflat at the mouth of the Harlem River at Inwood Hill Park (USFWS, 1997). Great blue herons are found along the flat in winter, and snowy and great egrets are common from spring through fall (NYC DPR, 2001).

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[59] George Frame, National Park Service, in written communication to EPA, 5/14/07

- **Lower Hudson River:** The estuarine portion of the Hudson River (below the Tappan Zee Bridge) has relatively little marsh. One exception is Piermont Marsh, a 411.6 hectare (1,017 acre) brackish wetland on the western shore of the lower Hudson River that has been designated for conservation management by New York State and NOAA (USFWS, 1997). The marsh supports breeding birds, including relatively rare species such as Virginia rail, swamp sparrow, black duck, least bittern, and sora rail. Anadromous and freshwater fish use the marsh's tidal creeks as a spawning and nursery area. Diamondback terrapin reportedly nest in upland areas along the marsh (USFWS, 1997).
- **Jamaica Bay:** Jamaica Bay, located in Brooklyn and Queens, is the largest area along the U.S. Atlantic Coast of protected wetlands in a major metropolitan area. The bay includes the Jamaica Bay Wildlife Refuge, which has been protected since 1972 as part of the Jamaica Bay Unit of the Gateway National Recreation Area. Despite extensive disturbance from dredging, filling, and development, Jamaica Bay remains one of the most important migratory shorebird stopover sites in the New York Bight (USFWS, 1997).The bay provides overwintering habitat for many duck species, and mudflats support foraging migrant species (Hartig, 2002). The refuge and Breezy Point, at the tip of the Rockaway Peninsula, support populations of 214 species that are state or federally listed or of special emphasis, including 48 species of fish and 120 species of birds (USFWS, 1997). Salt marshes such as Four Sparrow Marsh provide nesting habitat for declining sparrow species and serve 326 species of migrating birds (NYC DPR, unknown). Wetlands in some parts of the bay currently show substantial losses (Hartig, 2002). Loss of these wetlands reduces primary

production as well as the production of fish and shellfish within both the marsh and the surrounding estuary.

Relatively few areas of *beach* remain in the New York City metropolitan area, and most are heavily modified. Beach nourishment is anticipated for beaches at the Rockaways and Coney Island (NYS, DCP 1992). In Jamaica Bay, remaining estuarine beaches occur off Belt Parkway (*e.g.*, on Plumb Beach) and on the bay islands[60]. Although limited in area, the beaches support an extensive food web. Mud snails and wrack-based species (*e.g.*, insects, isopods, and amphipods) provide food for shorebirds (including some protected species such as the federally threatened piping plover)[61]. Horseshoe crabs lay their eggs on the small pockets of beach in the bay, supplying additional shorebird forage. Diamondback terrapin also nest on the bay's sandy habitats; filled wetlands of Jamaica Bay provide most of the nest sites for terrapins in the region.[62] Because of the importance of beach species for estuarine food webs, scientists have raised concerns about the ecological implications of the loss of estuarine beaches (Jackson, 2002).

Tidal flats, like beaches, are limited in the New York City metropolitan region. Large concentrations of shorebirds, herons, and waterfowl use the shallows and tidal flats of Piermont Marsh along the lower Hudson River as staging areas for both spring and fall migrations (USFWS, 1997). Tidal flats in Jamaica Bay are frequented by shorebirds and

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[60] Don Riepe, American Littoral Society. August 20, 2006 email to E. Strange, Stratus Consulting, entitled "Notes from phone conversation," in which he confirmed his visual observations of intertidal beaches and shoreline armoring along Jamaica Bay as discussed in an earlier phone call with E. Strange on August 11, 2006.

[61] Ibid.

[62] George Frame, National Park Service, personal observations provided in written communication to EPA, 5/14/07.

waterfowl, and an intensive survey of shorebirds in the mid-1980s estimated more than 230,000 birds of 31 species in a single year, mostly during the fall migration (Burger, 1984). Inundation with rising seas will eventually make flats unavailable to short-legged shorebirds, unless they can shift feeding to marsh ponds and pannes (Erwin, 2004). At the same time, disappearing saltmarsh islands in the area are transforming into intertidal mudflats[63]. This may increase habitat for shorebirds at low tide, but it leaves less habitat for refuge at high tide.

Extensive *shallow water habitat* exists in the Hudson River, from Stony Point south to Piermont Marsh, just below the Tappan Zee Bridge (USFWS, 1997). This area features the greatest mixing of ocean and freshwater and concentrates nutrients and plankton, resulting in a high level of both primary and secondary productivity. Thus, this part of the Hudson provides key habitat for numerous fish and bird species. It is a major nursery area for striped bass, white perch, tomcod, and Atlantic sturgeon, and a wintering area for the federally endangered shortnose sturgeon. Waterfowl also feed and rest here during spring and fall migrations (USFWS, 1997). Some submerged aquatic vegetation (SAV) is also found here, dominated by water celery, sago pondweed, and horned pondweed (USFWS, 1997). Sea-level rise will affect this productive area through salinity changes that will influence the composition and diversity of nearshore vegetation and associated fauna, although the ultimate ecological implications are uncertain.

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[63] George Frame, National Park Service, personal observations provided in written communication to EPA, 5/14/07.

Finally, *marsh and bay islands* throughout the region are vulnerable to sea-level rise. It is estimated that between 1974 and 1994, the smaller islands of Jamaica Bay lost nearly 80% of their vegetative cover (Hartig, 2002). Marsh loss has accelerated, reaching an average annual rate of 18 hectares (44.5 acres) per year between 1994 and 1999 (Hartig, 2002). The islands provide specialized habitat for an array of species:

- Regionally important populations of egrets, herons, and ibises are or have been located on North and South Brother islands in the East River and on Shooter's Island, Prall's Island, and Isle of Meadows in Arthur Kill and Kill van Kull (USFWS, 1997).
- North and South Brother islands have the largest black crowned night heron colony in New York State, along with large numbers of snowy egret, great egret, cattle egret, and glossy ibis (USFWS, 1997).
- Since 1984, an average of 1,000 state threatened common tern have nested annually in colonies on seven islands of the Jamaica Bay Wildlife Refuge.
- The heronry on Carnarsie Pol also supports nesting by great black-backed gull, herring gull, and American oystercatcher (USFWS, 1997).
- The only colonies of laughing gull in New York State, and the northernmost breeding extent of this species, occur on the islands of East High Meadow, Silver Hole Marsh, Jo Co Marsh, and West Hempstead Bay (USFWS, 1997).
- Diamondback terrapin nest in large numbers along the sandy shoreline areas of the islands of Jamaica Bay, primarily Ruler's Bar Hassock (USFWS, 1997).

B.3 EXISTING DEVELOPMENT AND SHORE PROTECTION

New York City. Table B.2 estimates the area of land within 1 meter of spring high water for the portion of New York City metropolitan area that drains into New York Harbor. David's Island, a 75-acre former military installation, is the only undeveloped land in the county; however, it is already protected by structures.

The State Environmental Protection Fund provided $25 million to acquire the 145-acre Mount Loretto property on the south shore of Staten Island (NYS DEC, 2006). The State Open Space Plan also identifies several coastal properties, known collectively as the Staten Island Blue Belt, as priorities for preservation in this area (NYS DEC, 2006).

North Jersey. The coastal areas of Bergen, Essex, Hudson, and Union counties are dominated by dense residential, commercial, industrial, and transportation uses.

Middlesex County has mostly natural shores along Raritan Bay, with substantial dunes. To a large extent, public roads, bike paths, and parks are immediately inland of the beach, with residential development farther inland. Above Perth Amboy along Arthur Kill is a mixture of armored shores and beaches, with dense development inland of the shore. Approximately 85–90% of the area potentially sensitive to erosion or inundation is within planning areas 1, 2, and 3 (see Appendix C for discussion of planning areas). Conservation areas along the South River preserve the Perth Amboy/Runyon and Duhernal water systems. Salt water is likely (but not certain) to advance upstream if sea-level rises enough to inundate these areas. Currently, some of these areas are nontidal freshwater wetlands, and conversion to tidal freshwater wetlands would not harm the aquifer protection function of these conservation lands. Conversion to salt marsh, by contrast, would contaminate the aquifer, and even occasional tidal flooding from saltwater could cause problems. By the time this area is threatened with sea-level rise, saltwater intrusion through the ground might be so great that protecting this recharge area from inundation would be insufficient to protect the wells[64].

B.4 POPULATION OF LANDS CLOSE TO SEA LEVEL

Table B.2 shows estimates of the population that inhabits the land within 50 centimeters, 1 meter, and 2 meters above spring high water. As shown, within the metropolitan area more than 1 million people reside within 2 meters of the water.

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[64] Personal communication from William Kruse, assistant planning director for Environment, Parks, & Comprehensive Planning, Middlesex County, New Jersey, to Jim Titus, December 1, 2004.

Table B.2 Block level population of the lands close to sea level by various scenarios of sea-level rise — low and high estimates.

County	Population (count)					
	50 centimeters		1 meter		2 meters	
	Low	High	Low	High	Low	High
NY, Bronx	0	79,146	0	87,939	33,330	109,519
NY, Brooklyn	10,398	125,089	10,398	215,673	105,606	355,954
NY, Manhattan	0	161,651	0	186,412	9,729	258,332
NY, Queens	8,000	119,545	8,000	157,433	109,052	215,560
NY, Staten Island	0	45,825	0	53,600	5,377	66,584
NJ, Bergen	0	53,938	0	60,510	10,774	72,904
NJ, Essex	0	21,994	0	28,447	0	38,712
NJ, Hudson	0	107,203	0	126,771	4,951	141,744
NJ, Middlesex	0	32,858	0	41,513	1,379	61,361
NJ, Union	0	21,227	0	23,577	0	38,914
Total	18,398	768,476	18,398	981,875	280,198	1,359,584

B.5 STATEWIDE POLICY CONTEXT: NEW YORK

New York State does not have written policies or regulations pertaining specifically to sea-level rise in relation to coastal zone management, although sea-level rise is recognized as a factor in coastal erosion and flooding by New York State Department of State (DOS) in the development of regional management plans. Policies regarding management and development in shoreline areas are primarily based on three laws. Under the Tidal Wetlands Act program, the Department of Environmental Conservation (DEC) classifies various wetland zones and adjacent areas where human activities may have the potential to impair wetland values or adversely affect their function; permits are required for most activities that take place in these areas. New construction greater than 100 square feet (excluding docks, piers, and bulkheads) as well as roads and other infrastructure must be set back 75 feet from any tidal wetland, except within New York City where the setback is 30 feet[65].

The Waterfront Revitalization and Coastal Resources Act (WRCRA) allows the DOS to address sea-level rise indirectly through policies regarding flooding and erosion hazards (NOAA, 1982). Seven out of 44 written policies related to management, protection, and use of the coastal zone address flooding and erosion control. These polices endeavor to:

- Move development away from areas threatened by coastal erosion and flooding hazards
- Protect natural protective features such as dunes
- Ensure that development activities do not exacerbate erosion or flooding problems
- Provide guidance for public funding of coastal hazard mitigation projects
- Encourage the use of nonstructural erosion and flood control measures where possible (NYS DOS, 2002).

In particular, Policy 13 states that erosion protection structures should be built only if the project is likely to control erosion for at least 30 years (NYS DOS, 2002). Currently, the DOS is refining and simplifying the policies and tailoring them more specifically to regions. The thrust of the policies, however, will remain the same. Local governments can also voluntarily participate in the coastal program by developing Local Waterfront Revitalization Programs (LWRPs), which require municipalities to adopt minimum state policy standards, including those for flooding and erosion.

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[65] Article 25, Environmental Conservation Law Implementing Regulations - 6NYCRR PART 661.

Under the Coastal Erosion Hazard Areas Act (CEHA) program, the DEC identified areas subject to erosion and established two types of erosion hazard areas (structural hazard and natural protective feature areas) where development and construction activities are regulated[66]. Permits are required for most activities in designated natural protective feature areas. New development (*e.g.*, building, permanent shed, deck, pool, garage) is prohibited in nearshore areas, beaches, bluffs, and primary dunes. These regulations, however, do not extend far inland and therefore do not encompass the broader area vulnerable to sea-level rise.

All five boroughs of New York City are functionally governed under the auspices of New York City and follow the same rules, regulations, and policies regarding coastal land use, construction, and management. The policies and regulations reflect the fact that the city is already densely developed and most of the coastal land is being used for some purpose.

For a discussion of the statewide policy context for areas along Raritan Bay (parts of Union, Essex, Bergen, Middlesex, Monmouth, and Hudson counties) (see Appendix C).

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Appendix C. The New Jersey Shore

Author: James G. Titus, U.S. Environmental Protection Agency

Contributing Author: E. M. Strange, Stratus Consulting Inc.

The New Jersey shore has included popular resorts since the steamship first facilitated travel from Philadelphia to Cape May, and from New York to Long Branch in the early 19th century (Salvini, 1995). As the dry land close to the ocean became developed, people began to build homes on lands that were somewhat more marginal. The narrow fringing marsh on the bay sides of barrier islands was often filled to create buildable lots[67]. Sea level has continued to rise in the ensuing decades, leaving some of the bay sides of developed barrier islands with some very low land. In some cases, the extensive marshes on the mainland side of the back-barrier bays have converted to dredge-and-fill canal estates, such as Beach Haven West.

Severe storms have been a regular feature of the New Jersey shore, although hits from hurricanes have been rare. The northern most numbered street in Barnegat Light is 4th Street, because other portions eroded until shoreline armoring and jetties were constructed to stabilize the inlet. Harvey Cedars extended 1-2 blocks farther seaward in the 1880s than today.

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[67] See, *e.g.*, Lloyd, J.B. Eighteen miles of history at Long Beach Island. Down The Shore Publishing. (showing substantial marsh on the bay side of Beach Haven in areas that are developed today).

The dense development of the New Jersey shore led many people to take the view that people should not simply retreat in response to storm erosion, but instead hold back the sea. In 1898 the U.S. Army built a seawall between Sandy Hook and Sea Bright to protect the operations at Fort Hancock (NPS, 2007). Over time, the seawall was extended south as far as Long Branch, and there was little or no beach along most portions of the New Jersey shore between Long Branch and Sandy Hook. During the 1970s oceanographer Orrin Pilkey and coastal geologists began to warn people around the nation about the disadvantages of what they called "New Jerseyization," by which they meant replacing beaches with seawalls (Pilkey, et al., 1978). As we discuss in this chapter, however, the state has reversed that trend and restored the beaches, although the seawalls remain.

BOX C.1: Tuckers Island, New Jersey's First Resort

In spite of the historical importance of Cape May and Long Branch, some historians believe that New Jersey's first seashore resort was Tuckers Island (Lloyd, 1994), a barrier island that was partly to the south and partly inland — and sheltered by — Long Beach Island. Tuckers Island was across the bay from Tuckerton, a major port, where ships destined for Philadelphia sometimes offloaded when the Delaware River was frozen (Nash, 1947). During the 1790s, wealthy Quakers who had made their fortunes in Tuckerton during the Revolution began organizing 5-day meetings on Tuckers Island (Lloyd, 1994). The Tucker family eventually converted their farm house on Tuckers Island to a boarding hotel. Soon there was regular stagecoach service from Camden to Tuckerton. After staying overnight in Tuckerston, visitors took a boat ride to Tuckers Island.

On nearby Long Beach Island, resort hotels opened in 1822 at what is now called Surf City and Holgate. A few decades later, several hotels were built in Beach Haven, Barnegat City, and the community of Bonds near the southern end of Long Beach Island. By 1880, Beach Haven was a small town. Still, proximity to Tuckerton kept Tuckers Island popular, even when rail was extended to Atlantic City. Streets were platted on Tuckers Island for a proposed community. But in 1886 the Pennsylvania Railroad connected to nearby Beach Haven, diverting most investor interest in the area to Long Beach Island.

But it was coastal processes, not the railroad, that caused the decline of Tuckers Island. During a storm in 1920, what we now call the Beach Haven inlet opened up near the southern most street on Long Beach Island. The portion of Long Beach Island that had sheltered Tuckers Island from the Atlantic Ocean — generally known as Tuckers Beach — was south of new inlet. Tuckers Beach eroded within five years, exposing Tuckers Island to the Atlantic Ocean. Residents relocated, and by 1933, the hotels, homes and lighthouse on Tuckers Island had all disappeared.

C.1 VULNERABILITY TO INUNDATION AND EROSION

The New Jersey shore has three types of ocean coasts (see Chapter 2 for more on ocean coasts). At the south end, Cape May and Atlantic Counties have short and fairly wide "tide-dominated" barrier islands. Behind the islands, 253 sq km of marshes dominate the relatively small open water bays. To the north, Ocean County has "wave dominated" coastal barrier islands and spits. Long Beach Island is 29 km (18 miles) long and only 2-3 blocks wide in most places; Island Beach to the north is also long and narrow. Behind Long Beach Island and Island Beach lies Barnegat and Little Egg Harbor Bays. These shallow estuaries ranges from 2 to 7 km wide, and have 167 sq km of open water (USFWS, 1997) with extensive eelgrass, but only 125 sq km of tidal marsh (Jones and Wang, 2008). Monmouth County's ocean coast is entirely headlands, with the exception of Sandy Hook at the Northern tip of the Jersey Shore.

Figures C.1 and C.2 show the elevations of lands close to sea level along the New Jersey shore, south and north of Tuckerton, respectively. Between 67 and 129 square kilometers of land lie within one meter above the tides along the Atlantic Ocean and adjacent back barrier bays (see Table C.1). Nontidal wetlands are immediately inland of the tidal wetlands along most of the mainland shore, and account for more than half of the land close to sea level[68].

Between 18 and 61 sq km of dry land are within 50 cm above the tides (Jones and Wang, 2008). The maps suggest that most of the land close to sea level is either on the bay side

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[68] The estimates are based on 2-foot contours and spot elevation data with RMS errors of 30 cm. Therefore, it was possible to derive a meaningful estimate of the land within 50 cm above the tides.

of a barrier island or relatively compact peninsulas of very low land that extend out into the marsh, such as Beach Haven West and Mystic Isle. Most of these “peninsulas” are dredge-and-fill developments that were created by filling the wetlands and thereby elevating the land surface.

The vulnerability suggested by the maps is consistent with what one actually sees when visiting these areas. In several neighborhoods in the southern half of Long Beach Island, streets and yards are flooded by spring high tides whenever the bay is elevated by either strong winds from the East or a rainy period. (See box on Long Beach Island and Figure C.3.) Portions of Sea Bright, Monmouth Beach, Manasquan (and small areas of Brielle and West Wildwood) also flood during spring tides. Small floodwalls have been constructed along the bay side of Avalon, and drainage is slow enough that pumping is often necessary. Water tables are often close enough to the land surfaces to prevent rainwater from draining into the soil, allowing water to stand for days in minor land surface depressions, generally in back yards. Over the last decade, the elevation of homes and yards has become commonplace.

Figure C.1 Cape May, Burlington, and Atlantic counties, New Jersey: Elevations relative to spring high water. Source: Titus and Wang, 2008.

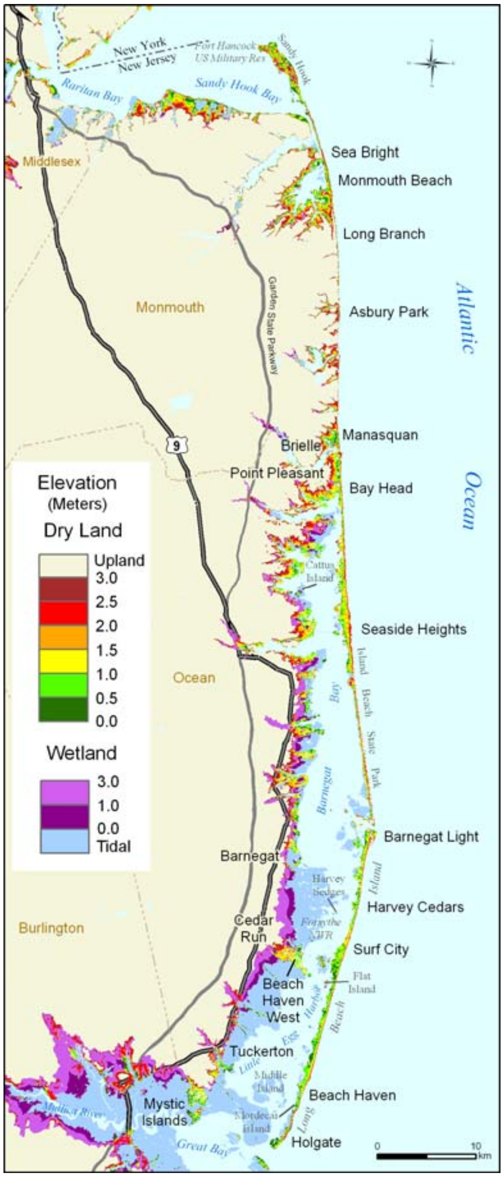

Figure C.2 Ocean and Monmouth counties, New Jersey: Elevations relative to spring high water. Source: Titus and Wang, 2008.

Table C.1 Low and high estimates for the area of dry and wet land close to sea level New Jersey Shore (square kilometers).

Elevations above spring high water:	**Tidal**	**50 cm**		**1 meter**		**2 meters**		**3 meters**		**5 meters**	
		Low	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
County	Cumulative (total) amount of Dry Land below a given elevation										
Cape May		7.6	21.8	23.8	42.0	56.1	73.5	78.4	102.2	124.2	144.1
Atlantic		4.0	13.5	14.0	29.0	40.8	53.9	57.3	71.0	88.5	105.8
Burlington		0.0	2.1	1.3	4.1	4.0	8.9	7.0	15.1	18.4	27.1
Ocean		4.6	18.7	21.8	44.0	67.3	80.6	93.2	106.8	136.6	149.1
Monmouth		2.1	4.9	5.5	9.4	15.3	19.9	26.4	31.8	50.4	54.9
Total		**18.3**	**61.1**	**66.5**	**128.5**	**183.5**	**236.9**	**262.3**	**326.9**	**418.1**	**481.0**
	Cumulative (total) amount of wetlands below a given elevation										
Cape May	153.2	2.9	12.0	10.2	20.4	22.2	33.1	32.2	42.7	47.6	55.2
Atlantic	204.0	4.8	17.9	14.7	29.2	31.9	50.1	48.3	68.2	82.0	102.9
Burlington	37.3	0.2	9.7	6.2	19.1	18.7	32.7	30.0	41.3	45.8	57.2
Ocean	124.8	2.3	11.6	10.0	21.7	25.8	38.3	39.0	49.4	56.5	65.8
Monmouth	4.4	0.5	0.9	1.0	1.4	1.9	2.3	2.9	3.2	4.8	5.1
Total	**523.6**	**10.7**	**52.1**	**42.1**	**91.9**	**100.5**	**156.5**	**152.4**	**204.9**	**236.5**	**286.3**
Dry and nontidal wetland		29	113	109	220	284	393	415	532	655	767
All land	524	553	637	632	744	808	917	938	1055	1178	1291

Source: Titus and Cacela, 2008. The low and high estimates are based on the on the contour interval and/or stated root mean square error (RMSE) of the data used to calculate elevations. See Chapter 1 for more details.

Figure C.3 Ship Bottom, New Jersey. Labor Day Weekend 2006, high tide, after a moderate northeaster.

The land within one meter above the tides is not the only land vulnerable to rising sea level. The ocean shores have been eroding. As we discuss below, substantial efforts are underway to rebuild these beaches to promote recreation and protect the buildings behind the beaches. A panel of USGS experts expects that, as long as sea-level rise does not accelerate by more than 2 mm/yr, the conditions that affect beaches today are likely to continue. The panel is almost certain, however, that if sea level were to rise one meter per century, most barrier islands would start to disintegrate over the next two hundred years unless shore protection activities are accelerated compared to what they have been in the past. During the next century, the long, narrow “wave-dominated” islands (and spits) of Ocean County appear to be more vulnerable than the short and wide “tide-dominated” islands of Cape May and Atlantic Counties. While refraining from predicting the future for any specific island, the USGS panel views disintegration of the narrow islands as "very likely," while the disintegration of the wider islands is only "more likely than not."

C.2 VULNERABLE HABITAT

Species and habitats along the Atlantic Coast of south-central New Jersey are potentially at risk because of sea-level rise. This region encompasses the barrier islands, barrier spits, and back-barrier lagoons of New Jersey's Ocean, Atlantic, and Cape May counties. The region contains important habitats for a wide variety of fishes, invertebrates, terrapins, and birds, and a great deal is known about the ecology and habitat needs of these species. Although it is possible to make qualitative statements about the ecological implications if sea-level rise causes a total loss of habitat, our ability to say what the impact might be if only a portion of the habitat is lost is more limited. A total loss of habitat might be expected if shores are protected with hard structures and the wetlands are unable to keep pace with sea level rise.

There have been many efforts to conserve and restore species and habitats in the barrier island backbarrier lagoon system. Some of the larger parks and wildlife areas in the region include Island Beach State Park, Great Bay Boulevard State Wildlife Management Area, and the E.B. Forsythe National Wildlife Refuge (Forsythe Refuge) in Ocean and Atlantic counties. Parts of the Cape May Peninsula are protected by the Cape May National Wildlife Refuge (TNC, date unknown), the Cape May Point State Park (NJDEP, DEP, date unknown), and The Nature Conservancy's (TNC's) Cape May Migratory Bird Refuge (NJDEP, date unknown). The peninsula is renowned as one of the primary stopover sites for migrating birds along the U.S. Atlantic Coast. The North Brigantine Natural Area is a critical nesting area for least terns and piping plovers, and a critical stopover habitat for a number of migrating shorebirds (Strange, 2008). Corson's Inlet State Park and Strathemere Natural Area, which straddle Corson's Inlet, have historically provided critical habitat area for black skimmers, least terns and piping plovers, and in an important stopover habitat for migratory shorebirds (Strange, 2008). Stone Harbor Point and Champagne Island, part of the Hereford Inlet system, are critical nesting areas for least terns, black skimmers, piping plovers, common terns, and American oystercatchers, and provide critical resting and feeding habitat for migrating shorebirds, including red knot (Strange, 2008). Marsh islands behind this inlet system and behind Stone Harbor host the largest concentration of nesting laughing gulls in the world (Strange, 2008). The TNC refuge alone supports an estimated 317 bird species, 42 mammal species, 55 reptile and amphibian species, finfish, and shellfish and other invertebrates (NPS, 2008). All of these areas are likely to be placed at increased risk by rising sea levels.

Tidal and Nearshore Nontidal Marshes. There are 18,440.7 ha (71.2 mi^2), 29,344.6 ha (113.3 mi^2), and 26,987.7 ha (104.2 mi^2) of tidal salt marsh in Ocean, Atlantic, and Cape May counties, respectively (Jones and Wang, 2008). Based on a review of available studies, a panel of accretion experts convened for this report concluded that marshes in the study are keeping pace with current local rates of sea-level rise of 4 mm/yr, but will become marginal with a 2 mm/yr acceleration, and will be lost with a 7 mm/yr acceleration except where they are near local sources of sediments (e.g., rivers such as the Mullica and Great Harbor rivers in Atlantic County) (Reed, 2008).

There is potential for wetland migration in Forsythe Refuge, and other lands that preserve the coastal environment such as parks and wildlife management areas. Conservation lands are also found along parts of the Mullica and Great Egg Harbor rivers in Atlantic County. However, many estuarine shorelines in developed areas are hardened, limiting the potential for wetland migration (Strange, 2008). The narrow fringing salt marshes along protected shorelines north of Barnegat Inlet could be lost even with a 2 mm/yr acceleration in rate of sea-level rise. With continued sea-level rise, natural sedimentary processes will be increasingly disrupted and lead to “drowning” of marshes. Many typical back-bay areas will likely become lakes.

As marshes along protected shorelines experience increased tidal flooding, there may be an initial benefit to some species. This is because as tidal creeks become wider, deeper, and more abundant, fish species may benefit because of increased access to forage on the marsh surface (Weinstein, 1979). Fish species such as Atlantic silverside, mummichog, and bay anchovy move into the creeks during low tide, but have greater access and are more common on the marsh surface during high tide (Talbot, 1984). Sampling of larval fishes in high salt marsh on Cattus Island, Beach Haven West, and Cedar Run in Ocean County showed that high marsh is important for production of mummichog, rainwater killifish, spotfin killifish, and sheepshead minnow (Talbot, 1984). The flooded marsh surface and tidal and nontidal ponds and ditches appear to be especially important for the larvae of these species (Talbot, 1984). However, as sea levels continue to rise, and marshes along hardened shorelines convert to open water, marsh fishes will lose access to these marsh features and the protection from predators, nursery habitat, and foraging areas provided by the marsh.

Loss of marsh area would also have negative implications for the dozens of bird species that forage and nest in the region's marshes. Initially, deeper tidal creeks and marsh pools will become inaccessible to short-legged shorebirds such as plovers (Erwin, 2004). Long-legged waterbirds such as the yellow-crowned night heron, which forages almost exclusively on marsh crabs (fiddler crab and others), will lose important food resources.[69] High marsh nesting birds such as northern harrier, black rail, clapper rail, and willet may be most at risk[70]. Eventually, complete conversion of marsh to open water will affect the hundreds of thousands of shorebirds that stop in these areas to feed during their migrations. The New Jersey Coastal Management Program estimated that some 1.5 million migratory shorebirds stopover on New Jersey's shores during their annual migrations (Cooper, 2005). Waterfowl also forage and overwinter in area marshes. Mid-winter aerial waterfowl counts in Barnegat Bay alone average 50,000 birds (USFWS, 1997). The tidal marshes of the Cape May Peninsula provide stopover areas for hundreds of thousands of shorebirds, songbirds, raptors, and waterfowl during their seasonal migrations (USFWS, 1997). The peninsula is also an important staging area and overwintering area for seabird populations. Surveys conducted by the U.S. Fish and Wildlife Service from July through December 1995 in Cape May County recorded more than 900,000 seabirds migrating along the coast (USFWS, 1997).

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[69] Dave Jenkins, Acting Chief, New Jersey Division of Fish and Wildlife, Endangered and Nongame Species Program, Trenton, New Jersey. Personal communication 7/25/07 in email to Stephen Keach of PQA.

[70] *Ibid*.

As feeding habitats are lost, local bird populations may no longer be sustainable. For example, avian biologists suggest that if marsh pannes and pools continue to be lost in Atlantic County as a result of sea-level rise, the tens of thousands of shorebirds that feed in these areas may shift to feeding in impoundments in the nearby Forsythe Refuge, increasing shorebird densities in the refuge by ten-fold and reducing population sustainability due to lower per capita food resources and disease from crowding (Erwin,et al., date unknown).

Local populations of marsh nesting bird species will also be at risk where marshes drown. This will have a particularly negative impact on rare species such as seaside and sharp-tailed sparrows, which may have difficulty finding other suitable nesting sites. According to synthesis of published studies in Greenlaw and Rising (1994) and Post and Greenlaw (1994), densities in the region ranged from 0.3 to 20 singing males per hectare and 0.3 to 4.1 females per hectare for the seaside and sharp-tailed sparrows, respectively (Greenlaw, et al., 1994). Loss and alteration of suitable marsh habitats are the primary conservation concerns for these and other marsh-nesting passerine birds (BBNEP, 2001). Non-passerine marsh nesting birds may also be at risk, particularly high marsh species such as northern harrier and black rail, which are state-listed as endangered. Species that nest in other habitat but rely on marshes for foraging, such as herons and egrets, will also be affected as marshes drown.

Shore protection activities are underway to protect the vulnerable freshwater ecosystems of the Cape May Meadows (The Meadows), which are located behind the eroding dunes near Cape May Point (USACE, 2008).Freshwater coastal ponds in The Meadows are found within a few hundred feet of the shoreline and therefore could easily be inundated as seas rise. The ponds provide critical foraging and resting habitat for a variety of bird species, primarily migrating shorebirds (Strange, 2008). Among the rare birds seen in The Meadows by local birders are buff-breasted sandpipers, arctic tern, roseate tern, whiskered tern, Wilson's phalarope, black rail, king rail, Hudsonian godwit, and black-necked stilt (Kerlinger, date unknown). TNC, the U.S. Army Corps of Engineers (USACE), and the New Jersey Department of Environmental Protection (NJDEP) have undertaken beach replenishment to protect a mile-long stretch of sandy beach found in the Cape May Migratory Bird Refuge that provides nesting habitat for the rare piping plover and least tern (Blair, date unknown).

Estuarine Beaches. Estuarine beaches will largely disappear as a result of erosion and inundation of sandy habitat as seas rise. This could eliminate the billions of invertebrates that are found within or on the sandy substrate or beach wrack along the tide line of estuarine beaches (Bertness, 1999). These species provide a rich and abundant food source for bird species. Small beach invertebrates include isopods and amphipods, blood worms, and beach hoppers, and beach macroinvertebrates include soft shell clams, hard clams, horseshoe crabs, fiddler crabs, and sand shrimp (Shellenbarger Jones, 2008).

Northern diamondback terrapin nests on estuarine beaches in the Barnegat Bay area (BBNEP, 2001). Loss of these habitats will make terrapins even more dependent on habitats modified by humans (roadways). Local scientists consider coastal development, which destroys terrapin nesting beaches and access to nesting habitat, one of the primary threats to diamondback terrapins, along with predation, roadkills and crab trap bycatch[71].

Loss of estuarine beach could also have negative impacts on the northeastern beach tiger beetle. There are two sub-species, *Cincindela dorsalis dorsalis*, which is a federally listed threatened species and a state species of special concern and regional priority, and *Cincindela dorsalis media*, which is considered rare, though it has not been considered for state listing[72]. In the mid-1990s, the tiger beetle was observed on the undeveloped ocean beaches of Holgate and Island Beach. The USFWS does not know whether this species is also found on the area's estuarine beaches, but studies indicate that it feeds and nests in a variety of habitats (USFWS, 1997). The current abundance and distribution of the northeastern beach tiger beetle in the coastal bays is a target of research (State of NJ, 2005). At present, there are plans to reintroduce the species in the study region at locations where natural ocean beaches remain (State of NJ, 2005).

Tidal Flats. The tidal flats of New Jersey's back-barrier bays are critical foraging areas for hundreds of species of shorebirds, passerines, raptors, and waterfowl (BBNEP, 2001). Tidal flats support invertebrates, such as insects, worms, clams, and crabs, that provide an

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[71] See the website of the Wetlands Institute's terrapin conservation program at http://www.terrapinconservation.org. Accessed January 24, 2008.

[72] Dave Jenkins, Acting Chief, New Jersey Division of Fish and Wildlife, Endangered and Nongame Species Program, Trenton, New Jersey. Personal communication 7/25/07 in email to Stephen Keach of PQA.

important food source for these and other birds that forage in the study region. Some shorebirds, such as semipalmated sandpiper, dunlin, and dowitcher, forage preferentially on mudflats and shallow impoundments (BBNEP, 2001). Important shorebird areas in the study region include the flats of Great Bay Boulevard Wildlife Management Area, North Brigantine Natural Area, and the Brigantine Unit of the Forsythe Refuge (USFWS, 1997). The USFWS estimates that the extensive tidal flats of the Great Bay alone total 1,358 ha (3,355 ac). Inundation of tidal flats with rising seas would eliminate critical foraging opportunities for the area's abundant avifauna. As tidal flat area declines, increased crowding in remaining areas could lead to exclusion and mortality of many foraging birds (Galbraith, 2002; Erwin, 2004). Some areas may become potential sea grass restoration sites, but whether or not "enhancing" these sites as eelgrass areas is feasible will depend on their location, acreage, and sediment type (Strange, 2008).[73]

Shallow Nearshore Waters and Submerged Aquatic Vegetation (SAV). The Barnegat Estuary is distinguished from the lagoons to the south by more open water and SAV and less emergent marsh. Within the Barnegat Estuary, dense beds of eelgrass are found at depths under 1 m (3.28 ft), particularly on sandy shoals along the backside of Long Beach Island and Island Beach, and around Barnegat Inlet, Manahawkin Bay, and Little Egg Inlet. Eelgrass is relatively uncommon from the middle of Little Egg Harbor south to Cape May, particularly locations where water depths are more than 1 m (3.28 ft), such as portions of Great South Bay (USFWS, 1997).

Seagrass surveys from the 1960s through the 1990s indicate that there has been an overall decline in seagrass in Barnegat Estuary, from 6,823 ha (16,847 ac) in a 1968 survey to an average of 5,677 ha (14,029 ac) of seagrass beds during the period 1996 to 1998 (BBNEP, 2001). Numerous studies indicate that eelgrass has high ecological value as a source of both primary (Thayer, et al. 1984) and secondary production (Jackson et al., 2001) in estuarine food webs. In Barnegat Estuary eelgrass beds provide habitat for invertebrates, birds, and fish that use the submerged vegetation for spawning, nursery, and feeding habitat (BBNEP, 2001). In addition, many species graze on eelgrass, including gastropods, fishes, ducks, and muskrats (BBNEP, 2001).

Short and Neckles (1999) suggested that a 50 cm (19.7 in) increase in water depth as a result of sea-level rise could reduce the light available for eelgrass photosynthesis by 50%, resulting in a 30-40% reduction in seagrass growth. The researchers suggested that this will, in turn, result in reduced productivity and functional values of eelgrass beds (Short and Neckles, 1999).

Results of a study in Barnegat Bay indicated that shoreline protection may exacerbate this problem. The study found that where shorelines are bulkheaded, SAV, woody debris, and other features of natural shallow water habitat are rare or absent. In these bulkheaded areas, there were reduced abundances of fishes compared to sites that were not bulkheaded sites (Byrne, 1995).

Marsh and Bay Islands. Large bird populations are found on marsh and dredge spoil islands of the back-barrier bays in the study region. These islands include nesting sites protected from predators for a number species of conservation concern, including gull-billed tern, common tern, Forster's tern, least tern, black skimmer, American oystercatcher, and piping plover (USFWS, 1997). Diamondback terrapins are also known to feed on marsh islands in the bays (USFWS, 1997).

Some of the small islands in Barnegat Bay and Little Egg Harbor are several feet above mean spring high water (Jones and Wang, 2008), but portions of other islands are very low, and some low islands are currently disappearing. Many of the islands used by nesting common terns, Forster's terns, black skimmers, and American oystercatchers are vulnerable to sea-level rise and erosion (MLT, date unknown). With the assistance of local governments, the Mordecai Land Trust is actively seeking grants to halt the gradual erosion of Mordecai Island, a 45-acre island just west of Beach Haven on Long Beach Island (MLT, date unknown). Members of the land trust have documented a 37% loss of island area since 1930. The island's native salt marsh and surrounding waters and SAV beds provide habitat for a variety of aquatic and avian species. NOAA Fisheries considers the island and its waters Essential Fish Habitat for spawning and all life stages of winter flounder as well as juvenile and adult stages of Atlantic sea herring, bluefish, summer flounder, scup, and black sea bass.[74] The island is also a strategically-located nesting island for many of New Jersey's threatened and endangered species, and it contains

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moderate-size black skimmer colony, common terns, and most recently, a very small colony of royal terns (Strange, 2008).

Sea-level fens. Sea-level fens are a tidally influenced seepage wetland, located at the upland/freshwater swamp/tideland interface where fresh groundwater seepage discharges and occasional tidal inundation occurs. New Jersey has identified 12 sea-level fens, encompassing 126 acres. This rare ecological community is restricted in distribution to Ocean County in New Jersey, between Forked River and Tuckerton, in an area of artesian groundwater discharge from the Kirkwood - Cohansey aquifer. Additional recent field surveys have shown possible occurrences in the vicinity of Tuckahoe in Cape May and Atlantic counties (Walz 2004).

These communities provide significant wetland functions in the landscape as well as supporting 18 rare plant species, of which one is listed as State Endangered. Sea-level fen is an ecological community recognized in the National Vegetation Classification System and is ranked as a G1, or critically globally imperiled, community. 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[75]. 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[76].

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[75] Chris Bason, Delaware Inland Bays Program, written communication to EPA 5/14/07.

[76] Barry Truitt,Chief Conservation Scientist, The Nature Conservancy, Virginia Coast Reserve, written communication to EPA, 7/25/07.

C.3 DEVELOPMENT AND SHORE PROTECTION

Chapter 5 describes the basis for ongoing studies that are analyzing land use plans, land use data, and coastal policies to create maps depicting the areas where shores may be protected and where wetlands may migrate inland. Because the maps from those studies have not yet been finalized, this section describes some of the existing and evolving conditions that may influence decisions related to future shore protection and wetland migration.

C.3.1 Statewide Policy Context

The implications of sea level rise for New Jersey are sensitive to policies related to the Coastal Facilities Review Act, the State Plan, an unusually strong public trust doctrine, and the state's strong support for beach nourishment — and opposition to both erosion-control structures and shoreline retreat — along ocean shores. The first three of these policies are discussed in Appendix D; we briefly describe the latter here.

In 1997, then-Governor Whitman promised coastal communities that: "There will be no forced retreat," and that the government would not force people to leave the shoreline. That policy does not necessarily mean that there will always be government help (in terms of state-sponsored shore protection, permits for private actions, guarantees of insurance availability, maintenance of bridges, highways and causeways, etc.) for shore protection. Nevertheless, although subsequent administrations have not expressed this view so succinctly, they have not withdrawn the policy either. If fact, the primary debate in New Jersey tends to be the level of public access required before a community is eligible to receive beach nourishment, not the need for shore protection itself[77].

The state generally prohibits new hard structures along the ocean front; but that was not always the case. A large portion of the Monmouth County shoreline was once protected with seawalls, with a partial or total loss of beach. During the 1970s, Orrin Pilkey and others pointed to the irony of governments subsidizing the owners of valuable homes by providing shore protection structures that protected the homes but destroyed the primary asset that made the homes valuable to begin with: a nearby beach. Sea Bright and Long Branch were commonly cited by coastal geologists who decried the “New Jerseyization” (i.e., shoreline hardening) of coastal communities elsewhere (Pilkey et al., 1978).

Today, beach nourishment is the preferred method for reversing beach erosion and providing ocean front land with protection from coastal storms (Maureillo, 1991). The entire Monmouth County shoreline now has a beach in front of the old seawalls. Beach nourishment has been undertaken or planned for at least one community in every coastal county from Middlesex along Raritan Bay, to Salem along the Delaware River.

Coastal officials are well-aware of the dynamic nature of barrier islands and have often sought to develop plans to allow development to adapt to shifting shores. If a catastrophic storm caused substantial beach erosion and property damage, it might be economically infeasible to reclaim all the land lost to ocean side erosion. A severe storm might also cause new land to be created on the bay sides of some barrier islands, through

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[77] See Chapter 7.

the geological overwash process. Nevertheless, current plans assume that permanent changes to the shoreline along the densely developed New Jersey shore would be confined to a very small number of unusually vulnerable areas.

C.3. RESPONSES TO SEA LEVEL RISE

With extensive development and tourism along its shore, New Jersey has a well-established policy in favor of shore protection along the ocean shores[78]. In particular, the state's policies specifically promote the use of beach nourishment to protect property and tourism[79]. For example, Island Beach State Park, a barrier spit along the central portion of Barnegat Bay just north of Long Beach Island, is heavily used by New Jersey residents and includes the official beach house of the Governor. Although it is a state park, it is currently included in the authorized Corps of Engineers Project for beach nourishment from Manasquan to Barnegat Inlet. In the case of Cape May Meadows, however,[80] environmental considerations have prompted shore protection efforts (USACE, 2008). The areas critical freshwater ecosystem is immediately behind dunes that have eroded severely as a result of the jetties protecting the entrance to the Cape May Canal.

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[78] For example, the primary coastal policy document during the Whitman administration suggested that even mentioning the term "retreat" would divide people and impede meaningful discussion of appropriate policies. See NJDEP, 1997 ("The mere use of the word serves to divide people . . . . '[R]etreat' can mean government-imposed prohibition on construction or reconstruction of oceanfront development . . . . [which] often fuels the divisive `retreat' debate . . . ."). Governor Whitman promised coastal mayors and residents that "there will be no forced retreat."

[79] See Coastal Engineering N.J.A.C. 7:7E –7.11

[80] The Meadows are within Cape May Point State Park and the Nature Conservancy's Cape May Migratory Bird Refuge.

Chapter 2 suggests the possibility of disintegrating barrier islands along the New Jersey shore. If this risk is substantiated, it is more likely to be a motivation for continued nourishment than an abandonment of these coastal communities. Communities are just starting to think about how the low bay sides of barrier island shores should be protected. Although the baysides of these islands are bulkheaded, communities are unlikely to seriously consider the option of being encircled by a dike as sea-level rises (see BOX C.2 on Long Beach Island). However, Avalon uses a combination of floodwalls and checkvalves to prevent tidal flooding; and Atlantic City's stormwater management system includes underground tanks with checkvalves. These systems have been implemented to address current flooding problems; but they would also be a logical first step in a strategy to protect low lying areas with structural solutions as sea-level rises[81].

With 72 square kilometers of nontidal wetlands within 1 meter above the tides (Jones and Wang, 2008), wetlands along the back-barrier bays of New Jersey's Atlantic coast are likely to have some room to migrate inland. On effort at the state level to preserve such coastal resources is the State's Stormwater Management Plan, which establishes a special water resource protection area that limits development within 300 feet along most of its coastal shore (NJDEP, DWM, April 2004). While the primary objective of the regulation is to improve coastal water quality and reduce potential flood damage, it serves to preserve areas suitable for the landward migration of wetlands.

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[81] See Chapter 5 for explanation of progression of structural mechanisms to combat flooding.

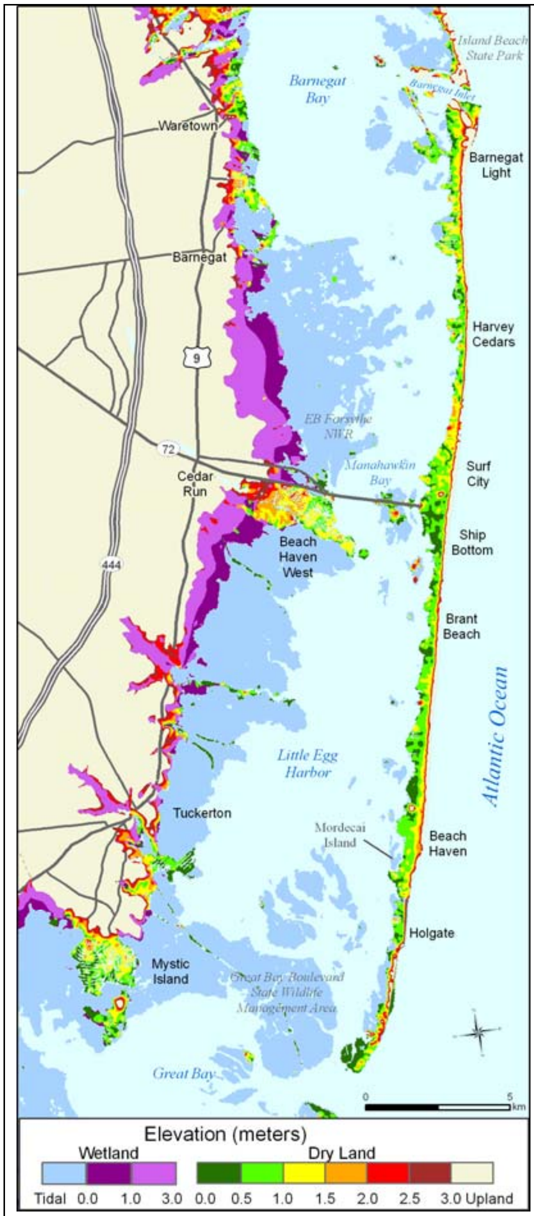
BOX C.2: Shore Protection on Long Beach Island

The effects of sea-level rise can be observed on both the ocean and bay sides of this 18-mile long barrier island. Along the ocean side, shore erosion has threatened homes in Harvey Cedars and portions of Long Beach township. During the 1990s, a steady procession of dump trucks brought sand onto the beach from inland sources. In 2007, the Corps of Engineers began to restore the beach at Surf City and areas immediately north. The beach had to be closed for a few weeks, however, after officials discovered that munitions (which had been dumped offshore after World War II) had been inadvertently pumped onto the beach.

High tides regularly flood the main boulevard in the commercial district of Beach Haven, as well as the southern two blocks of Central Avenue in Ship Bottom. Referring to the flooded parking lot during spring tides, the billboard of a pizza parlor in Beach Haven Crest boasts “Occasional Waterfront Dining.”

EPA’s 1989 Report to Congress used Long Beach Island as a model for analyzing alternative responses to rising sea level, considering four options: a dike around the island, beach nourishment and elevating land and structures, an engineered retreat which would include the creation of new bayside lands as the ocean eroded, and making no effort to maintain the island’s land area. Giving up the island was the most expensive option. The study concluded that a dike would be the least expensive in the short run, but unacceptable to most residents due to the lost view of the bay and risk of being on a barrier island below sea level. In the long run, fostering a landward migration would be the least expensive, but it would unsettle the expectations of bayfront property owners and hence require a leadtime of a few generations between being enacted and new bayside land actually being created. Thus, the combination of beach nourishment and elevating land and structures appeared to be the most realistic, and EPA used that assumption in its nationwide cost estimate.

Long Beach township, Ship Bottom, Harvey Cedars, and Beach Haven went through a similar thinking process in considering their preferred response to sea-level rise. In resolutions enacted by their respective councils, they concluded that a gradual elevation of their communities would be preferable to either dikes or the retreat option. In the last ten years, several structural moving companies have had ongoing operations, continually elevating homes.



Box Figure C.2-1 Elevations relative to spring high water on and around Long Beach Island. Source: Titus and Wang, 2008.

C.4 POPULATION OF LANDS CLOSE TO SEA LEVEL

Table C.2 estimates the population of lands close to sea level for each of the counties along the Atlantic coast of New Jersey. Because Census data measures official residents, these figures omit the many summer residents. Nevertheless, thousands of people inhabit the very-low lying lands along the back barrier bays of Ocean, Cape May, and Monmouth Counties. Tens of thousands of people live within two meters above the tides in coastal communities from Cape May to Sea Bright.

Table C.2 Population of lands close to sea level: New Jersey Shore.

County	**Low and high estimates of population below a given elevation (thousands)**					
	50cm		**1m**		**2m**	
	Low	**High**	**Low**	**High**	**Low**	**High**
Jersey						
Atlantic	0.1	39.6	21.3	67.1	72.4	86.6
Burlington[1]	0.0	23.7	0.0	27.6	2.6	46.2
Cape May[1]	2.1	30.5	17.3	44.2	38.9	56.9
Monmouth[2]	4.9	19.5	15.2	36.8	46.5	68.5
Ocean	1.0	21.6	11.3	50.4	64.8	89.5
Total	**8.1**	**134.9**	**65.1**	**226.1**	**225.2**	**347.7**

[1] Figures are for the entire county. County is split between New Jersey Shore and Delaware Bay Watersheds.

[2] Figures are for the entire county. County is split between New Jersey Shore and Hudson River Watersheds.

C.5 STATEWIDE POLICY CONTEXT

We will see in Appendix D (Delaware Estuary) that the implications of sea-level rise for New Jersey are sensitive to policies related to the Coastal Facilities Review Act, the State Plan, and an unusually strong public trust doctrine. Let us now examine the state's strong support for beach nourishment — and opposition to both erosion-control structures and shoreline retreat — along ocean shores.

Strong Commitment to Beach Nourishment. In 1997, then-Governor Whitman promised coastal communities that: "There will be no forced retreat," and that the government would not force people to leave the shoreline. That policy does not necessarily mean that there will always be government help (in terms of state-sponsored shore protection, permits for private actions, guarantees of insurance availability, maintenance of bridges, highways and causeways, etc.) for shore protection. Nevertheless, although subsequent administrations have not expressed this view so succinctly, they have not withdrawn the policy either. If fact, the primary debate in New Jersey tends to be the level of public access required before a community is eligible to receive beach nourishment, not the need for shore protection itself[82].

The state generally prohibits new hard structures along the ocean front; but that was not always the case. A large portion of the Monmouth County shoreline was once protected with seawalls, with a partial or total loss of beach. During the 1970s, Orrin Pilkey and others pointed to the irony of governments subsidizing the owners of valuable homes by providing shore protection structures that protected the homes but destroyed the primary asset that made the homes valuable to begin with: a nearby beach. Sea Bright and Long Branch were commonly cited by coastal geologists who decried the “New Jerseyization” (i.e., shoreline hardening) of coastal communities elsewhere (Pilkey et al., 1978).

Today, beach nourishment is the preferred method for reversing beach erosion and providing ocean front land with protection from coastal storms (Maureillo, 1991). The entire Monmouth County shoreline now has a beach in front of the old seawalls. Beach nourishment has been undertaken or planned for every coastal county from Middlesex along Raritan Bay, to Salem along the Delaware River.

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[82] See Chapter 7.

If a catastrophic storm caused substantial beach erosion and property damage, it might be economically infeasible to reclaim all the land lost to ocean side erosion. A severe storm might also cause new land to be created on the bay sides of some barrier islands, through the geological overwash process. Nevertheless, current plans assume that permanent changes to the shoreline along the densely developed New Jersey shore would be confined to a very small number of unusually vulnerable areas.

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Appendix D. Delaware Estuary

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Much of this report examines the difference between protecting the current boundary between dry land and wetlands and allowing that boundary to retreat. At one time, there was a third option: *advance* the shore seaward by converting marsh to dry land. Environmental policies ended that practice in the United States. But the methods and results of preventing dry land from becoming wet have many similarities with creating dry land from water: Just as we can prevent land from becoming water by elevating land and beaches with fill material, at one time people converted water to land by filling wetlands and shallow waters[83]. Just as we can prevent dry lands from becoming wetlands by building dikes inland of the existing wetlands, at one time people created farmland by building dikes seaward of the marsh.

Nowhere in the United States was more marsh converted to dry land than along the Delaware River and Delaware Bay. (See Box D.1) Although most of the dikes used to

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[83] E.g., See discussion about filling of the Potomac River in Washington D.C. in Appendix F.

reclaim land from the sea have been dismantled, some still persist. Even where the dikes have been dismantled, their effects are still noticeable.

This report uses the term "Delaware Estuary" as shorthand for referring to both the Delaware Bay and the tidal portions of the Delaware River. From the head-of-tide at Trenton to Commodore Barry Bridge near the Delaware–Pennsylvania border, the river is generally fresh. This chapter examines the coastal elevations and environmental vulnerability. We divide the discussion between land above and below the Commodore Barry Bridge over the Delaware River, which roughly defines the boundary between fresh and brackish water.

BOX D.1: Land Reclamation in the Delaware Estuary

Nowhere in the United States was more marsh converted to dry land than along the Delaware River and Delaware Bay. A Dutch governor of New Jersey diked the marsh on Burlington Island. In 1680, after the English governor had possession of the island, observers commented that the marsh farm had achieved greater yields of grain than nearby farms created by clearing woodland (Danckaerts, 1913). Shortly after, an English governor ordered the construction of dikes to facilitate construction of a highway through the marsh in New Castle County (Sebold, 1992).

Colonial (and later state) governments in New Jersey chartered and authorized "meadow companies" to build dikes and take ownership of the reclaimed lands. During the middle of the 19th century, the state agriculture department extolled the virtues of reclaimed land for growing salt hay.[1] By 1866, 20,000 acres of New Jersey's marshes had been reclaimed from Delaware Bay, mostly in Salem and Cumberland counties (State Geologist, 1866), and by 1892, more than 15,000 acres had been reclaimed in Salem County alone (Vermeule, 1984). In 1885, the U.S. Department of Agriculture cited land reclamation in Cumberland County, New Jersey, as among the most impressive in the nation.[2] On the other side of the river, by 1885, land reclamation had converted 10,000 out of 15,000 acres of the marsh in New Castle County to agricultural lands, as well as 8,000 acres in Delaware's other two counties (Nesbit, 1885). In Pennsylvania, most of the reclaimed land was just south of the mouth of the Schuylkill along the Delaware River, near the present location of Philadelphia International Airport.

During the 20th century, these land reclamation efforts were reversed. In many cases, lower prices for salt hay led farmers to abandon the dikes (DDFW, 2007).In some cases, where dikes remain, rising sea level has limited the ability of dikes to drain the land, and the land behind the dike has converted to marsh (see Box D.4 on Gibbstown Levee). Efforts are under way to restore the hydrology of many lands that were formerly diked (DDFW, 2007). The momentum of these environmental restoration efforts has extended inland in both Delaware and New Jersey. Much of the formerly diked lands are now part of conservation areas.

Notes:

1. "In 1857 the Cape May County, New Jersey, had 58,824 acres of marsh, of which 1,918 acres were improved through reclamation and 17,223 acres were used as meadow. The [state geologist] encouraged reclamation because once landowners shut off the tidal waters using banks and sluices, the marshes would become fresh and capable of improvement for cultivation. The state geologist asserted that unimproved salt marsh could be made profitable by improving it just enough to grow salt hay; all one had to do was dig ditches and open salt holes to allow the flow of the tide to escape." (State of New Jersey, 1885)
2. "The superiority of diked land over poor upland is nowhere better illustrated than along the Maurice River, in New Jersey. There the banked meadows, some of which have been in cultivation, without manure, for generations, are wonderfully fertile, and the upland immediately adjoining is only able to produce scrub oak and stunted pine" (State of New Jersey, 1885)

D.1 THE NATURAL ENVIRONMENT

D.1.1 Delaware Bay and the Lower Delaware River

D.1.1.1 Coastal Elevations

Figure D.1 depicts the elevations of lands close to sea level. Salem County in New Jersey and Kent County in Delaware have the most dry land within 2 meters of spring high water. Salem County has between 54 and 84 square kilometers of dry land below 2 meters, and Kent County has between 48 and 78 square kilometers (see Table D.1). Approximately 90–186 square kilometers of dry land lie within 1 meter above the tides along the shores of the Delaware Estuary south of the Pennsylvania/Delaware and Salem/Gloucester County, New Jersey, border. Within this area, a similar area of nontidal wetlands exists, with 71–131 square kilometers.

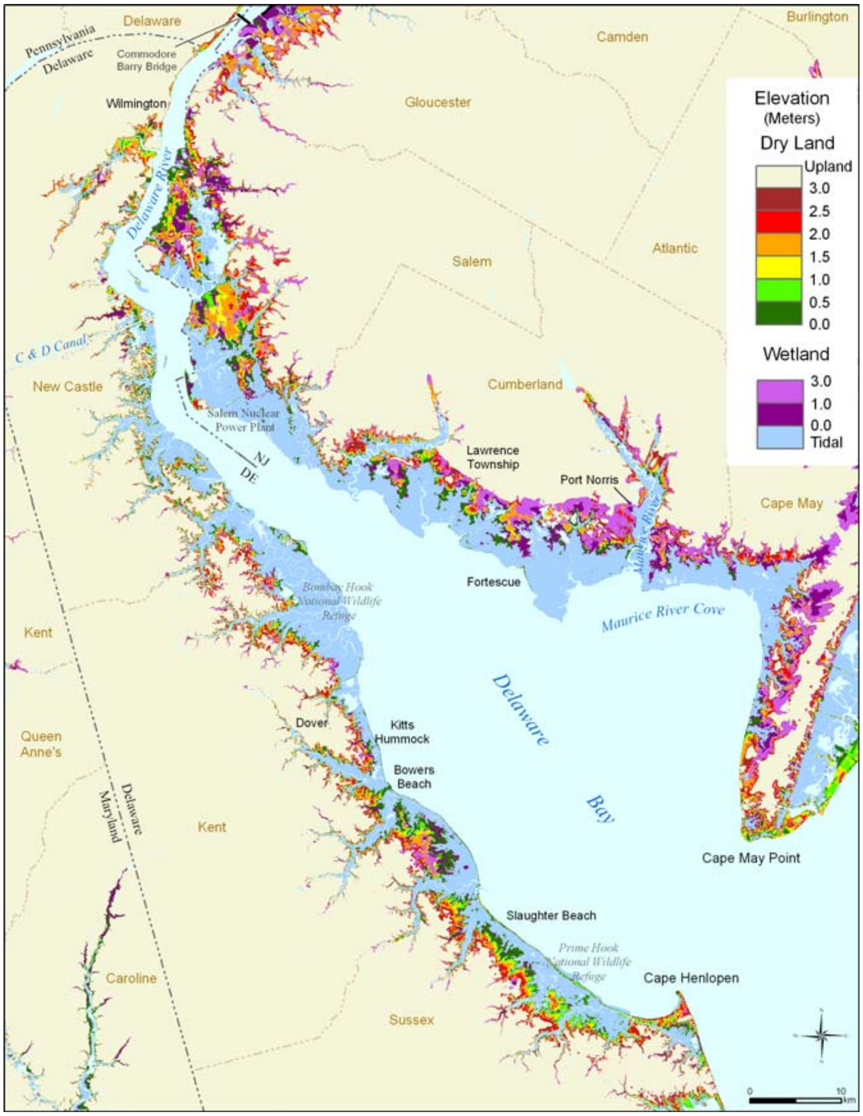

Figure D.1 Delaware Bay: Elevations relative to spring high water.

Table D.1 Low and high estimates for the area of dry and wet land close to sea level, Delaware Estuary (square kilometers).

Elevations above spring high water:		Tidal	50 cm		1 meter		2 meters		3 meters		5 meters	
			Low	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Locality	**State**	Cumulative (total) amount of dry land below a given elevation										
Sussex	DE		6.4	18.2	15.8	30.8	37.3	55.2	60.0	78.6	103.3	119.7
Kent	DE		8.8	24.8	21.9	40.6	47.9	77.6	86.1	119.2	177.8	209.9
New Castle	DE		7.1	19.0	16.8	29.9	34.4	52.2	54.2	75.0	99.0	119.0
Delaware	PA		0.4	6.1	4.0	12.1	11.5	18.0	17.2	20.7	22.2	25.9
Philadelphia[1]	PA		3.6	6.1	6.8	12.4	20.0	24.8	31.6	36.8	51.5	54.8
Bucks	PA		0.0	4.4	0.2	8.5	5.3	18.0	11.9	27.4	25.3	42.1
Mercer	NJ		0.0	0.1	0.0	0.1	0.1	0.2	0.2	0.4	0.3	0.4
Burlington	NJ		0.1	4.3	0.4	8.4	5.3	16.4	11.0	24.5	22.5	42.2
Camden	NJ		0.0	3.8	0.1	7.3	4.3	14.8	9.5	22.4	20.4	34.5
Gloucester	NJ		0.2	9.2	6.1	18.4	17.7	33.3	29.6	46.5	53.5	69.3
Salem	NJ		5.9	26.9	21.3	48.7	53.8	84.4	83.9	114.0	135.5	160.3
Cumberland	NJ		3.0	15.8	12.1	28.9	30.3	53.2	49.5	76.9	90.8	114.3
Cape May	NJ		0.4	3.5	2.5	7.5	8.6	19.9	20.9	36.9	55.5	68.0
Total			**35.9**	**142.0**	**108.0**	**253.7**	**276.5**	**468.0**	**465.7**	**679.2**	**857.7**	**1060.4**
		Cumulative (total) amount of wetlands below a given elevation										
Sussex	DE	67.4	2.1	4.8	4.6	6.2	6.8	8.6	9.0	10.6	12.3	13.3
Kent	DE	168.7	4.9	11.4	10.4	16.6	19.0	24.6	25.9	30.9	38.8	43.5
New Castle	DE	73.5	1.8	3.8	3.5	4.8	5.1	6.7	6.7	8.4	9.7	11.1
Delaware	PA	3.6	0.1	0.8	0.6	1.7	1.6	2.2	2.2	2.3	2.3	2.3
Philadelphia	PA	0.6	0.5	0.6	0.6	0.9	1.2	1.4	1.6	1.7	1.9	1.9
Bucks	PA	1.9	0.0	0.9	0.1	1.9	1.2	4.1	2.9	6.3	6.2	8.2
Mercer	NJ	1.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Burlington	NJ	5.4	0.0	0.6	0.0	1.2	0.7	2.3	1.5	3.4	3.1	5.8
Camden	NJ	1.5	0.0	0.3	0.1	0.7	0.5	1.3	0.9	1.9	1.8	2.7
Gloucester	NJ	18.0	0.2	8.8	5.9	17.4	16.8	25.9	25.0	28.8	30.4	33.5
Salem	NJ	110.1	9.6	25.1	22.3	35.8	38.2	49.0	48.9	55.4	60.3	67.6
Cumberland	NJ	212.6	4.7	23.6	18.1	42.1	43.6	65.5	63.5	80.6	89.8	103.2
Cape May	NJ	48.3	4.3	14.7	12.2	25.1	28.2	40.3	41.5	51.2	58.6	63.7
Total		**713.5**	**28.3**	**95.5**	**78.5**	**154.2**	**163.0**	**231.8**	**229.7**	**281.6**	**315.1**	**356.8**
Dry and nontidal wetland			64	237	187	408	440	700	695	961	1173	1417
All land		713	778	951	900	1121	1153	1413	1409	1674	1886	2131

Source: Titus and Cacela, 2008: Uncertainty Ranges Associated with EPA's Estimates of the Area of Land Close to Sea Level. Section 1.3 in: Background Documents Supporting Climate Change Science Program Synthesis and Assessment Product 4.1: Coastal Elevations and Sensitivity to Sea Level Rise, J.G. Titus and E. Strange (eds.). EPA 430R07004. U.S. EPA, Washington, DC. The low and high estimates are based on the contour interval and/or stated root mean square error (RMSE) of the data used to calculate elevations. For more details, see Chapter 1..

1. This number includes Philadelphia's 2.4 square kilometers of dry land below spring high water, of which 0.87, 0.26, 0.054, and 0.005 are at least 0.5, 1, 2, and 3 meters below spring high water, respectively. Most of this land is near Philadelphia International Airport.

Nontidal wetlands account for more than half of the land below 1 meter on the New Jersey side, but only one quarter on the Delaware side.

D.1.1.2 Vulnerable Habitats

On both sides of Delaware Bay, most shores are either tidal wetlands or sandy beaches with tidal wetlands immediately behind them. In effect, the sandy beach ridges are similar to the barrier islands along the Atlantic, only on a smaller scale. Several substantial communities with wide sandy beaches on one side and marsh on the other side are along Delaware Bay — especially on the Delaware side of the bay. Shoreline erosion has been a more immediate threat to these communities. Nevertheless, Bowers Beach, Slaughter Beach, and Fortescue are all within 2 meters above spring high water.

Delaware Bay is home to hundreds of species of ecological, commercial, and recreational value (Dove and Nyman, 1995). Unlike other estuaries in the Mid-Atlantic, the tidal range is greater than the ocean tidal range, generally about 2 meters. Beaches account for 52% of the bay’s shore, with marsh and eroding peat accounting for most of the remainder (Lathrop, et al., 2006). We briefly discuss the possible loss of Delaware Bay’s tidal marshes and beaches.

Tidal Marsh

Like most large estuaries, Delaware Bay has freshwater, brackish, and salt marshes. The bay’s low marsh is dominated by smooth cordgrass, *Spartina alterniflora*, whereas high marsh is dominated by salt hay, *Spartina patens (*Kreeger and Newell, 2000). High marsh habitat is less common than low marsh, and likely to be more vulnerable. Among the many bird species that rely on high marsh are black rail and the coastal plain swamp sparrow (*Melospiza Georgiana nigrescens*), which has nearly its entire breeding distribution in Delaware Estuary[84].

In some areas, dikes have been removed to restore tidal flow and natural marsh habitat and biota, but in some areas invasion by common reed (*Phragmites australis)* has been a problem (Able et al., 2000; Weinstein, et al. 2000).

Habitat Change as Sea Level Rises

Can Marshes Keep Pace with Rising Sea Level? The net gain or loss of tidal marshes as sea level rises depends on tide range, the ability of the wetlands to keep pace with rising sea level, and their ability to migrate inland. With a 2 meter daily tide range, it would take almost a 1 meter rise to submerge all the existing low marsh, or to convert high marsh into low marsh.

In much of Delaware Bay, however, tidal marshes appear to be at the low end of their potential elevation range, increasing their vulnerability (Kearney et al., 2002). Recent research indicates that 50 to 60% of Delaware Bay’s tidal marsh has been degraded, primarily because the surface of the marshes is not rising as fast as the sea (Kearney et al., 2002). One possible reason is that channel deepening projects and consumptive withdrawals of fresh water have changed the sediment supply to the marshes (Kreeger et

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[84] Kevin Kalasz, Delaware Natural Heritage Program, Division of Fish and Wildlife in written communication to EPA, 5/14/07.

al., 2007). Marshes are also eroding at their seaward edges; for example, the mouth of the Maurice River near Port Norris, New Jersey. But the wetlands along Bombay Hook National Wildlife Refuge on the Delaware side, and between Fortescue and the Salem Nuclear Power Plant on the New Jersey side, are already marginal and would mostly be lost from even a sea-level rise acceleration of 2 mm/year.

Can Wetlands Migrate Inland as Sea Level Rises? Along Delaware Bay, most of the shore is undeveloped. If these lands do not receive shore protection, they would be available for potential wetland migration. Each acre of land submerged, however, would not necessarily correspond to an acre of increased wetland habitat: Landward migration of tidal wetlands may occur at the expense of existing nontidal wetlands along much of the shore. Moreover, no one has established that the tidal inundation of the freshwater wetlands would lead to creation of salt marsh; in many areas such inundation converts the wetlands to open water instead.

Implications of Habitat Change. The loss of tidal marsh as sea level rises would harm species that depend on these habitats for food, and shelter, including invertebrates, finfish, and a variety of bird species. Great blue herons, black duck, blue and green-winged teal, Northern harrier, osprey, rails, red winged blackbirds, widgeon, and shovelers all use the salt marshes in Delaware Bay. Blue crab, killifish, mummichog, perch, weakfish, flounder, bay anchovy, silverside, herring, and rockfish rely on tidal marshes for feeding on the mussels, fiddler crabs, and other invertebrates and for protection from predators (Dove and Nyman, 1995).

Invertebrates associated with cordgrass stands in the low intertidal zone include grass shrimp, ribbed mussel, coffee-bean snail, and fiddler crabs (Kreamer 1995). Blue crab, sea turtles, and shorebirds are among the many species that prey on ribbed mussels; fiddler crabs are an important food source for bay anchovy and various species of shorebirds (Kreamer, 1995). Wading birds such as the glossy ibis feed on marsh invertebrates (Dove & Nyman, 1995). Waterfowl, particularly dabbling ducks, use low marsh areas as a wintering ground.

Beaches

Habitat Change. Sandy beaches and foreshores account for 54% of the Delaware and New Jersey shores of Delaware Bay. Table D.2 shows additional estimates of the status of the bay's shoreline, with an emphasis on the vulnerability of beach habitat. As sea level rises, beaches can be lost if either shores are armored or if the land behind the existing beach has too little sand to sustain a beach as the shore retreats (Nordstrom, 2005). As shown in Table D.2, so far, only 4 (Delaware) and 6 (New Jersey) percent of the natural shores have been replaced with shoreline armoring. Another 15 (Delaware) and 4 (New Jersey) percent of the shore is developed. Although conservation areas encompass 58% of Delaware Bay's shores, they include only 32% of beaches that are optimal or suitable habitat for horseshoe crabs.

BOX D.2: Horseshoe Crabs, Limulus polyphemus, and Estuarine Beaches

The Atlantic horseshoe crab (*Limulus polyphemus)*, an ancient species that has survived virtually unchanged for more than 350 million years enters estuaries each spring to spawn along sandy beaches. The species has experienced recent population declines, apparently due to over harvesting as well as habitat loss and degradation (Berkson and Shuster, 1999).

Population Status and Sea-Level Rise

In Delaware Bay, as elsewhere along its range, horseshoe crabs depend on narrow sandy beaches and the alluvial and sand bar deposits at the mouths of tidal creeks for essential spawning habitat. A product of wave energy, tides, shoreline configuration, and over longer periods, sea-level rise, the narrow sandy beaches utilized by horseshoe crabs are diminishing at sometimes alarming rates due to beach erosion as a product of land subsidence and sea level increases (Nordstrom 1989; Titus et al. 1991). At Maurice Cove in Delaware Bay, for example, portions of the shoreline have eroded at a rate of 4.3 m per year between 1842 and 1992 (Weinstein and Weishar 2002); an estimate by Chase (1979) suggests that the shoreline retreated 150 m landward in a 32-year period, exposing ancient peat deposits that are believed to be suboptimal spawning habitat (Botton et al. 1988). As human infrastructure along the coast leaves estuarine beaches little or no room to transgress inland as sea level rises, there will likely be concomitant loss of horseshoe crab spawning habitat. Kraft et al. (1992) estimated this loss, concomitant with wetland “drowning” as > 90% in Delaware Bay (~ 33,000 ha).

Horseshoe Crab Spawning and Shorebird Migrations

Each spring, horseshoe crab spawning coincides with the arrival of hundreds of thousands of shorebirds migrating from South America to their sub-Arctic nesting areas. While in Delaware Bay, shorebirds feed extensively on horseshoe crab eggs to increase their depleted body mass before continuing their migration (Castro and Myers 1993; Clark 1996). Individual birds may increase their body weight by nearly one-third before leaving the area. How shorebirds might be affected by horseshoe crab population decline is uncertain (Smith et al., 2006).

Table D.2 The shores of Delaware Bay: Habitat type and conservation status of shores suitable for horseshoe crabs.

Shoreline length	**Delaware**		**New Jersey**		**NJ+DE**
…by Habitat Type (percent of bay shoreline)[1]	km	%	km	%	%
Beach	68	74	62	42	54
Armored Shore	3.7	4	8.3	6	5
Organic	20	22	78	53	41
Total Shoreline	91	100	148	100	100
… by Existing Development					
Development[1]	13	15	5.7	3.8	8
…by Suitability for Horseshoe Crab (percent of Bay shoreline)					
Optimal Habitat[2]	31.3	34	26.0	18	24
Suitable Habitat[2]	10.5	12	5.1	3.5	6.6
Less Suitable Habitat[2]	29.0	32	49.0	33	33
Unsuitable Habitat[2]	20.0	22	67.0	46	37
…Within Conservations Lands by Suitability for Horseshoe Crab (percent of equally suitable lands)					
Optimal Habitat[3]	12.9	41	9.6	37	39
Optimal and Suitable Habitat[3]	13.6	33	9.8	32	32
Optimal, Suitable, and Less Suitable Habitat[3]	32.2	46	43.3	54	50
All Shores[3]	44.7	49	92.7	63	58

[1] Delaware and New Jersey results from Lathrop et al., 2006.

[2] Delaware and New Jersey results from Lathrop et al., 2006 at p.16 Table 9. “Unsuitable” includes both “avoided” and “disturbed.”

[3] From Lathrop et al. at p.18 Table 1. Lathrop et al. report results for the categories separately, while we aggregate the categories.

Beach nourishment has been relatively common along the developed beach communities on the Delaware side of the bay. Although beach nourishment can diminish the quality of habitat for horseshoe crabs, nourished beaches are more beneficial than an armored shore. But many Delaware Bay beaches have a relatively thin layer of sand. Although these small beaches have enough sand to protect the marshes immediately inland from wave action, it is uncertain whether some beaches would survive accelerated sea-level rise even without shoreline armoring. In a few cases, Delaware has already nourished beaches with the primary purpose of restoring horseshoe crab habitat (Smith, 2006).

Implications of Habitat Change. Delaware Bay is a major stopover area for six species of migratory shorebirds, including most of the Western Hemisphere population of red knot[85]. On their annual migrations from South America to the Arctic, nearly a million shorebirds move through Delaware Bay, where they feed heavily on invertebrates in tidal mudflats, and particularly on horseshoe crab eggs on the bay's sandy beaches and foreshores (Walls, 2002). The Delaware Estuary is home to the largest spawning population of horseshoe crabs in the world. Although these animals can lay eggs in tidal marshes, their preferred nesting sites are the mid- and high intertidal zones of sandy beaches.

A sea-level rise modeling study estimated that a 2 foot rise in relative sea level over the next century could reduce shorebird foraging areas in Delaware Bay by 57% or more by 2100 (Galbraith et al., 2002). If these foraging habitats are lost and prey species such as horseshoe crab decline, there are likely to be substantial reductions in the numbers of shorebirds supported by the bay (Galbraith et al., 2002). In fact, since 1991 there has been a dramatic decline in horseshoe crabs in Delaware Bay and a corresponding decline in shorebird numbers (NJDEP, date unkown).

Numerous other animals, including diamondback terrapins, and Kemp's and Ridley sea turtles, rely on the sandy beaches of Delaware Bay to lay eggs or forage on invertebrates such as amphipods and clams. When tides are high, numerous fish also forage along the

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[85] For example, see discussion of migratory shorebirds in Delaware Bay at http://www.state.nj.us/dep/fgw/ensp/shorebird_mig.htm, accessed 1/23/08.

submerged sandy beaches, such as killifish, mummichog, rockfish, perch, herring, silverside, and bay anchovy (Dove and Nyman, 1995).

BOX D.3: Finfish and Tidal Salt Marshes

Tidal salt marshes are among the most productive habitats in the world (Teal, 1986). In addition to directly benefiting resident salt marsh species, marsh-associated organic matter is incorporated into food webs supporting marine transient fish production in open waters. Marine transients are adapted to life on a "coastal conveyor belt," often spawning far out on the continental shelf and producing estuarine dependent young that are recruited into coastal embayments year-round (Deegan, 2000).

Tidal salt marshes serve two critical functions for young finfish (Boesch and Turner, 1984). First, abundant food and the warm shallow waters of the marsh are conducive to rapid growth of both resident and temporary inhabitants. Combined with the low abundance of large predators, marshes and their drainage systems may serve as shelters from predation. Rapid growth and the ability to deposit energy reserves from the rich marsh diet prepare young fish for the rigors of migration and/or overwintering (Weinstein, et al., 2005; Litvin and Weinstein, 2008).

Effects of Sea-Level Rise

Because intertidal and shallow subtidal waters of estuarine wetlands are "epicenters" of material exchange, primary (plant) and secondary (animal) production, and serve as primary nurseries for the young of many fish and shellfish species (Childers et al., 2000; Weinstein, 1979; Deegan et al., 2000) , the prospect of sea-level rise, sometimes concomitant with land subsidence, human habitation of the shore zone and shoreline stabilization place these critical resources at risk. Such ecological hotspots could be lost as a result of sea-level rise because human presence in the landscape leaves tidal wetlands little or no room to migrate inland. Because of lack of a well-defined drainage system, small bands of intertidal marsh located seaward of armored shorelines have little ecological value in the production of these taxa (Weinstein et al., 2005; Weinstein, 1983).

D.1.2 Delaware River: Above the Commodore Barry Bridge

Figure D.2 shows coastal elevations along the tidal freshwater portion of the Delaware River, with a contour interval of 1 meter. Figure D.3 focuses on Philadelphia with a contour interval of 50 centimeters, based on the 2-foot contour elevation data the City provided EPA. Approximately half of Pennsylvania's low land is in Philadelphia, which has between 6.8 and 12.4 square kilometers within 1 meter above spring high water, of which 3.6 to 6.1 square kilometers are below 50 centimeters (Table D.1). Because of the long history of dike construction, Philadelphia has 2.4 square kilometers of dry land below spring high water, including about 24 hectares that are more than 1 meter below spring high water, mostly near Philadelphia International Airport.

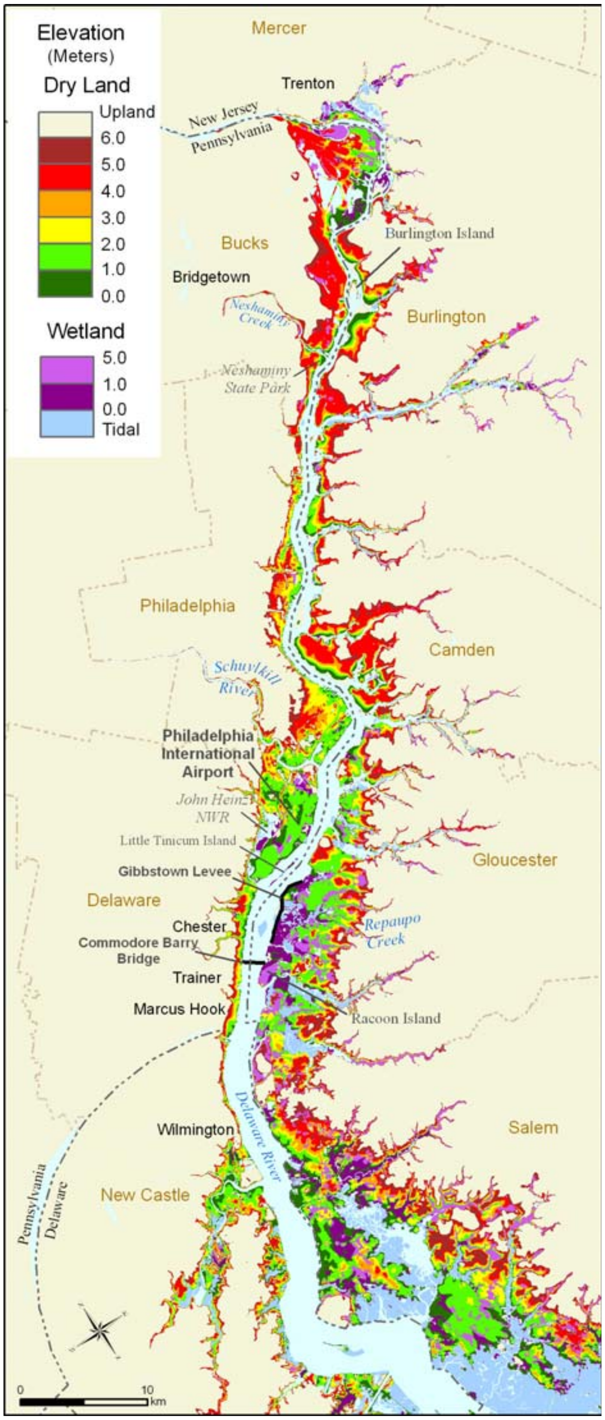

Figure D.2 Delaware River: Elevations relative to spring high water.

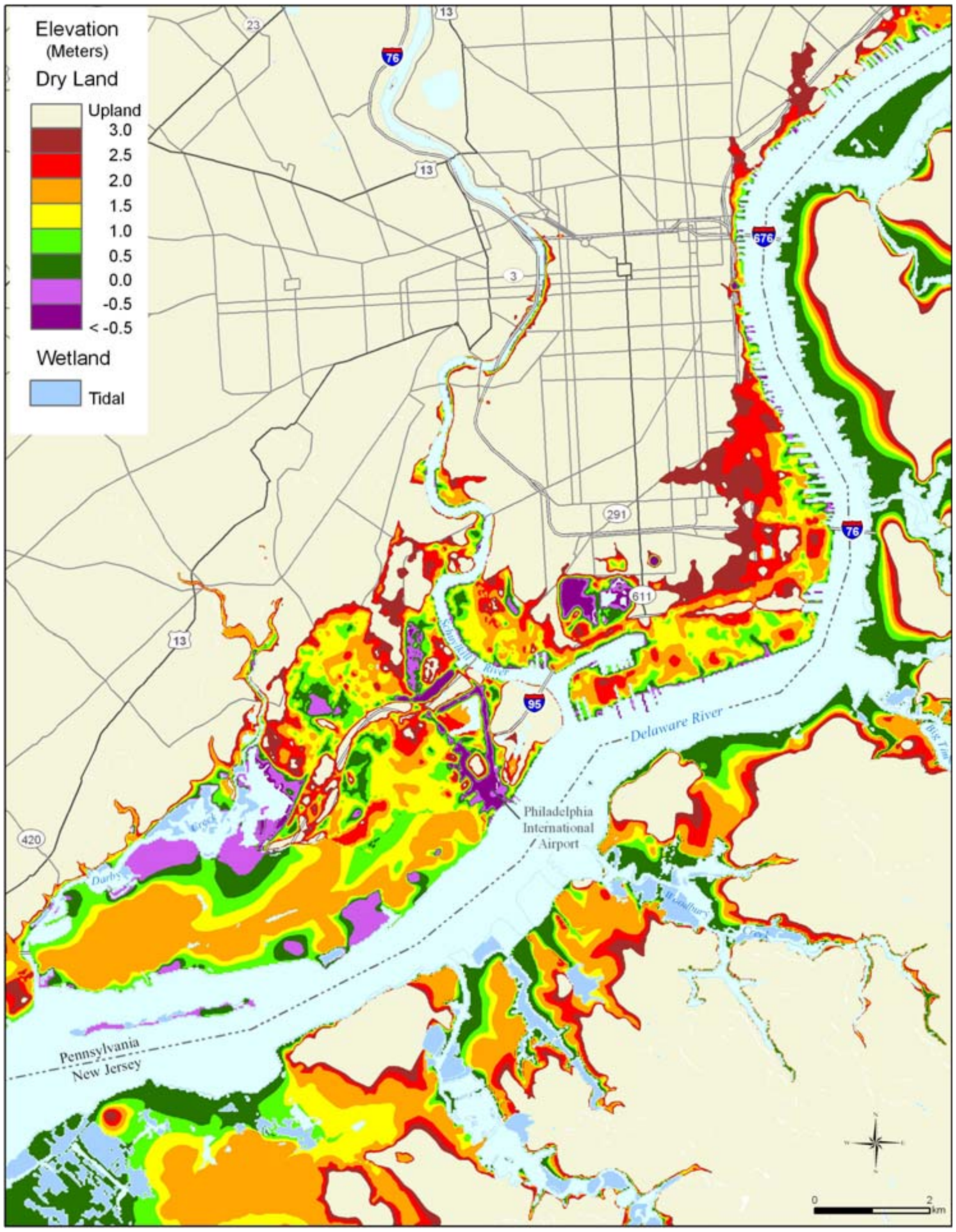

Figure D.3 Philadelphia: Elevation relative to spring high water.

New Jersey's lowest land along the Delaware River is in Gloucester County, behind a dike known as the Gibbstown Levee[86]. "The Gibbstown Levee runs 4.5 miles along the Delaware River in Logan Township and Greenwich Township in Gloucester County, NJ. It protects the 21-square-mile Repaupo Creek watershed inhabited by approximately 6,700 residents."(USACE, 2004). Several square miles are below the 00-foot (NGVD) contour shown on the USGS 7.5 minute map of the area. Most of this low area is some form of freshwater wetland, but there are also a few homes and a trailer park along Floodgate Road below the 00-foot contour (which is 20–25 centimeters below sea level; see Chapter 1 box on "Tides, Wetlands, and Reference Elevations"). This dike once served a function similar to the dikes in Cumberland County, preventing tidal inundation and lowering the water table to a level below mean sea level. When the dike was built 300 years ago (USACE, not dated), the tides were 3 feet lower; and hence the combination dike and tide gate was able to keep the water levels low enough to permit cultivation. But rising sea level has left this land barely above low tide, so that many lands do not completely drain during low tide. Hence, they are now nontidal wetlands. Parts of Raccoon Island near the entrance to the Commodore Barry Bridge, for example, are below mean sea level.

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[86] Dikes are often mistakenly called levees, just as groins are mistakenly called jetties. A levee is built to protect an area from surging river levels; a dike is built to protect low lands from tidal inundation or storm surges.

D.2 DEVELOPMENT AND SHORE PROTECTION

Chapter 5 describes the basis for ongoing studies that are analyzing land use plans, land use data, and coastal policies to create maps depicting the areas where shores may be protected and where wetlands may migrate inland. Because the maps from those studies have not yet been finalized, this section describes some of the existing and evolving conditions that may influence decisions related to future shore protection and wetland migration.

D.2.1 Delaware Bay and Lower Delaware River

Policies that may be relevant for adapting to sea-level rise in New Jersey include policies related to the Coastal Facilities Review Act (CAFRA), the State Plan, an unusually strong public trust doctrine, and strong preference for beach nourishment along the Atlantic Ocean over hard structures or shoreline retreat. The first three of these policies are discussed here, and the fourth is discussed in Appendix C (New Jersey Shore). The policy context for shore protection in Delaware is discussed in Appendix E.

CAFRA sometimes limits development in the coastal zone, primarily to reduce runoff of pollution into the state's waters (State of New Jersey, 2001). Like Maryland's Critical Areas Act (see Appendix E), this statute may indirectly reduce the need for shore protection by ensuring that homes are set back farther from the shore than would otherwise be the case.

The New Jersey State Plan provides a statewide vision of where growth should be encouraged, tolerated, and discouraged — but local government has the final say. In most areas, lands are divided into five planning areas:

1. Metropolitan areas
2. Suburban areas
3. Fringe areas
4. Rural areas, where the rural character ought to be maintained
5. Land with valuable ecosystems, geologic features, or wildlife habitat, including coastal wetlands and barrier spits/islands (State of New Jersey, 2001).

The state encourages development in planning areas 1 and 2, as well as areas in planning area 3 that are either already developed or part of a well-designed new development. The state discourages development in most portions of planning areas 4 and 5 (State of New Jersey, 2001). However, even these areas include developed enclaves, known as "centers" where development is recognized as a reality (State of New Jersey, 2001). Most developed barrier islands are part of a center within planning area 5, for example. The preservation of rural and natural landscapes in planning areas 4 and 5 is likely to afford opportunities for wetlands to migrate inland as sea level rises.

The public trust doctrine in New Jersey has two unusual aspects. First, the public has an easement along the dry beach between mean high water and the vegetation line. Although other states have gradually acquired these easements in most recreational communities, few states have general access along the dry beach[87]. As a result, people are entitled to walk along river and bay beaches, where public demand for access would not have otherwise been sufficient for governments to acquire such universal access. The laws of Delaware and Pennsylvania, by contrast, grant less public access along the shore. In most states, the public owns the land below mean high water. In these two states, the public owns the land below mean low water. The public has an easement along the wet beach between mean low and mean high water, but only for navigation, fishing, and hunting — not for recreation.

Even more remarkably, the New Jersey Supreme Court has held that the public is entitled to perpendicular access to the beach[88]. The holding does not mean that someone can indiscriminately walk across any landowner's property to get to the water (which would be an unconstitutional taking), but it does require governments to take prudent measures to ensure that public access to the water accompanies new subdivisions[89]. As sea level rises, the unusual public access to all New Jersey shores is likely to support a greater public demand for ensuring the continued survival of estuarine beaches than would be the case if the public had no access to those beaches (Titus, 1998).

New Jersey policies to manage stormwater may also facilitate the migration of wetlands. The State's stormwater management regulations limit new development within 300 feet of the shore along the majority of Delaware Bay (NJDEP, DWM, April 2004). Although encroachment into the protection area is allowed under certain circumstances, the

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[87] See Chapter 7 for additional details.
[88] Matthews v Bay Head Improvement Association, 471 A.2d 355. Supreme Court of NJ (1984).
[89] Federal law requires similar access before an area is eligible for beach nourishment.

functional value and overall condition of the protection area must be maintained to the maximum extent practicable. The establishment of this protection area will help preserve areas suitable for the inland migration of the extensive wetlands located in the area. Of the 147 square kilometers of land within approximately 1 meter above the tides on the New Jersey side (Salem, Cumberland, and Cape May counties), 82 square kilometers are nontidal wetlands (Jones and Wang, 2008).

In Cumberland County, salt marsh has been reclaimed for agricultural purposes for more than 200 years (Sebold, 1992; State of New Jersey, various years). Over the last few decades, many of those dikes have been dismantled. Some have failed during storms. Others have been purchased by conservation programs seeking to restore wetlands, most notably PSE&G in its efforts to offset possible environmental effects of a nuclear power plant. Although the trend is for dike removal, the fact that diked farms have been part of the landscape for centuries leads one to the logical inference that dikes may be used to hold back a rising sea once again. In fact, dikes may be more effective at protecting currently arable dry land than protecting former marsh, because drained wetlands often subside. Cumberland County has relatively little coastal development, yet the trend in coastal communities that have not become part of a conservation program has been for a gradual retreat from the shore. Several small settlements along Delaware Bay are gradually being abandoned.

Delaware On the Delaware side, dry land accounts for 80 of the 104 square kilometers of land within approximately 1 meter of the tides (Jones and Wang, 2008). Kent County does not permit subdivisions — and generally discourages most development — in the 100-year coastal floodplain, as does New Castle County south of the Chesapeake and Delaware Canal.[90] Because the 100-year floodplain for storm surge extends about 2 meters above spring high water, this is likely to be more effective at allowing wetlands to migrate inland than limiting development within a fixed width of a few hundred feet. Nevertheless, if sea level continues to rise, this buffer would not last forever.

Preservation easements and land purchases have also contributed to a major conservation buffer that will almost certainly allow wetlands to migrate inland as sea level rises. The State is purchasing agricultural preservation easements in the coastal zone, and a significant portion of the shore is in Prime Hook or Bombay Hook National Wildlife Refuge. More than 80% of the shore south of the canal is part of some form of preservation or conservation land.

Whether wetland migration on the New Jersey side of Delaware Bay is more sustainable than along the Delaware side would partly depend on whether the Delaware county floodplain regulations or the New Jersey State Plan is more effective at discouraging development in the coastal floodplain.

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[90] See Kent County Ordinances Section 7.3 and New Castle Ordincance 40.10.313

D.2.2 Delaware River: Freshwater Portion

D.2.2.1 Policy Context[91]

Pennsylvania is the only state in the nation along tidal water without an ocean coast[92]. The resulting lack of barrier islands and communities vulnerable to coastal erosion and life-threatening hurricanes has often led observers to ignore the impact of sea-level rise on Pennsylvania (USGS, not dated). To be sure: Pennsylvania's sensitivity to sea-level rise is different than other states. Floods in the tidal Delaware River are as likely to be caused by extreme rainfall as storm surges. The Delaware River is usually fresh along almost all of the Pennsylvania shore. Because Philadelphia relies on freshwater intakes in the tidal river, the most important impact may be the impact of salinity increases from rising sea level on the city's water supply.

Pennsylvania has no policies that directly address the issue of sea-level rise[93]. The lack of an ocean coast implies that Pennsylvania has less need for the types of policies that have been motivated by hazards along the ocean. Nevertheless, the state has several coastal policies that might form the initial basis for a response to sea level rises, including state policies on tidal wetlands and floodplains, public access, and redeveloping the shore in response to the decline of water-dependent industries.

Tidal Wetlands and Floodplains

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[91] This section only addresses the Pennsylvania side of the river because Appendix C addressed the policy context for shore protection in New Jersey.

[92] This statement also applies to the District of Columbia.

[93] But Philadelphia's flood regulations consider sea level rise.

Pennsylvania's Dam Safety and Waterway Management Rules and Regulations[94] require permits for construction in the 100-year floodplain or wetlands[95]. The regulations do not explicitly indicate whether landowners have a right to protect property from erosion or rising water level. A permit for a bulkhead or revetment seaward of the high-water mark can be awarded only if the project will not have a "significant adverse impact" on the "aerial extent of a wetland" or on a "wetland's values and functions." A bulkhead seaward of the high-water mark, however, eliminates the tidal wetlands on the landward side. If such long-term impacts were viewed as "significant," permits for bulkheads could not be awarded except where the shore was already armored. But the State has not viewed the elimination of mudflats or beaches as "significant" for purposes of these regulations; hence it is possible to obtain a permit for a bulkhead.

The rules do not restrict construction of bulkheads or revetments landward of the high water mark. But they do prohibit permits for any "encroachment located in, along, across or projecting into a wetland, unless the applicant affirmatively demonstrates that…the … encroachment will not have an adverse impact on the wetland…"[96] Therefore, shoreline armoring can eliminate coastal wetlands (or at least prevent their inland expansion[97]) as sea level rises by preventing their landward migration.

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[94] These regulations were issued pursuant to the Dam Safety and Encroachment Act of 1978. Laws of Pennsylvania, The Dam Safety and Encroachments Act of November 26, 1978, P.L. 1375, No. 325.

[95] See Chapter 5.

[96] Pennsylvania Code, Chapter 105. Dam Safety and Waterway Management, Pennsylvania Department of Environmental Protection, 1997. Subchapter 105.18b.

[97] This assessment concludes that most tidal wetlands in Pennsylvania can keep pace with projected rates of sea level rise. But that finding does not address erosion of wetlands at their seaward boundary. Even though wetlands can keep vertical pace with the rising water level, narrow fringing wetlands along rivers can be eliminated by shoreline armoring as their seaward boundaries erode and their landward migration is prevented. Moreover, even where the seaward boundary keeps pace, preventing an expansion of wetlands might be viewed as significant.

Like the shore protection regulations, Pennsylvania's Chapter 105 floodplains regulations consider only existing floodplains, not the floodplains that would result as the sea rises.

Public Access

Public Access is for recreation is an objective of the Pennsylvania Coastal Zone Management (PA CZM) program. This policy, coupled with ongoing redevelopment trends in Pennsylvania, may tend to ensure that future development includes access along the shore. If the public access is created by setting development back from the shore, it may tend to also make a gradual retreat possible. Even if shores are armored, however, public access need not be eliminated by responses to sea level rise if keeping public access if a policy goal of the authority awarding the permit for shore protection (Titus 1998).

Development and Redevelopment

Industrial, commercial, residential, recreational, wooded, vacant, transportation, and environmental land uses all occupy portions of Pennsylvania's 100-kilometer coast. Generally speaking, however, the Pennsylvania coastal zone is consistently and heavily developed. Only about 18% of the coastal area is classified as undeveloped (DVRPC, 2000). Much of the shoreline was filled or modified with bulkheads, docks, wharfs, piers, riprap shorelines, and other hard structures over the past two centuries (DVRPC, 2000). The existing armoring enhances the vulnerability of remaining environmentally valuable areas with natural shorelines such as mudflats and tidal wetlands.

The Pennsylvania coast is moving from an industrial to a post-industrial landscape. Historically, the river’s edge was a favorable location for the region’s extensive manufacturing and industrial enterprises. The coastal zone is still dominated by manufacturing and industrial land uses, but a steady decline in the industrial economy over the past 60 years has led to the abandonment of many industrial and manufacturing facilities. Some of these facilities sit empty and idle; others have been adapted for uses that are not water dependent.

A majority of the Delaware River shore is classified as developed, but sizable expanses, especially near the water, are blighted and stressed (DVRPC, 2003). Because of the decaying industrial base, many residential areas along the Delaware River have depressed property values, declining population, high vacancy rates, physical deterioration, and high levels of poverty and crime (DVRPC, 2003). These trends are part of a larger regional pattern of sprawl, disinvestment in older communities, and urban decline. Many —perhaps most—of the refineries, chemical processing plants, and other manufacturing facilities that operate profitably today may close in the next 50 to 100 years as the U.S. economy continues to shift away from a manufacturing and industrial base. Regardless of whether the manufacturing decline continues at its current pace, the coastal area has passed its industrial prime and many facilities have long since been abandoned (PDEP, 2006).

New paradigms of waterfront development have emerged that offer fresh visions for southeastern Pennsylvania's waterfront. In late 2001, Philadelphia released the Comprehensive Redevelopment Plan for the North Delaware Riverfront—a 25-year redevelopment vision for a distressed 10-mile stretch of waterfront led by the design firm Field Operations. Delaware County, meanwhile, developed its Coastal Zone Compendium of Waterfront Provisions (1998) to guide revitalization efforts along its coast. Likewise, Bucks County just finished a national search for a design firm to create a comprehensive plan outlining the revitalization of its waterfront. Meanwhile, the Schuylkill River Development Corporation produced the Tidal Schuylkill River Master Plan.

All of these plans and visions share common elements. They view the region's waterfronts as valuable public amenities that can be capitalized on, and they view the estuary as something for the region to embrace, not to turn its back on. They emphasize public access along the water's edge, the creation of greenways and trails, open spaces, and the restoration of natural shorelines and wetlands where appropriate. Revitalization strategies also aim to take advantage of the quality of life benefits to be had from public access and an attractive, ecologically healthy waterfront by constructing vibrant, mixed-use communities within the coastal zone (DRCC, 2006).

D.2.2.2 Responses to Sea Level Rise

Pennsylvania

The greatest opportunity to plan for sea-level rise in Pennsylvania may lie in the ongoing redevelopment of the industrial areas along the Delaware River and other navigable waters. State and local government has the opportunity to decide whether the public will have access, and whether wetlands, beaches, and mudflats will be restored or eliminated as sea level rises.

Given the transitional state of Pennsylvania's coastal area and the visions that have been proposed, much of what is along the shore today will probably not be there in 50 or 100 years. Although these areas will generally be developed, the reintroduction of public access, natural shorelines, and open spaces along the water's edge will be a key element of revitalization efforts (PDEP, 2006). Redevelopment may not be designed to allow ecosystems to migrate inland, but in some cases the redevelopment may be landward of today's shore, preserving public access, natural shores, and an opportunity for a limited landward migration of intertidal shores.

In Delaware County,[98] the John Heinz National Wildlife Refuge, which is separated from the river by Philadelphia International Airport, is the largest protected, intact tidal wetland ecosystem in the Pennsylvania coastal zone[99]. Little Tinicum Island, which is

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[98] A small part of this refuge is in Philadelphia.

[99] The remainder of Delaware County's coastal wetlands mostly consists of smaller tidal wetlands along the river's shore and some larger nontidal wetlands in and around the Philadelphia airport.

located in the river channel across from the airport, is publicly owned and surrounded by mudflats or sandy beaches on all sides.

In Bucks County, a portion of Neshaminy State Park up the Neshaminy Creek away from the river contains forested wetlands and is managed by the state for conservation purposes. The Nature Conservancy owns or leases approximately 18 acres of marshy ground just to the southwest of Bristol Borough (TNC, undated). The Nature Conservancy has an explicit policy of allowing wetlands to migrate inland.

New Jersey

The State Plan contemplates a substantial degree of agricultural and environmental preservation along the Delaware River and its tidal tributaries in Salem and lower Gloucester County. An agricultural easement program in Gloucester County is reinforcing that expectation. Although farmers in the past built dikes for agriculture, regulatory authorities may not allow any new dikes. In this case, wetlands may be able to migrate inland along parts of the Salem and Gloucester shores as sea level rises.

BOX D.4: The Gibbstown Levee

The Gibbstown Levee once served a function similar to the dikes in Cumberland County, preventing tidal inundation and lowering the water table to a level below mean sea level. When the dike was built 300 years ago (USACE, undated), the tides were 3 feet lower and the combination dike and tide gate kept the water levels low enough to permit cultivation. But rising sea level and land subsidence have left this land barely above low tide, and many lands drain too slowly to completely drain during low tide. Hence, farmland has converted to nontidal wetland.

By keeping the creek a meter or so lower than it would be if it rose and fell with the tides, the levee improves drainage during rainstorms for Greenwich Township. Nevertheless, it is less effective today than when the sea was 50–100 centimeters lower. During extreme rainfall, the area can flood fairly easily because the tide gates have to be closed most of the day. Heavy rain during a storm surge is even more problematic because for practical purposes there is no low tide to afford the opportunity to get normal drainage by opening the tide gate. Evacuations were necessary during hurricane Floyd when part of this dike collapsed as a storm tide brought water levels of more than 10 feet above mean low water (NCDC, 1999).

Officials in Greenwich Township are concerned that the dikes in Gloucester County are in danger of failing. “The Gibbstown Levee was repaired in many places in 1962 by the Corps of Engineers under Public Law 84-99.”(USACOE, 2004) Part of the problem appears to be that most of these dikes are the responsibility of meadow companies originally chartered in colonial times. These companies were authorized to create productive agricultural lands from tidal marshes. Although harvests of salt hay once yielded more than enough revenue to maintain the dikes, this type of farming became less profitable during the first half of the 20th century. Moreover, as sea level has continued to rise, the land protected by the dikes has mostly reverted to marsh. Revenues from these lands, if any, are insufficient to cover the cost of maintaining the dikes (DiMuzio, 2006). As a result, the dikes are deteriorating, leading officials to fear a possible catastrophic dike failure during storm, or an increase in flood insurance rates (DELO, 2006).The officials hope to obtain federal funding (DELO, 2006).

Even if these dikes and their associated tide gates are fortified, the dry land will gradually be submerged unless pumping facilities are installed, because much of the area is barely above low tide even today. Although freshwater marshes in general seem likely to be able to keep pace with rising sea level, wetlands behind dikes do not always fare as well as those exposed to normal tidal currents. Over longer periods of time, increases in salinity of the Delaware River resulting from rising sea level and reduced river flows during droughts could enable saltwater to invade these fresh marshes, which would convert them to open water ponds.

Pumping facilities may not be sufficient for a daily pumping of all the very low lands protected by the dikes. Rather, the primary impact of the dikes would be to prevent flooding from storm surges and ordinary tides. For the isolated settlements along Marsh Dike Road and elsewhere, elevating homes and land surfaces may be cost-effective; although property values are less than along the barrier islands, sources for fill material are closer. Gibbstown, Bridgetown, and other more populated communities could be encircled with a ring dike with a pumping system that drains only the densely developed area; or they too may find it cost-effective to elevate land as the sea rises.

The industrial northeastern half of Gloucester County’s riverfront and almost all of Camden and Burlington’s riverfront are on high ground, generally more than 5 feet above the tides. In the industrial and commercial areas, most of the shoreline there is already bulkheaded, to provide the vertical shore that facilitates docking — but the effect is also to stop coastal erosion. The eventual fate of existing dikes, which protect lightly developed areas, is unclear (see Box D.4 on the Gibbstown Levee).

D.3 POPULATION OF LANDS CLOSE TO SEA LEVEL

Table D.3 provides the likely range for the population of lands close to sea level for each of the counties along the Delaware Estuary. Philadelphia provided the best elevation data, and hence the uncertainty range is least. The table suggests that between 1000 and 3500 people live on land within 50 cm above spring high water. Approximately 600 people live in Census blocks that are entirely within 1 meter above the tides.

Several shorefront communities along the Delaware side of the estuary include populations living close to sea level. The results for Cape May and Sussex County largely reflect the population of land along the Atlantic Ocean and associated coastal bays, rather than Delaware Bay. The elevation data was too coarse to identify population within 50 cm above spring high water in New Jersey, but a few thousand people live on land within 2 meters above the tides in Salem and Gloucester counties in such towns as Pennville and Gibbstown.

Table D.3 Population of lands close to sea level: Delaware Estuary.

	Low and high estimates of population below a given elevation (thousands)					
	50cm		**1m**		**2m**	
County	**Low**	**High**	**Low**	**High**	**Low**	**High**
Delaware						
Kent[1]	*	*	*	*	*	*
New Castle	0.2	4.1	0.2	7.4	2.3	12.3
Sussex[2]	1.1	7.2	1.1	9.5	7.1	17.0
New Jersey						
Burlington[3]	0.0	23.7	0.0	27.6	2.6	46.2
Cape May[3]	2.1	30.5	17.3	44.2	38.9	56.9
Cumberland	0.0	3.0	0.0	3.6	0.4	6.6
Gloucester[1]	0.0	11.9	0.0	15.1	2.1	18.2
Salem	0.0	15.3	0.0	19.7	9.3	26.5
Pennsylvania						
Bucks	0.0	4.8	0.0	6.4	0.0	18.4
Delaware	0.0	12.9	0.0	13.4	1.7	15.6
Philadelphia	1.0	3.5	2.9	7.3	9.4	16.4
Total	**4.4**	**117.0**	**21.6**	**154.1**	**73.8**	**234.1**

* Data unavailable.

[1] Figures are for the entire county. County is split between Chesapeake and Delaware Bay Watersheds.

[2] Figures are for the entire county. County is split between Chesapeake, Atlantic Coast, and Delaware Bay Watersheds.

[3] Figures are for the entire county. County is split between Delaware River and New Jersey Shore Watersheds.

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Appendix E. The Atlantic Coast of Virginia, Maryland, and Delaware (including coastal bays)

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Along the Atlantic Ocean between the mouths of the Chesapeake and Delaware bays lie approximately 200 kilometers of ocean beaches—mostly barrier islands--and only 30 kilometers have been developed. But the oceanfront development includes major resorts such as Ocean City (MD), Rehoboth (DE) and Dewey Beach (DE). The mainland behind those barrier islands is starting to become developed, especially in Delaware and Maryland.

This appendix examines some of the implications of rising sea level on the Atlantic Coast of the DelMarVa Peninsula. We present maps and summary statistics on the low land vulnerable to rising sea level (section E.1). We then discuss the species that rely on vulnerable habitat, with a focus on the coastal bays that lie behind the barrier islands (E.2). We then briefly discuss existing coastal policies (E.3), and development and shore protection (E.4). We do not evaluate whether the implications of accelerated sea-level rise might cause those policies to change. Finally, we present new estimates of the population that inhabits the land that could be potentially inundated as sea level rises (E.5).

E.1 COASTAL ELEVATIONS AND INUNDATION

Figures E.1 and E.2 show the elevations of lands close to sea level along the Atlantic Coast of the DelMarVa peninsula. Most noticeable is the 764 square kilometers of tidal wetlands behind Virginia's undeveloped barrier islands, of which 375 square kilometers are mudflats, giving this area the largest concentration of mudflats in the Mid-Atlantic. The peninsula also has about 90–180 square kilometers of dry land and non-tidal wetlands within 1 meter above spring high water (see Table E.1).

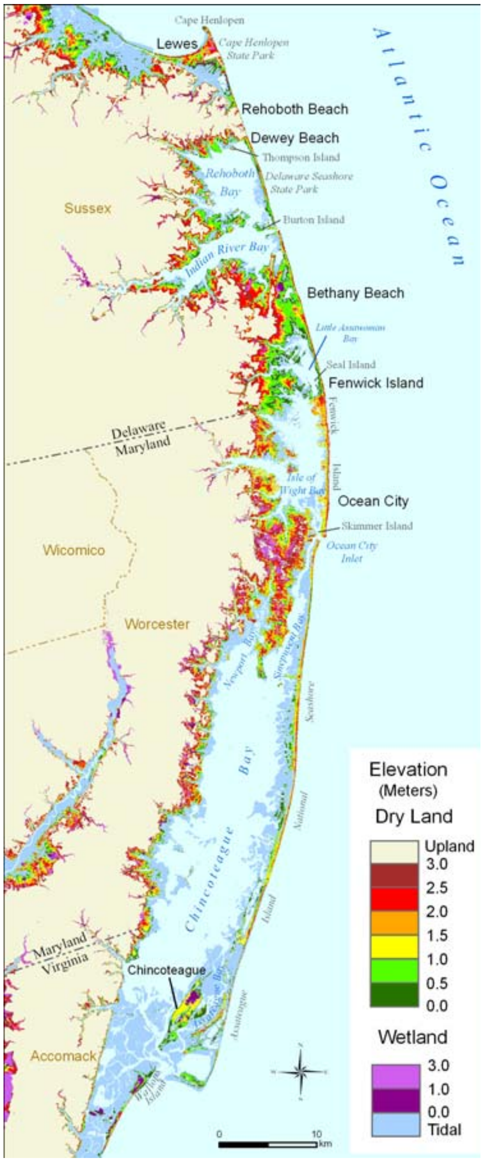

Figure E.1 Lands close to sea level, DelMarVa Atlantic Coast from Chincoteague to Cape Henlopen.

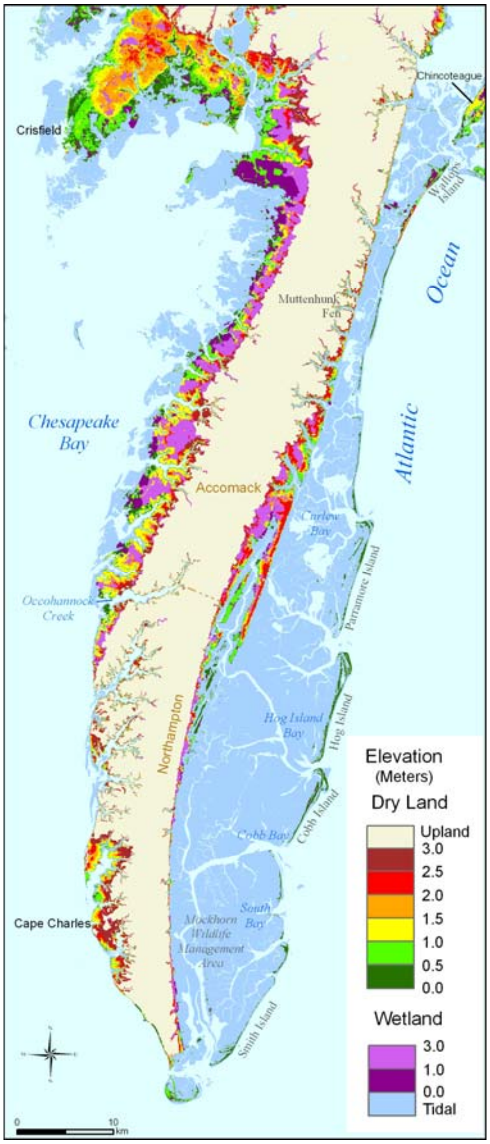

Figure E.2 Lands close to sea level, the Virginia Eastern Shore from Cape Charles to Saxis and Wallops Island.

Table E.1 Low and high estimates for the area of dry and wet land close to sea level DelMarVa Atlantic Coast (square kilometers).

Elevations above spring high water:		**Tidal**	**50 cm**		**1 meter**		**2 meters**		**3 meters**		**5 meters**	
			Low	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Locality	State	Cumulative (total) amount of Dry Land below a given elevation										
Northampton	VA		5.1	14.5	13.0	16.8	17.9	20.6	21.4	24.6	30.5	35.0
Accomack	VA		7.5	22.6	20.1	37.7	44.5	61.7	65.8	81.2	103.7	118.9
Worcester	MD		3.7	18.6	21.7	42.4	77.5	102.8	134.0	154.6	219.1	234.6
Sussex	DE		11.1	32.4	27.6	53.5	64.5	94.9	104.2	139.5	196.5	234.2
Total			**27.4**	**88.1**	**82.5**	**150.3**	**204.4**	**280.0**	**325.4**	**399.9**	**549.9**	**622.7**
		Cumulative (total) amount of wetlands below a given elevation										
Northampton	VA	436.4	0.3	0.8	0.7	2.1	2.8	4.4	4.6	5.2	5.8	6.1
Accomack	VA	327.3	1.3	4.1	3.5	10.4	13.5	20.7	21.9	26.2	31.2	33.7
Worcester	MD	118.5	0.4	4.3	5.0	8.8	14.1	18.1	23.4	27.0	36.0	37.6
Sussex	DE	41.0	1.7	4.9	4.2	7.5	8.8	12.2	12.9	15.7	18.9	20.7
Total		**923.3**[1]	**3.7**	**14.1**	**13.4**	**28.7**	**39.2**	**55.4**	**62.7**	**74.1**	**91.9**	**98.1**
Dry and Non-tidal wetland			31	102	96	179	244	335	388	474	642	721
All Land		923	954	1025	1019	1102	1167	1259	1311	1397	1565	1644

Source: Titus and Cacela, 2008. Uncertainty Ranges Associated with EPA's Estimates of the Area of Land Close to Sea Level. Section 1.3 in: Background Documents Supporting Climate Change Science Program Synthesis and Assessment Product 4.1: Coastal Elevations and Sensitivity to Sea-level Rise, J.G. Titus and E. Strange (eds.). EPA 430R07004. U.S. EPA, Washington, DC. The low and high estimates are based on the on the contour interval and/or stated root mean square error (RMSE) of the data used to calculate elevations. See Chapter 1 for more details.

[1] Includes 375 square kilometers of tidal mudflats in Northampton and Accomack counties.

The greatest concentrations of dry land within a few meters above spring high water appear to be along a few necks between the southern border of Accomack County and Wachapreague (opposite Cedar and Parramore islands), Chincoteague Island, and the mainland between Chincoteague Bay and Indian River Bay (opposite Bethany and Ocean City). The barrier islands are a small portion of the low land.

E.2 VULNERABLE HABITAT

Numerous species and habitats in the back-barrier bays of Maryland, Delaware, and Virginia's Eastern Shore are potentially at risk because of sea-level rise[100]. This region contains the largest stretch of natural coastline along the Atlantic Coast of the United States. The region includes extensive tidal flats, back-barrier lagoonal marshes, and areas of estuarine beach behind the region's barrier islands. Fringing salt marshes occur on the mainland side of the lagoons. Habitats of particular significance include salt marsh, beach, marsh and bay islands, tidal flats, submerged aquatic vegetation, sea-level fens, and coastal plain ponds.

*Tidal Marshes***.** The region's tidal marshes provide roosting, nesting and foraging areas for a variety of bird species, including black-bellied plover, dunlin, and horned grebe, wading birds such as herons and egrets, migratory shorebirds, and many species of waterfowl[101]. Ducks and geese, including mallards, pintails, blue and green winged teals, gadwalls, canvasbacks, loons, buffleheads, mergansers, and goldeneyes, overwinter in the bays' marshes[102]. The marshes also provide nesting habitat for many species of concern to federal and state agencies, including American black duck, Nelson's sparrow, salt marsh sharp-tailed sparrow, seaside sparrow, coastal plain swamp sparrow, black rail, Forster's tern, gull-billed tern, black skimmers, and American oystercatchers.

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[100] The Maryland Coastal Bays include Chincoteague, Sinepuxent, Newport, Isle of Wight, and Assawoman bays. The Delaware Inland Bays are three interconnected bays (Little Assawoman Bay, Indian River Bay, and Rehoboth Bay).

[101] Wilson, Dave, Maryland Coastal Bays Program. In 13 June 2006 email to E. Strange, Stratus Consulting, entitled "Follow up to my visit," providing review of draft text and recounting personal observations reported in a meeting on 16 May 2006. (Dave Wilson is the outreach coordinator for the Maryland Coastal Bays Program.)

[102] DNREC, Date unkown and personal observations of Chris Bason, Center for the Delaware Inland Bays, written communication to EPA, 5/14/07.

Sea-level rise is considered a major threat to bird species in the Virginia Barrier Island/Lagoon Important Bird Area (IBA) (Watts, 2006). Biologists at the Patuxent Wildlife Research Center suggest that submergence of lagoonal marshes in Virginia would have a major negative effect on marsh-nesting birds such as black rails, seaside sparrows, saltmarsh sharp-tailed sparrows, clapper rails, and Forster's terns (Erwin, 2004). The U.S. Fish and Wildlife Service considers black rail and both sparrow species "birds of conservation concern" because populations are already declining in much of their range (USFWS, 2002). The number of bird species in Virginia marshes was found to be directly related to marsh size; the minimum marsh size found to support significant marsh bird communities was 4.1–6.7 ha (10–15 acres) (Watts, 1993).

The region's tidal marshes also support a diversity of resident and transient estuarine and marine fish and shellfish species that move in and out of marshes with the tides to take advantage of the abundance of decomposing plants in the marsh, the availability of invertebrate prey, and refuge from predators (Boesch and Turner, 1984; Kneib, 1997). Marine transients include recreationally and commercially important species that depend on the marshes for spawning and nursery habitat, including black drum, striped bass, bluefish, Atlantic croaker, sea trout, and summer flounder. Important forage fish that spawn in marsh areas include spot, menhaden, silver perch, and bay anchovy. Shellfish species found in the marshes include clams, oysters, shrimps, ribbed mussels, and blue crabs (Casey and Doctor, date unknown).

Salt Marsh Adaptation to Sea-level Rise. Salt marshes occupy thousands of acres in eastern Accomack and Northampton counties (Fleming *et al.*, 2006). Marsh accretion experts believe that most of these marshes are keeping pace with current rates of sea-level rise, but may be unable to continue to do so if the rate of sea-level rise increases by another 2 mm/yr (Reed *et al.*, 2008). Some local field measurements indicate that accretion rates may be insufficient to keep pace even with current rates of sea-level rise. Accretion rates as low as 0.9 mm/yr (Phillips Creek Marsh) and as high as 2.1 mm/yr (Chimney Pole Marsh) have been reported (Kastler and Wiberg, 1996), and the average relative sea-level rise along the Eastern Shore is estimated as 2.8–4.2 mm/yr (May, 2002). Although some wide marshes may survive under an increase of 2 mm/year in the rate of sea-level rise, the fringing marshes along the mainland are likely to be lost (Reed *et al.*, 2008).

In some areas, marshes may be able to migrate onto adjoining dry lands. For instance, lands in Worcester County that are held for the preservation of the coastal environment might allow for wetland migration. . Portions of eastern Accomack County that are opposite the barrier islands and lagoonal marshes owned by TNC are lightly developed today, and in some cases already converting to marsh. In unprotected areas, marshes may be able to migrate inland in low-lying areas. Kastler and Wiberg (1996) found that from 1938 to 1990 mainland salt marshes on the Eastern Shore increased in area by 8.2%, largely as a result of encroachment of salt marsh into upland areas (Kastler and Wiberg, 1996).

Where sea-level rise leads to increased flooding of the marsh, some fishes may benefit, at least in the short term, from an increase in tidal creeks and channels, providing greater access to the marsh. However, where marshes drown, the loss of marsh primary production will impair the value of the habitat for fish and shellfish. The area's highly valued commercial and recreational fishing industry may be harmed if fish and shellfish production declines as marshes are lost.

Marsh and Bay Islands. Another key habitat vulnerable to sea-level rise is the *islands* within the coastal bays. These islands are undergoing rapid erosion. For example, Big Piney Island in Rehoboth Bay experienced erosion rates of 30 ft/yr between 1968 and 1981, and is now gone (Swisher, 1982). Seal Island in Little Assawoman Bay is eroding rapidly after being nearly totally devegetated by greater snow geese (Strange *et al.*, 2008). Island shrinking is also apparent along the Accomack County, Virginia shore; from 1949 to 1990, Chimney Pole marsh showed a 10% loss to open water (Kastler and Wiberg, 1996). The U.S. Army Corps of Engineers has created many small dredge spoil islands in the region, many of which are also disappearing as a result of erosion (Federal Register, 2006).

Sea-level rise can have both a direct and an indirect effect on these islands. The direct effect is the inundation and shore erosion discussed throughout this report. The indirect effect is that shoreline stabilization activities can prevent the formation of new islands, by limiting overwash and formation of new inlets and flood tidal deltas (US Army Corps of Engineers, 1998). The interruption of these processes may have a more important impact than the loss of dredge spoil islands, which were never designed to be permanent features.

The loss of these bay islands is a concern both because they protect other natural and developed shorelines and marshes from increased erosion, and because they directly support numerous bird species. For example, hundreds of horned grebes prepare for migration at the north end of Rehoboth Bay near Thompson's Island (Ednie, undated). Several bird species of concern in this region nest on shell piles (shellrake) on marsh islands, including gull-billed terns, common terns, black skimmers, royal tern, and American oystercatchers, (Erwin, 1996; Rounds *et al.*, 2004). Shell piles are generally free of mammalian predators. However, marsh islands are also subject to tidal flooding which reduces the reproductive success of island-nesting birds (Eyler *et al.*, 1999). Therefore, as islands experience more erosion and flooding as a result of sea-level rise, local populations of island-nesting birds may decline.

Sea-Level Fens. A rare sea-level fen vegetation community grows in the Angola Neck Natural Area along Rehoboth Bay. Because of its location, the Angola Neck sea-level fen could be lost as rising seas move inland, bringing nutrient-rich waters that are not tolerated by sea-level fen vegetation. On the other hand, sea-level rise could cause groundwater discharge to increase in volume at some locations, which would benefit fens (Strange, 2008).

Another rare sea-level fen community — one of only four in Virginia — is found in the Mutton Hunk Fen Natural Area Preserve fronting Gargathy Bay in eastern Accomack County (VA DCR, date unknown). The Division of Natural Heritage within the Virginia Department of Conservation and Recreation believes that chronic sea-level rise with intrusions of tidal flooding and salinity poses “a serious threat to the long-term viability” of sea-level fens (VA DCR, 2001). If rising seas reach the Mutton Hunk Fen Natural Area, the influx of nutrient-rich waters may destroy the populations of the rare plant species at this site, including the carnivorous sundew, and bladderwort (VA DCR, date unknown).

Shallow Waters and Submerged Aquatic Vegetation (SAV). The potential effects of sea-level rise on eelgrass beds have not been studied directly. However, Short and Neckles (1999) estimate that, in general, 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 SAV growth (Short and Neckles, 1999).Where this occurs would depend on current local conditions such as water depth, the maximum depth of eelgrass growth, and water clarity.

Eelgrass beds are essential habitat for summer flounder, bay scallop, and blue crab, all of which support substantial recreational and commercial fisheries in the coastal bays (MCBP, 1999). Various waterbirds feed on eelgrass beds, including brant, canvasback duck, and American black duck (Perry and Deller, 1996).

Tidal Flats. Tidal flats are abundant in this region. 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 seaward, further increasing sediment deposition and leading to an increase in low marsh and a reduction in tidal flats (Redfield, 1972). Where sediment deposition is comparatively low, marsh may revert to unvegetated flat, at least in the short term, before the area becomes fully inundated (Brinson *et al.*, 1995).

Loss of tidal flats would eliminate a rich invertebrate food source for a number of bird species, including whimbrels, dowitchers, dunlins, black-bellied plovers, and semi-palmated sandpipers (Watts and Truitt, 2002). Eighty-percent of the Northern Hemisphere's whimbrel population feeds on area flats (TNC, 2006). The whimbrel is considered a species "of conservation concern" by the U.S. Fish and Wildlife Service, Division of Migratory Bird Management (USFWS, 2002).

Coastal Plain Ponds. Coastal plain ponds are small, groundwater-fed ponds that contain many rare plant species. Because they are near sea level, these unique plant communities are particularly vulnerable to sea-level rise. Such areas occur along the Eastern Shore and in the Delaware Inland Bays, especially within Assawoman Wildlife Management Area on Little Assawoman Bay[103].

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[103] Kevin Kalasz, Wildlife Biologist, Natural Heritage & Endangered Species Program, Delaware Division of Fish and Wildlife in written communication to EPA, 5/14/07 and Chris Bason, Center for the Delaware Inland Bays, written communication to EPA, 5/14/07.

Beaches. The beaches on the mainland behind the barrier island complex of the Eastern Shore occur as small strips that are relatively stable because they are protected from high energy wave action. Where beaches erode in front of shoreline protection structures and are not replenished, there will be a reduction in beach habitat. Loss of beach habitat due to sea-level rise and erosion below protective structures could have a number of negative consequences for species that use these beaches:

- Horseshoe crabs rarely spawn unless sand is at least deep enough to nearly cover their bodies, about 10 cm (4 inches) (Weber, 2001). Shoreline protection structures designed to slow beach loss can also block horseshoe crab access to beaches and can entrap or strand spawning crabs when wave energy is high (Doctor and Wazniak, 2005).
- The rare northeastern tiger beetle depends on beach habitat (USFWS, 2004).
- *Photuris bethaniensis* is a globally rare firefly located only in interdunal swales on Delaware barrier beaches. The firefly's habitat is at risk because of beach stabilization and shoreline hardening, which limit dune migration and the formation of interdunal swales[104].
- Erosion and inundation may reduce or eliminate beach wrack communities of the upper beach, especially in developed areas where shores are protected. Beach wrack contains insects and crustaceans that provide food for many species, including migrating shorebirds (Dugan *et al.*, 2003).

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[104] Kevin Kalasz, Wildlife Biologist, Natural Heritage & Endangered Species Program, Delaware Division of Fish and Wildlife in written communication to EPA, 5/14/07.

Coastal Habitat for Migrating Neotropical Songbirds. Southern Northampton County is one of the most important bird areas along the Atlantic Coast of North America for migrating neotropical songbirds such as indigo buntings and ruby-throated hummingbirds (Watts, 2006). Not only are these birds valued for their beauty but they also serve important functions in dispersing seeds and controlling insect pests. It is estimated that a pair of warblers can consume thousands of insects as they raise a brood (Mabey *et al.*, not dated).

Migrating birds concentrate within the tree canopy and thick understory vegetation found within the lower 10 km (6 mi) of the peninsula within 200 m (200 yd) of the shoreline. Loss of this understory vegetation as a result of rising seas would eliminate this critical stopover area for neotropical migrants, many of which have shown consistent population declines since the early 1970s (Mabey, not dated).

E.3 COASTAL POLICY CONTEXT

Less than one fifth of the Delmarva's ocean coast is developed. Unless conservation policies are reversed or conservation organizations change their priorities, the portion that is now developed is probably all that will be developed during the next century. All of Virginia Eastern Shore's 124-km ocean coast is owned by the U.S. Fish and Wildlife Service, NASA, the State, or The Nature Conservancy. Of Maryland's 51 kilometers of ocean coast, 36 kilometers are along Assateague Island National Seashore. The densely populated Ocean City occupies only approximately 15 kilometers. More than three-quarters of the barrier islands and spits in Delaware are part of Delaware Seashore State

Park, while the mainland coast is about evenly divided between Cape Henlopen State Park and resort towns such as Rehoboth, Dewey Beach, and Bethany Beach. With approximately 15 kilometers of developed ocean coast each, Maryland and Delaware have pursued beach nourishment to protect valuable coastal property and preserve the beaches that make the property so valuable (Hedrick *et al.*, 2000).

The mainland along the back barrier bays has been developed to a greater extent than the respective ocean coast in all three states. Development pressures are greatest at the northern end of the DelMarVa due to the relatively close proximity to Washington, Baltimore, and Philadelphia. Although connected to the densely populated Hampton Roads area by the Chesapeake Bay Bridge-Tunnel, southern portions of the DelMarVa are not as developed as the shoreline to the north.

Maryland has the most stringent policies governing development along coastal bays. Recently, the preservation policies of the Chesapeake Bay Critical Areas Act[105] have been extended to the coastal bays of Worcester County, requiring new development to be set back 100 feet from the wetlands or open water[106], and limiting future development density to 1 home per 20 acres along most undeveloped areas[107]. The Virginia counties of the DelMarVa have shores along both the Atlantic Ocean and Chesapeake Bay, and the 100-foot setback that applies along Chesapeake Bay[108] applies to the coastal bays as well.

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[105] See Appendix D for a discussion of these policies.
[106] Code of Maryland Regulations §27.01.00.01 (C)
[107] Maryland Natural Resources Code §8-1807(b).
[108] See Appendix F for a discussion of these policies.

The Delaware Department of Natural Resources has proposed a 100-foot setback along the coastal bays (DNREC, 2007); Sussex County currently requires a 50-foot setback[109].

E.4 DEVELOPMENT AND SHORE PROTECTION

As Chapter 5 discussed, ongoing studies are analyzing land use plans, land use data, and coastal policies to create maps depicting the areas where shores may be protected and where wetlands may migrate inland. Because the maps from those studies have not yet been finalized, this section describes some of the existing and evolving conditions that may influence decisions related to future shore protection and wetland migration

With development accounting for only 15-20% of the ocean coast, the natural shoreline processes are likely to dominate along most of these shores. Within developed areas, counteracting shoreline erosion in developed areas with beach nourishment may continue as the primary activity in the near term. The Corps of Engineers has begun to actively plan for beach nourishment of the northern part of Assateague Island, to prevent the increased risks of flooding to nearby developed areas that might otherwise accompany a disintegration of this barrier island (US Army Corps of Engineers, 2001).

Preventing the inundation of low-lying lands may eventually be necessary as well. Elevating these low areas appears to be more practical than erecting a dike around a narrow barrier island (Titus, 1990). Most land surfaces on the bayside of Ocean City were elevated during the initial construction of residences (McGean, 2003). In an appendix for

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[109] Sussex County, DE. 2007. Buffer zones for wetlands and tidal and perennial nontidal waters. Section 115-193, Sussex County Code. Enacted July 19, 1988 by Ord. No. 521.

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EPA's 1989 Report to Congress, Leatherman concluded that the only portion of Fenwick Island where bayside property would have to be elevated with a 50 cm rise in sea level would be the portion in Delaware (*i.e.*, outside of Ocean City) (Leatherman, 1989). He also concluded that Wallops Island, South Bethany, Bethany, and Rehoboth Beach are high enough to avoid tidal inundation for the first 50–100 cm of sea-level rise.

Along the coastal bays, market forces have led to extensive development in Delaware but relatively sparse development in Virginia, largely due to their relative proximity to major population centers. Worcester County, Maryland, reflects a balance between development and environmental protection resulting from both recognition of existing market forces and a conscious decision to preserve Chincoteague Bay. Development is extensive along most shores opposite Ocean City. Development is along the bay shores near Ocean City inlet. In the southern portion of the county, conservation easements or the Critical Areas Act preclude development along most of the shore. Although the Critical Areas Act encourages shore protection, and conservation easements in Maryland preserve the right to armor the shore, these low-lying lands are more vulnerable to inundation than erosion and are therefore possible candidates for wetland migration. Since 2004, the Maryland Department of Natural Resources has been working with the U.S. Geological Survey (USGS) to model the risk of flooding and inundation as sea level rises for Worcester County (MDNR and USGS, 2006). Maryland's Coastal Bays National Estuary Program has long included sea-level rise as a factor to be addressed in plans to protect the bays.

The Maryland Coastal Bays Program considers erosion (due to sea-level rise) and shoreline hardening major factors contributing to a decline in natural shoreline habitat available for estuarine species in the northern bays (MCBP, 1999). Much of the shoreline of Maryland’s northern coastal bays is protected using bulkheads or stone riprap, resulting in unstable sediments and loss of wetlands and shallow water habitat (MCBP, 1999). Armoring these shorelines will prevent inland migration of marshes, and any remaining fringing marshes will ultimately be lost. The Maryland Coastal Bays Program estimated that more than 607 hectares (1,500 acres) of salt marshes have already been lost in the coastal bays as a result of shoreline development and stabilization techniques (MCBP, 1999). If shores in the southern part of Maryland’s coastal bays remain unprotected, marshes in low-lying areas will be allowed to potentially expand inland as seas rise.

E.5 POPULATION OF LANDS CLOSE TO SEA LEVEL

Table E.2 shows the populations of lands close to sea level for the four counties along the Atlantic Coast of the DelMarVa peninsula. Because Maryland provided LIDAR elevation data, the estimates for Worcester county are most reliable. In spite of the higher population densities, Worcester County has fewer people vulnerable to a 50 cm rise than Sussex County, presumably in part because Ocean City's bay side is mostly 1-2 meters above spring high water. (See elevation map of Ocean City.) The two counties have similar populations within two meters above spring high water. With the undeveloped barrier islands and generally steep slopes along the mainland, the Virginia counties have very few people living close to sea level along the Atlantic side.

Table E.2 Population of Lands Close to Sea Level: The Atlantic Coast of Virginia, Maryland, and Delaware.

County	**Low and high estimates of population below a given elevation (thousands)**					
	50cm		**1m**		**2m**	
	Low	**High**	**Low**	**High**	**Low**	**High**
Delaware						
Sussex[1]	1.1	7.2	1.1	9.5	7.1	17.0
Maryland						
Worcester[2]	0.0	1.1	0.6	3.2	6.4	12.6
Virginia						
Accomack[2]	0.8	7.0	0.8	7.6	6.9	9.3
Northampton[2]	0.0	0.3	0.0	0.6	0.2	1.1
Total	**1.9**	**15.5**	**2.5**	**20.8**	**20.6**	**40.0**

[1] Figures are for the entire county. County is split between Chesapeake, Atlantic Coast, and Delaware Bay Watersheds.

[2] Figures are for the entire county. County is split between Chesapeake and Atlantic Coast Watersheds.

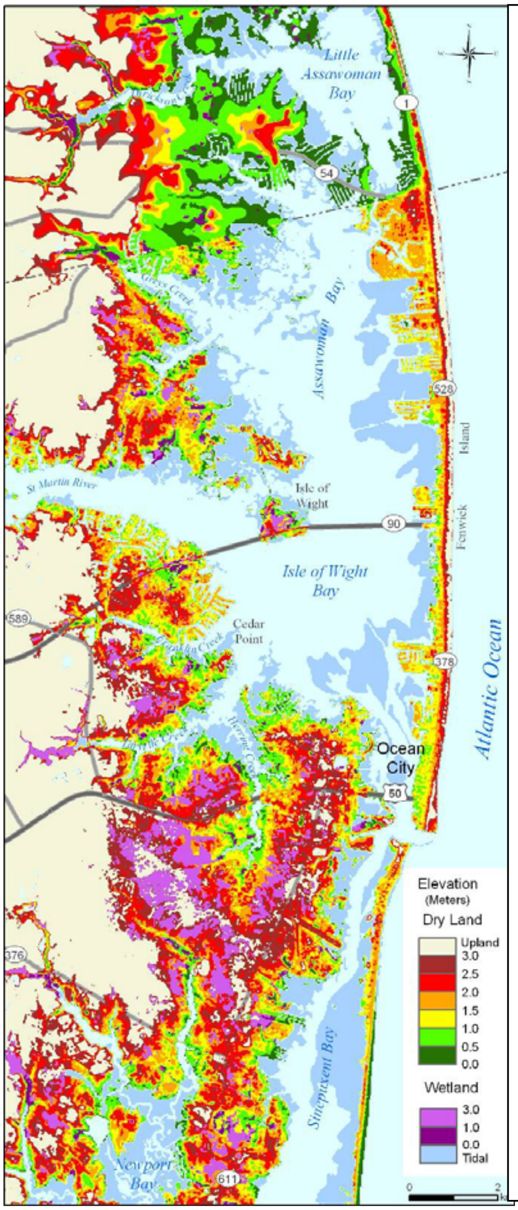

Figure E.3

BOX E.1: Elevating Ocean City as Sea Level Rises

Logistically, the easiest time to elevate low land is when it is still vacant, or during a coordinated rebuilding. Low parts of Ocean City's bay side were elevated during the initial construction. As sea level rises, the town of Ocean City has started thinking about how it might ultimately elevate.

Ocean City's relatively high bay sides make it much less vulnerable to inundation by spring tides than other barrier islands. Still, some streets are below the 10-year flood plain, and as sea level rises, flooding will become increasingly frequent.

However, the town cannot elevate the lowest streets without considering the implications for adjacent properties. A town ordinance requires property owners to maintain a 2% grade so that yards drain into the street. The town construes this rule as imposing a reciprocal responsibility on the town itself to not elevate roadways above the level where yards can drain, even if the road is low enough to flood during minor tidal surges. Thus, the lowest lot in a given area dictates how high the street can be.

As sea level rises, failure by a single property owner to elevate could prevent the town from elevating its streets, unless it changes this rule. Yet public health reasons require drainage, to prevent standing water in which mosquitoes breed. Therefore, the town has an interest in ensuring that all property owners gradually elevate their yards so that the streets can be elevated as the sea rises without causing public health problems.

Ocean City has developed draft rules that would require that, during any significant construction, yards be elevated enough to drain during a 10-year storm surge for the life of the project, considering projections of future sea-level rise. The draft rules also state that Ocean City's policy is for all lands to gradually be elevated as the sea rises.[1]

Note: 1. This discussion is based on the presentation by Terry McGean, city engineer, Town of Ocean City, to *Coastal Zone 2003.*

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Appendix F. Chesapeake Bay

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In 1607, a group of English settlers landed three ships near the mouth of North America's largest estuary, and established Jamestown, the first permanent town in what eventually became the United States of America. Jamestown was the capital of Virginia until 1699, when a fire destroyed the statehouse. Rising sea level was probably also a contributing factor in the decision to move the capital to Williamsburg[110], because it was making the Jamestown peninsula less habitable than it had been during the previous century (Blanton, 2000). Because the James River was brackish, groundwater was the only reliable source of freshwater. But the low elevations on Jamestown limited the thickness of the freshwater table — especially during droughts. As Figure F.1 shows, a 10 cm rise in sea level can reduce the thickness of the freshwater table by 4 meters on a low-lying island where the freshwater lens floats atop the salt water.

Rising sea level has continued to alter Jamestown. Two hundred years ago, the isthmus that connected the peninsula to the mainland eroded, creating Jamestown Island (Johnson

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[110] Geologist Carl Hobbs contributed this idea as part of the stakeholder review process for the report. Carl Hobbs. (2007). Stakeholder Review Process. Stakeholder Comments.

and Hobbs, 1994 p. 11). Shore erosion also threatened the location of the historic town itself, until a stone revetment was constructed (Johnson and Hobbs, 1994, p. 11). As the sea rose, the shallow valleys between the ridges on the island became freshwater marsh, and then tidal marsh (Johnson and Hobbs, 1994, p. 9). Maps from the 17th century show agriculture on lands that today are salt marsh. Having converted mainland to island, the rising sea will eventually convert the island to open water, unless the National Park Service continues to protect it from the rising water.

Other shorelines along Chesapeake Bay have also been retreating over the last four centuries. Several bay island fishing villages have had to relocate to the mainland as the islands on which they were located eroded away (Leatherman, 1992). Low-lying farms on the eastern shores are converting to marsh, while the marshes in wildlife refuges convert to open water. As sea level rises, the risk of flooding is increasing from Poquoson, Virginia, to Fells Point (Baltimore) Maryland.

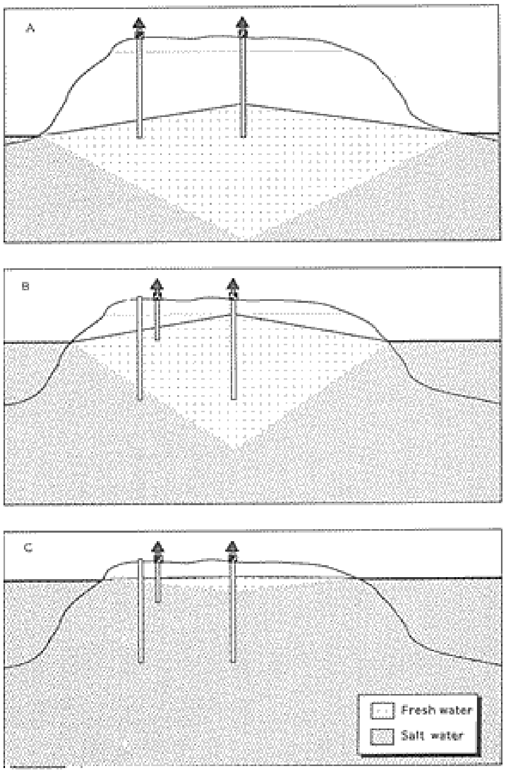

Figure F.1 Impact of sea-level rise on an island freshwater table. (A) The freshwater table extends below sea level 40 cm for every 1 cm by which it extends above sea level. (B) For islands with substantial elevation, a 1 meter rise in sea level simply shifts the entire water table up 1 meter, and the only problem is that a few wells will have to be replaced with shallower wells. (C) However, for very low islands the water table cannot rise because of runoff, evaporation, and transpiration. A rise in sea level would thus narrow the water table by 40 cm for every 1 cm that the sea level rises, effectively eliminating groundwater supplies for the lowest islands.

This appendix examines the sensitivity of Chesapeake Bay and some of its tributaries to rising sea level. We first examine coastal elevations and vulnerable habitat (Section F.1) and then summarize policies related to the impacts of sea-level rise (F.2). Finally, we briefly discuss new estimates of the population that resides in the areas most vulnerable to sea-level rise (F.3). Sections F.2 and F.3 start with Hampton Roads and then proceed clockwise around the Bay to Virginia’s Middle Peninsula and Northern Neck, then up the

Potomac River to Washington DC, then up Maryland's Western Shore, around to the Upper Eastern Shore, and finally down to the Lower Eastern Shore. The discussions for Virginia are largely organized by planning district; the Maryland discussions are organized by major section of shore.

F.1 IMPACTS ON THE PHYSICAL ENVIRONMENT

F.1.1 Hampton Roads

Hampton Roads is the southernmost coastal planning district in Virginia. Extending from the North Carolina border to the York River, the region has 16 localities whose combined population is more than 1.5 million. Lands vulnerable to sea-level rise include beaches along the Atlantic Ocean and Chesapeake Bay, both sides of the lower James River, a barrier spit and back barrier bays near North Carolina's Outer Banks, and parts of the York River.

Elevations

Figure F.2 shows the elevations of lands close to sea level in the Hampton Roads area (see also Table F.1). As shown, most of the vulnerable dry land is located within Virginia Beach and Chesapeake. These low areas are not, however, in the urban portions of those jurisdictions. Most of Virginia Beach's very low land is either along the back-barrier bays near the North Carolina border, or along the North Landing River. The lightly developed southern half of this city is mostly within 3 meters above mean spring high water. Most of Chesapeake's low land is around the Northwest River near the North Carolina border, or the along the Intracoastal Waterway[111]. Hampton and Newport News have substantial areas between the 1.5- and 3-meter contours, with a few areas within 1 meter above the tides.

The town of Poquoson is extensively developed and probably the community that is most vulnerable to rising water levels (see Figures F.3 and F.4). Although the city's corporate limits include some high ground, the town is approximately 50% wetland and almost all residential lands are less than 3 meters above the tides; several neighborhoods are vulnerable to even minor surges in Chesapeake Bay. The localities located farther up the James and York rivers have less low land. An important exception is historic Jamestown Island, which has been gradually submerged by the rising tides since the colony was established 400 years ago.

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[111] The intracoastal waterway includes the North Landing River which flows into Currituck Sound (NC), the southern branch of the Elizabeth River, which flows into Chesapeake Bay, and an East-West canal that connects these two rivers.

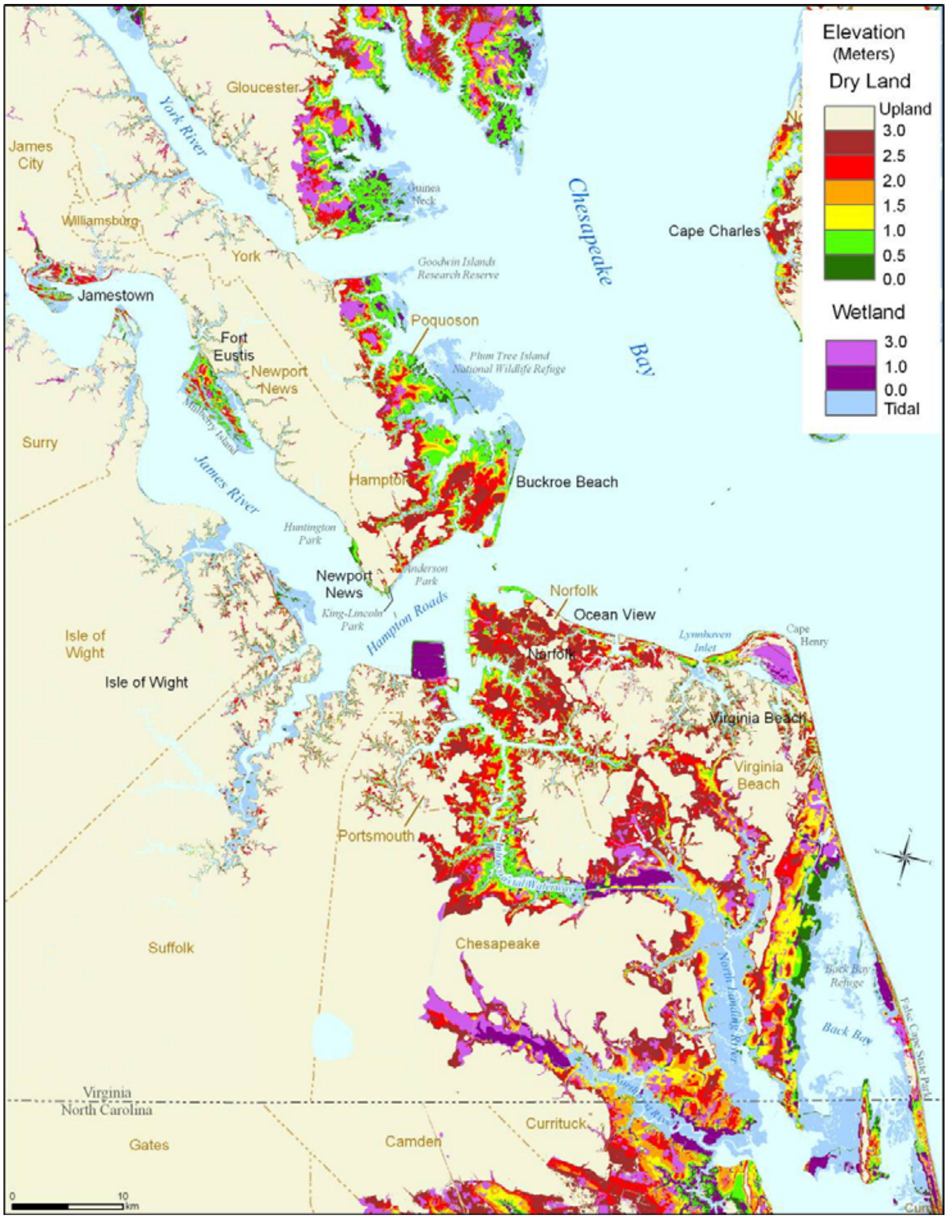

Figure F.2 Hampton Roads: Elevations relative to spring high water.

Table F.1 Low and high estimates for the area of dry and wet land close to sea level, Hampton Roads, Virginia (square kilometers).

	Tidal	**50 cm**		**1 meter**		**2 meters**		**3 meters**		**5 meters**	
		Low	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Locality	Cumulative (total) amount of Dry Land below a given elevation										
Virginia Beach		9.3	33.0	30.3	68.7	93.6	163.2	184.7	272.9	378.1	418.2
Chesapeake		3.5	11.9	10.8	30.6	44.6	86.6	100.4	204.5	353.0	429.7
Norfolk		1.9	5.8	5.2	17.1	24.0	42.4	52.4	91.2	121.7	128.2
Portsmouth		1.2	3.9	3.5	9.6	12.8	22.0	26.7	45.0	62.6	69.9
Suffolk		0.7	4.3	3.1	7.1	7.5	15.2	13.0	31.0	47.3	73.3
Isle of Wight		0.2	3.4	2.1	6.2	6.0	12.8	10.1	21.6	26.8	42.0
Surry		0.0	1.4	0.7	2.7	2.7	5.3	4.6	7.1	8.1	11.2
James City		0.1	3.8	2.2	7.2	7.0	14.2	11.8	22.1	26.7	38.7
York		1.4	6.0	4.8	13.1	16.3	27.7	28.3	37.3	44.3	51.3
Newport News		2.2	6.9	6.1	11.0	12.9	17.9	19.3	24.8	34.9	42.3
Poquoson		1.4	4.5	4.1	8.8	10.9	16.3	16.4	16.6	16.7	16.7
Hampton		1.9	5.9	5.3	18.1	25.4	45.3	51.2	73.8	94.7	102.4
Total		**23.8**	**90.8**	**78.2**	**200.2**	**263.6**	**468.9**	**519.0**	**847.9**	**1214.9**	**1423.8**
	Cumulative (total) amount of wetlands below a given elevation										
Virginia Beach	111.9	4.2	14.5	13.3	24.9	29.1	40.9	43.5	49.6	56.5	59.3
Chesapeake	39.7	4.5	16.6	15.4	32.1	36.4	58.3	55.7	120.2	180.3	250.8
Norfolk	4.7	0.1	0.3	0.2	0.5	0.7	1.1	1.1	1.5	1.7	1.7
Portsmouth	3.7	2.4	7.7	6.8	8.9	9.1	9.5	9.6	10.3	10.9	11.2
Suffolk	26.4	0.0	0.2	0.1	0.3	0.3	0.8	0.5	1.8	2.9	33.1
Isle of Wight	28.6	0.0	0.3	0.2	0.6	0.6	1.4	1.0	3.1	4.0	7.3
Surry	11.5	0.0	0.6	0.3	1.3	1.2	2.4	2.1	2.7	2.9	3.4
James City	32.8	0.0	0.8	0.4	1.5	1.4	2.8	2.5	3.7	4.2	5.6
York	17.0	0.2	0.9	0.7	2.7	3.7	6.7	6.9	8.0	9.2	9.9
Newport News	15.1	0.1	0.3	0.3	0.7	0.9	1.3	1.4	1.4	1.6	1.7
Poquoson	23.7	0.0	0.1	0.1	0.4	0.6	1.1	1.1	1.1	1.1	1.1
Hampton	14.3	0.1	0.2	0.2	0.4	0.5	0.9	1.1	2.2	4.4	6.2
Total	**329.4**	**11.7**	**42.4**	**38.0**	**74.2**	**84.5**	**127.1**	**126.5**	**205.4**	**279.5**	**391.1**
Dry and Nontidal wetland		35	133	116	274	348	596	645	1053	1494	1815
All Land	329	365	463	446	604	677	925	975	1383	1824	2144

Source: Titus and Cacela, 2008. Uncertainty Ranges Associated with EPA's Estimates of the Area of Land Close to Sea Level. Section 1.3 in: Background Documents Supporting Climate Change Science Program Synthesis and Assessment Product 4.1: Coastal Elevations and Sensitivity to Sea-level Rise, J.G. Titus and E. Strange (eds.). EPA 430R07004. U.S. EPA, Washington, DC.The low and high estimates are based on the on the contour interval and/or stated root mean square error (RMSE) of the data used to calculate elevations.

Figures F.3 and F.4 Poquoson, Virginia. Homes Close to Sea Level. (a) The water levels in the roadside ditches rise and fall with the tides. A bulkhead is on one side of the ditch, while marsh grasses have colonized the other side (October 2002). (b) A home being elevated after Hurricane Isabel (October 2004).

Vulnerable Habitat

Sandy beaches with dune systems comprise the Chesapeake Bay shoreline of the City of Virginia Beach and Norfolk, from Cape Henry to the mouth of the James River (Hardaway, *et al.*, 2005). Overall trends in the last century show the dunes east of the Lynnhaven inlet advancing into the Bay. West from the inlet, erosion, beach nourishment, and fill operations as well as condominium development and shoreline armoring have affected the accretion and erosion patterns (Hardaway, *et al.*, 2005). Along the shores of Norfolk, the rate of erosion is generally low, and beach accretion occurs along much of the shore (Berman *et al.*, 2002). Most of the shore along Chesapeake Bay is protected by groins and breakwaters, and hence relatively stable (Hardaway *et al.*, 2005, p.9). On the other side of the James River, the Bay shoreline is dominated by marshes, many of which are eroding.

Along the bay shores of the Hampton Roads planning district, current sea-level trends or a modest acceleration (e.g. current rate plus 2mm/yr) are unlikely to substantially diminish beach habitat, compared to the existing impact from human activities. Urbanization and foot traffic impair beach habitat compared with a pristine environment[112]. Nevertheless, the commitment to maintain the existing beaches make further habitat degradation unlikely because the beaches will continue to exist, unless sea-level rise accelerates enough to cause officials to rethink that commitment.

Other tidal habitat is more vulnerable. Approximately one quarter of the tidal wetlands in the area is within Poquoson's Plum Tree Island National Wildlife Refuge (see Table F.1)[113]. Unlike most mid-Atlantic wetlands, these wetlands appear to be unable to keep pace with the current rate of sea-level rise (Reed *et al.*, 2008). This refuge has very limited human access because unexploded ordnance remains on the island from its prior use as a bombing range. The relative isolation of the area has made it a haven for over 100 different species of birds, including northern harrier (*Circus cyaneus*), black duck (*Anas rubripes*), sedge wren (*Cistothorus platensis*), sharp-tailed sparrow (*Ammodramus caudacutus*), bald eagle, peregrine falcon (*Falco peregrinus*), black-necked stilts (*Himantopus mexicanus*), and little blue heron (*Egretta caerulea*). In addition to the salt marsh, the refuge has substantial forested dune hummocks (CPCP, 1999). A variety of mammals (muskrats, red fox, and white-tailed deer) use the higher ground of the refuge. Endangered sea turtles, primarily the loggerhead, use the nearshore waters. Oyster, clams,

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[112] A possible exception is Grandview Beach Nature Preserve in Hampton. The preserve has over two miles of beach shoreline on Chesapeake Bay and is home to a population of northeastern beach tiger beetles (Cicindela dorsalis dorsalis), federally listed as threatened (USFWS, 1994). U.S. Fish and Wildlife Service. 1994. Northeastern Beach Tiger Beetle (Cicindela dorsalis dorsalis) Recovery Plan. Hadley Massachusetts. 60 pp. page 6.

[113] The refuge has the vast majority of Poquoson's tidal wetlands.

and blue crabs inhabit the shallow waters and mudflats, and striped bass, mullet, spot, and white perch have been found in the nearshore waters and marsh (USFWS, date unkown).

The wetlands in York County appear able to keep pace with the current rate of sea-level rise; but assuming that they are typical of most wetlands on the western side of Chesapeake Bay, they would become marginal with a modest acceleration and be lost if sea-level rise accelerates to 1 cm/yr (Reed *et al.*, 2008). Bald eagles currently nest in the Goodwin Islands National Estuarine Research Reserve (Watts and Markham, 2003).This reserve includes intertidal flats, 300 acres of eelgrass and widgeon grass (VIMS, date unknown), and salt marshes dominated by salt marsh cordgrass (*Spartina alterniflora*) and salt meadow hay (*Spartina patens*). Even if the wetlands keep pace with rising sea level, the habitat just above the wetlands could be lost as it converts to marsh. This habitat includes forested wetland ridges, dominated by estuarine scrub/shrub vegetation, and ridges with oak and pine black gum (*Nyssa sylvatica*), and cottonwood (*Populus deltoides*) (VIMS, date unknown).

F.1.2 York River to Potomac River

Elevations

Two planning districts lie between the York and Potomac rivers. The Middle Peninsula Planning District includes the land between the York and Rappahannock rivers. The Northern Neck is between the Rappahannock and Potomac rivers.

As Figure F.5 shows, the Middle Peninsula includes Mathews and Middlesex counties, which are along Chesapeake Bay. Gloucester County is between the York River and Mobjack Bay, with very little of the county actually on Chesapeake Bay. Gloucester is the most developed county, while the remainder of the Middle Peninsula consists of a mix of rural areas and seasonally occupied coastal homes.

The Northern Neck planning district is primarily rural, with approximately one-third of the land area currently farm land. Major developed areas lie along the shores of Chesapeake Bay and the Potomac River, while the Rappahannock River banks remain largely undeveloped, especially upstream from Lancaster County.

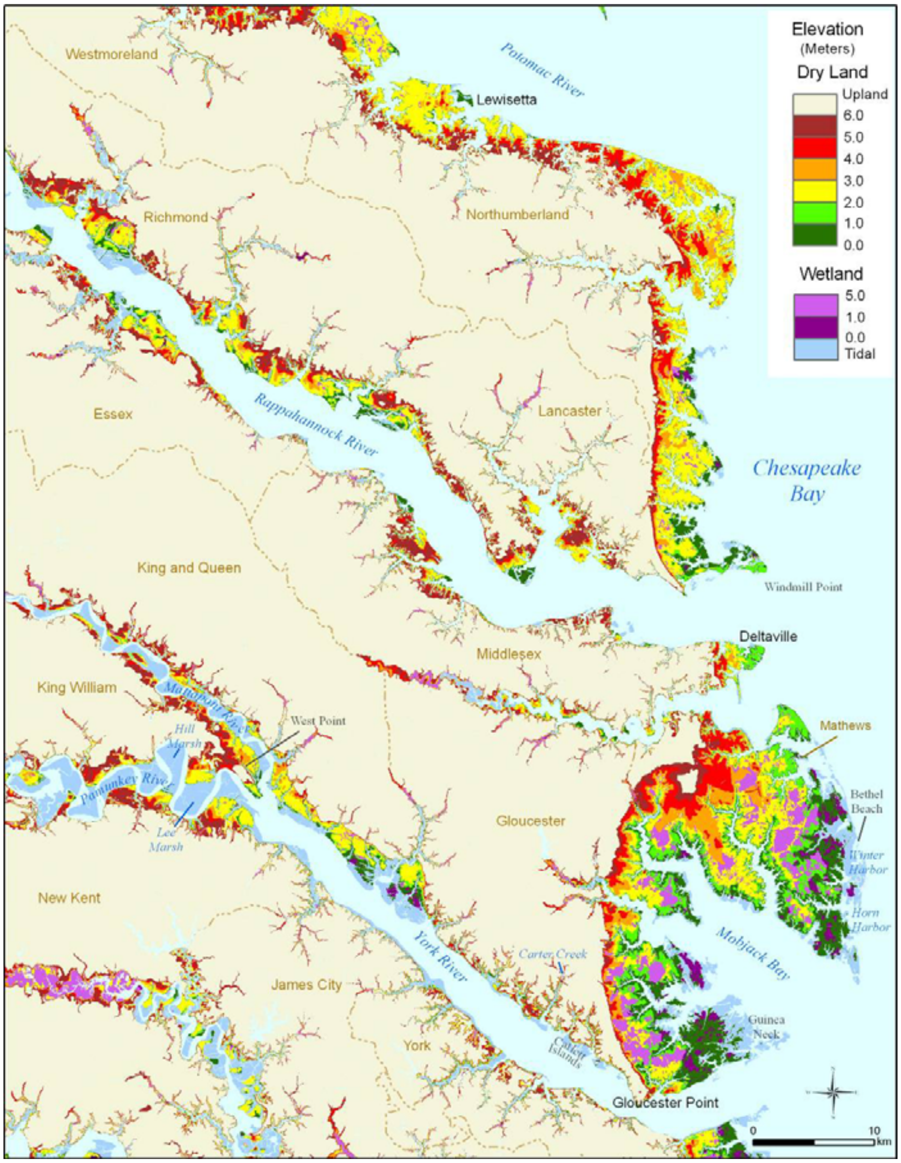

Figure F.5 Middle Peninsula and Northern Neck: Elevations relative to spring high water. Contour interval is 1 meter because data quality is insufficient to display 50 cm at this scale.

Figure F.5 and Table F.2 report elevations relative to spring high water for the two planning districts. Gloucester County has between 13 and 33 square kilometers of dry land within 1 meter above the coastal wetlands. Most of that land is on the Guinea Neck. The long-established communities on this neck may be the most vulnerable to rising sea level along the Western Shore of Chesapeake Bay.

The vast majority of Mathews County is less than 6 meters above spring high water, as Figure F.5 shows. For the most part, the very low dry land in this county tends to be undeveloped forests lying just inland of the tidal wetlands. Its most vulnerable development is in the southernmost neck, between Horn Harbor and Mobjack Bay, approximately 1–1.5 meters above spring high water. The other counties have relatively little low land. In spite of its name, for example, Deltaville (Middlesex) is generally 4 meters above sea level and not vulnerable to inundation.

For the most part, the Northern Neck has rolling hills with relatively few low spots. Many coastal homes are along bluffs, some of which are eroding. The available topographic data suggest that within the Northern Neck planning district, Lancaster County has the most dry land located below 2 meters (between 14 and 28 square kilometers)[114].

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[114] The available topographic data does not allow a meaningful estimate of the land within one meter above the tides. See Map 1.1 in Chapter 1.

Table F.2 Low and high estimates for the area of dry and wet land close to sea level Chesapeake Bay, Middle Peninsula and Northern Neck Areas, Virginia (square kilometers).

	Tidal	**50 cm**		**1 meter**		**2 meters**		**3 meters**		**5 meters**	
		Low	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Locality	Cumulative (total) amount of Dry Land below a given elevation										
Gloucester		4.1	16.0	13.2	32.9	40.5	66.9	66.9	84.2	96.4	110.8
Mathews		4.7	14.8	13.4	33.1	43.9	73.1	78.6	96.8	114.7	120.7
Middlesex		0.2	3.4	2.0	6.8	7.3	14.4	13.1	22.8	28.1	38.9
King William		0.0	1.6	0.9	3.2	3.1	8.4	5.4	17.7	22.7	36.1
King and Queen		0.0	2.9	1.7	5.7	5.5	11.9	9.6	19.0	22.7	32.9
Essex		0.0	3.8	2.0	7.3	7.1	15.5	12.3	27.9	34.2	52.8
Lancaster		0.1	7.0	3.6	13.8	13.8	28.0	24.0	41.5	48.4	67.9
Northumberland		0.0	5.9	2.8	11.5	11.0	24.1	19.2	63.8	84.5	140.9
Richmond		0.0	4.6	2.4	8.9	8.7	18.5	15.0	31.6	38.2	56.5
Caroline		0.0	0.4	0.3	0.9	0.9	1.8	1.5	2.8	3.4	5.2
Spotsylvania		0.0	0.1	0.1	0.2	0.2	0.3	0.3	0.5	0.5	0.8
Fredericksburg		0.0	0.1	0.0	0.1	0.1	0.2	0.2	0.3	0.4	0.5
Total		**9.2**	**60.5**	**42.4**	**124.2**	**142.1**	**263.2**	**246.0**	**409.0**	**494.2**	**664.0**
	Cumulative (total) amount of wetlands below a given elevation										
Gloucester	43.5	1.4	5.5	4.5	11.9	14.7	24.8	24.6	30.8	34.4	38.5
Mathews	27.0	1.2	3.8	3.5	8.6	11.4	19.0	21.6	33.6	48.1	55.1
Middlesex	9.7	0.0	0.7	0.4	1.4	1.4	2.8	2.4	3.5	3.8	4.8
King William	35.6	0.0	0.4	0.2	0.7	0.7	1.4	1.2	2.0	2.3	3.3
King and Queen	21.6	0.0	0.9	0.5	1.7	1.6	3.1	2.8	4.0	4.4	5.8
Essex	27.5	0.0	0.8	0.4	1.5	1.5	2.9	2.5	3.9	4.4	5.9
Lancaster	9.8	0.0	0.5	0.3	1.1	1.1	2.1	1.8	2.8	3.2	4.2
Northumberland	11.4	0.0	0.5	0.3	1.1	1.0	2.2	1.8	5.1	6.6	10.8
Richmond	21.7	0.0	0.9	0.4	1.7	1.6	3.3	2.8	4.5	5.1	6.9
Caroline	6.3	0.0	0.1	0.0	0.1	0.1	0.3	0.2	0.7	0.9	1.5
Spotsylvania	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1
Fredericksburg	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	**214.3**	**2.6**	**14.1**	**10.5**	**29.7**	**35.1**	**62.0**	**61.7**	**90.9**	**113.5**	**136.9**
Dry and Nontidal wetland		12	75	53	154	177	325	308	500	608	801
All Land	214	226	289	267	368	392	539	522	714	822	1015

Source: Titus and Cacela, 2008. Uncertainty Ranges Associated with EPA's Estimates of the Area of Land Close to Sea Level. Section 1.3 in: Background Documents Supporting Climate Change Science Program Synthesis and Assessment Product 4.1: Coastal Elevations and Sensitivity to Sea-Level Rise, J.G. Titus and E. Strange (eds.). EPA 430R07004. U.S. EPA, Washington, DC. The low and high estimates are based on the on the contour interval and/or stated root mean square error (RMSE) of the data used to calculate elevations. For additional details, see Chapter 1.

Vulnerable Habitat

Like the marshes of Poquoson to the south, the marshes of the Guinea Neck and adjacent islands are not keeping pace with the current rates of sea-level rise (Reed *et al.*, 2008). For more than three decades, scientists have documented their migration onto farms and forests (Moore, 1976). Thus, the continued survival of these marshes depends on land use and shore protection decisions. As a general rule, loss of marsh can eliminate nesting and forage habitat for birds and fish, and reduce the food supply of invertebrates such as crabs and shrimp, as well as the birds that feed on these species[115].

Upstream from the Guinea Neck, sea-level rise is evident in the York River's tributaries, not because wetlands are converting to open water but because the composition of wetlands is changing. Along the Pamunkey and Mattaponi rivers, dead trees reveal that tidal hardwood marshes are converting to brackish or freshwater marsh[116]. Tidal hardwood marshes provide nesting sites for piscivorous species such as ospreys, bald eagles, and double-crested cormorants (Robbins and Blom, 1996). The freshwater marshes also host a variety of migratory and breeding birds.

Some scientists are concerned about the implications of a shift from high marsh to low marsh. In a study of the Lee and Hill marshes in the lower Pamunkey River, the authors posit that brackish marshes, due to their locations at transitions between tidal freshwater and oligohaline marshes, may face greater risk than marshes with more extreme, nontransitional salinities. If sea-level rise were to convert 100 hectares of high marsh big cordgrass (*Spartina cynasuroides*) to low marsh arrow arum (*Peltandra virginica*), the authors estimate a reduction in the number of breeding red-winged blackbirds that currently depend on the big cordgrass portions of the marshes (Paxton and Watts, 2002). However, the change to an arrow arum-dominated marsh may increase bird density and

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115 See Chapter 4.

116 Written communication from Gary Fleming, Vegetation ecologist for the Virginia Natural Heritage Program, cited in Shellenbarger Jones and Bosch, 2007a.

diversity during winter, particularly for waterfowl and shorebirds. Arrow arum dies back in winter, creating an open mud flat that provides birds with improved access to invertebrate prey (Paxton and Watts, 2002, pp 25-26).

In Mathews County, Bethel Beach (a natural area preserve separating Winter Harbor from Chesapeake Bay) is currently migrating inland over an extensive salt marsh area (Shellenbarger Jones and Bosch, 2008a). The beach is currently undergoing high erosion (Berman *et al.*, 2000), and is home to a population of the Northeastern beach tiger beetle (federally listed as threatened) and a nesting site for least terns, which scour shallow nests in the sand. In the overwash zone extending toward the marsh, a rare plant is present, the sea-beach knotweed (*Polygonum glaucum*). The marsh is also one of few Chesapeake Bay nesting sites for northern harriers (*Circus cyaneus*), hawks that commonly nest in more northern areas (VA DCR, 1999). As long as the shore is able to migrate, these habitats will remain intact; but eventually, overwash and inundation of the marsh could reduce the sea-beach knotweed and the northeastern beach tiger beetle population, as well as the nesting area for least terns and northern harriers (Shellenbarger Jones and Bosch, 2008a).

F.1.3 The Potomac River

Elevations

Virginia Side. The available topographic data do not allow a meaningful estimate of the land within 1 meter above the tides; but it does suggest that the counties along the Potomac River have between 24 and 53 square kilometers of dry land (and between 4 and

8 square kilometers of nontidal wetlands) below 2 meters (Table F.3). Although Westmoreland and King George County have the greatest amount of low land (a combined area of between 14 and 33 square kilometers below 2 meters), the low areas are well distributed, as shown in Figure F.6. Many coastal homes are along bluffs, some of which are eroding.

The most low-lying community on the Virginia side of the Potomac River is Lewisetta in Northumberland County. Lewisetta appears to be the only community along the Potomac River vulnerable to tidal inundation with a 50–100 cm rise in sea level. Water in some ditches rises and falls with the tides, and some areas drain through tide gates. With a fairly modest rise in sea level, wetlands may begin to take over portions of people's yards, the tide gates will close more often, and flooding will be more frequent. Somewhat higher, Old Town Alexandria and Belle Haven (Fairfax County) both flood occasionally from high levels in the Potomac River. But outside a small number of communities, shore erosion–not inundation–will almost certainly be the primary factor forcing people to choose between shore protection and land loss.

Table F.3 Low and high estimates for the area of dry and wet land close to sea level, Potomac River (square kilometers).

		Tidal	**50 cm**		**1 meter**		**2 meters**		**3 meters**		**5 meters**	
			Low	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Locality	**State**	Cumulative (total) amount of Dry Land below a given elevation										
Westmoreland	VA		0.0	4.7	2.4	9.3	9.0	21.2	15.5	53.0	69.2	112.3
King George	VA		0.0	2.7	1.5	5.4	5.2	11.4	9.0	21.9	27.3	42.8
Stafford	VA		0.0	1.4	0.8	2.7	2.7	5.4	4.6	8.1	9.5	13.5
Prince William	VA		0.0	1.0	0.5	2.0	1.9	3.9	3.3	5.5	6.4	8.8
Fairfax	VA		0.0	2.0	1.1	3.9	3.8	7.6	6.6	10.7	12.4	18.1
Alexandria	VA		0.0	0.4	0.3	0.9	0.9	1.7	1.5	2.5	2.9	4.0
Arlington	VA		0.0	0.2	0.1	0.5	0.5	1.3	0.8	2.6	3.4	5.0
DC			1.6	3.0	2.8	4.4	5.5	7.4	8.9	11.1	15.9	17.7
Prince George’s	MD		0.1	1.1	0.5	2.2	1.6	4.0	3.2	5.4	6.6	9.9
Charles	MD		0.7	10.9	4.6	19.4	14.1	38.4	28.3	64.0	74.2	96.0
St. Mary’s	MD		1.6	12.0	5.6	19.8	14.9	39.2	27.9	70.1	81.2	99.8
Total			**4.1**	**39.5**	**20.1**	**70.4**	**60.0**	**141.5**	**109.5**	**255.1**	**308.9**	**428.1**
		Cumulative (total) amount of wetlands below a given elevation										
Westmoreland	VA	14.4	0.0	0.5	0.3	1.0	1.0	2.2	1.7	5.6	7.3	12.0
King George	VA	13.5	0.0	0.5	0.3	1.0	1.0	2.0	1.7	2.8	3.3	4.6
Stafford	VA	6.8	0.0	0.5	0.3	1.0	1.0	1.9	1.7	2.6	3.0	3.9
Prince William	VA	5.1	0.0	0.2	0.1	0.3	0.3	0.6	0.5	0.7	0.8	0.9
Fairfax	VA	4.9	0.0	0.2	0.1	0.4	0.4	0.7	0.6	0.9	1.1	1.4
Alexandria	VA	0.2	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Arlington	VA	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DC		0.5	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.2	0.3	0.3
Prince George’s	MD	1.6	0.0	0.3	0.1	0.5	0.4	0.8	0.7	0.9	1.2	2.1
Charles	MD	22.9	0.1	3.6	1.4	6.2	4.6	11.3	9.0	15.9	17.8	22.2
St. Mary’s	MD	11.7	0.3	1.8	0.8	3.3	2.4	7.1	4.9	12.9	15.4	22.5
Total		**81.5**	**0.5**	**7.6**	**3.5**	**13.9**	**11.1**	**26.8**	**21.0**	**42.7**	**50.1**	**70.1**
Dry and Nontidal wetland			5	47	24	84	71	168	130	298	359	498
All Land		82	86	129	105	166	153	250	212	379	441	580

Source: Titus and Cacela, 2008. Uncertainty Ranges Associated with EPA’s Estimates of the Area of Land Close to Sea Level. Section 1.3 in: Background Documents Supporting Climate Change Science Program Synthesis and Assessment Product 4.1: Coastal Elevations and Sensitivity to Sea-level Rise, J.G. Titus and E. Strange (eds.). EPA 430R07004. U.S. EPA, Washington, DC. The low and high estimates are based on the on the contour interval and/or stated root mean square error (RMSE) of the data used to calculate elevations. For further details, see Chapter 1.

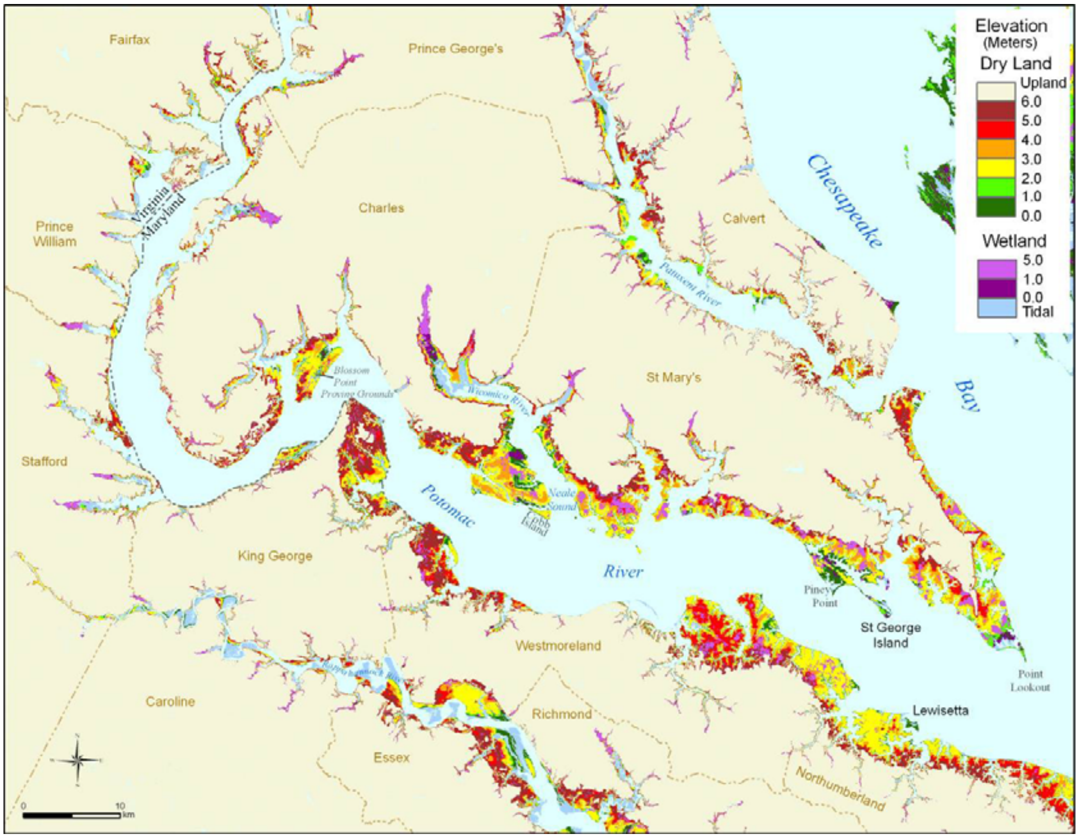

Figure F.6 Lower Potomac. Elevations relative to spring high water.

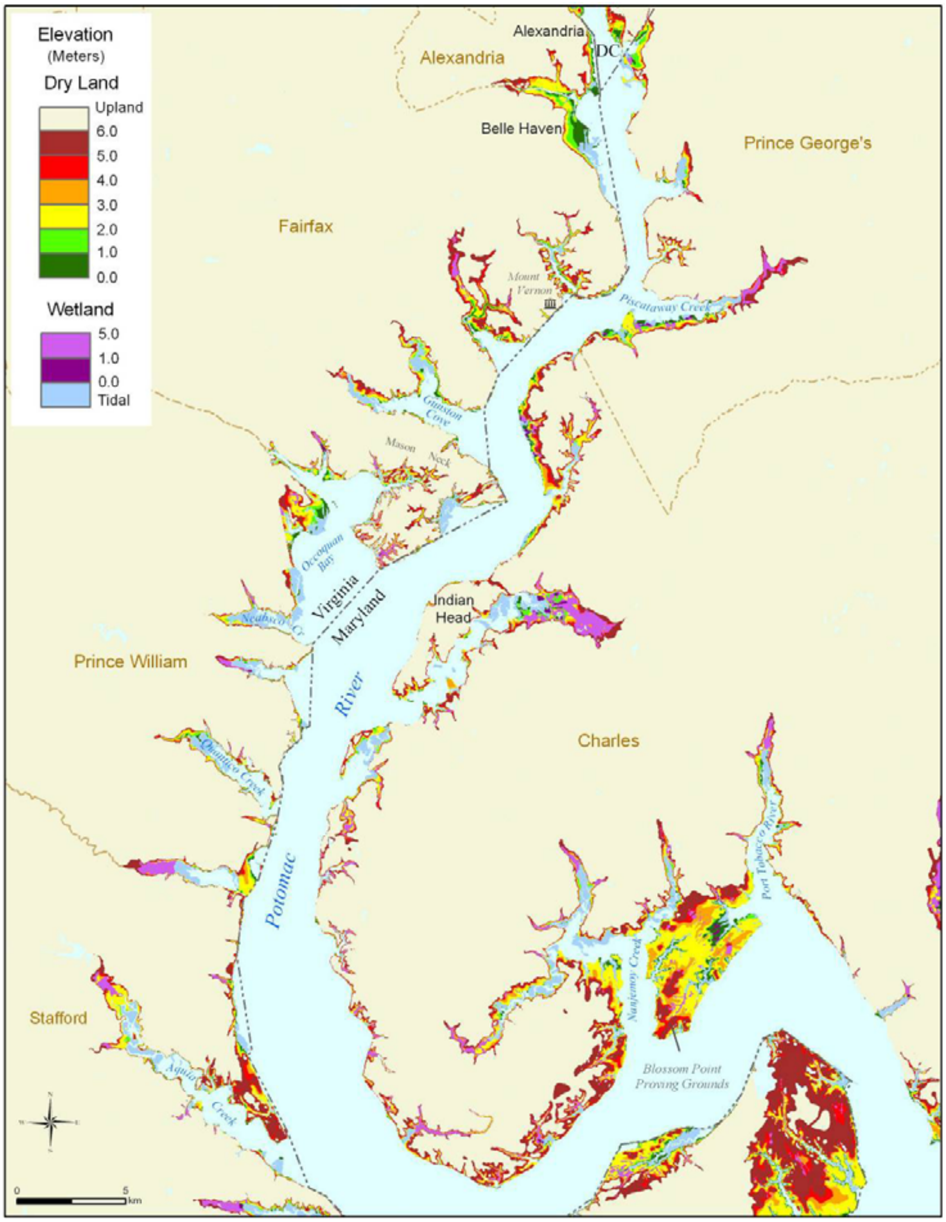

Figure F. 7 Upper Tidal Potomac. Elevations relative to spring high water.

Maryland Side. Over the last several years, the Maryland Department of Natural Resources and other state agencies have collected LIDAR data for most of the state. In the near future it will be possible to provide a very precise estimate of the amount of land close to sea level along the Maryland side of the Potomac River. Although such an estimate was not available as this report was written, a rough estimate of the land within 1 meter above the tides is possible because the DNR provided EPA with spot elevation data. Table F.3 suggests that the Maryland side of the Potomac River has between 11 and 41 square kilometers of dry land and between 2 and 10 square kilometers of nontidal wetlands within 1 meter above spring high water. As Figure F.6 shows, the land within about 1 meter above the tides is concentrated around St. George Island and Piney Point in St. Mary's County, and along the Wicomico River and along Neal Sound opposite Cobb Island in Charles County. Substantial areas are within three meters of spring high water, including the southern 5 to 6 kilometers of St. Mary's County, almost all of Cobb and St. George Islands, and most of Blossom Point Proving Grounds. Relatively steep bluffs, however, are also common. Comparing the area of land close to sea level on the Maryland side to the 1300 km of shoreline along the River and its tributaries, the one-meter contour is, on average, less than 20 meters inland of the shore[117]. The inundation of low-lying lands is very unlikely to be a serious problem along the Maryland side of the Potomac River if sea level rises one meter.

Vulnerable Habitat

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[117] The total shoreline length of the Potomac and its tributaries is approximately 1300 km and 29 square kilometers are within one meter of the tides (Jones and Wang 2008).

The Lower Potomac River includes a diverse mix of land uses and habitat types. The implications of sea-level rise vary from one place to the next, depending on the land use, habitat type, and current or anticipated shoreline protection measures. The following description highlights key resources and impacts, but broad characterization of environmental implications is difficult and subject to exceptions.

Freshwater tidal marshes in the Lower Potomac are found in the upper reaches of tidal tributaries. For example, freshwater tidal marshes in the Caledon Natural Area and Chotank Preserve (in Virginia) provide habitat for catfish, perch, sunfish, and carp, and support numerous turtles, including the red-eared palm slider, its close relative the yellow-belly palm slider, painted turtles, and snapping turtles. Green heron and great blue heron feed on fish and invertebrates in the marshes. Local ponds attract numerous waterfowl, including Canada geese, tundra swan, and many duck species. Other major freshwater marshes are found on Virginia’s Crow’s Nest Peninsula and in Maryland’s Zekiah Swamp Environmental Area. In general, freshwater tidal marshes in the Lower Potomac are keeping pace with sea-level rise through sediment and peat accumulation, and are expected to continue to do so, even under higher sea-level rise scenarios (Reed *et al.*, 2008).

Brackish tidal marshes are a major feature of the downstream portions of the region’s rivers. For instance, major brackish marshes are found throughout Maryland’s Nanjemoy Peninsula. In general, these marshes are keeping pace with sea-level rise today, but are considered marginal under moderate sea-level rise rate increases and are likely to be lost if sea level accelerates by 2 mm/yr or more (Reed *et al.*, 2008). Loss of brackish tidal marshes would eliminate nesting, foraging, roosting, and stopover areas for migrating birds. Significant concentrations of migrating waterfowl forage and overwinter in these marshes in fall and winter. Rails, coots, and migrant shorebirds are transient species that feed on fish and invertebrates in and around the marshes and tidal creeks. The rich food resources of the tidal marshes also support rare bird species such as bald eagle and northern harrier (White, 1989). Fish species common in the brackish waters of the region include resident marsh species such as killifishes, anchovies, silversides, blennies, gobies, and hogchoker. Striped bass and white perch move in and out of marshes year-round. Anadromous fishes, including herrings and shad, as well as marine transients such as Atlantic menhaden and drum species, are present in late spring and early fall (White, 1989).

Unnourished *beaches and tidal flats* of the Lower Potomac are likely to erode as sea levels rise. Impacts on beaches are highly dependent on the nature of shoreline protection measures selected for a specific area. For example, at the mouth of the Wicomico River in Maryland are the developed areas of Wicomico Beach and Cobb Island. Assuming that the shores of Cobb Island continue to be protected, sea-level rise is likely to eliminate most of the island’s remaining beaches and tidal flats. Likewise, at the mouth of Aquia Creek, north of Virginia’s Crow’s Nest Peninsula, shoreline protection could eliminate the beaches. The remainder of the county shoreline north of Aquia Creek is also primarily sandy beach; without nourishment, these beaches are likely to be eliminated in areas where armoring restricts shoreline retreat. Beach habitats often contain a high diversity and abundance of species ranging from microscopic organisms to filter-feeding bivalves and deposit-feeders such as fiddler crabs and mud snails. In turn, numerous predators feed on these invertebrates, including predatory snails (such as the oyster drill), blue crab, and a variety of fishes and birds[118].

Finally, where the *cliffs and bluffs* along the Lower Potomac are not protected (*e.g.*, Westmoreland State Park, Caledon Natural Area), natural erosional processes will generally continue, helping to maintain the beaches below.

Above Indian Head, the Potomac River is fresh. Tidal wetlands are generally expected to keep pace with rising sea level in these areas (see Chapter 3). Nevertheless, the Dyke Marsh Preserve faces an uncertain future. Its freshwater tidal marsh is one of the last major remnants of the original freshwater tidal marshes of the Upper Potomac River (Johnston, 2000, p. 242). The marsh proper is dominated by common freshwater tidal marsh plants, and an adjacent embayment contains one of the largest mudflats along the Upper Potomac (Johnston, 2000, p. 228). A recent survey found 62 species of fish, nine species of amphibians, seven species of turtles, two species of lizards, three species of snakes, 34 species of mammals, and 76 species of birds in Dyke Marsh (Engelhardt *et al.*, 2005, p 4). The rare least bittern and the federally listed bald eagle breed in the marsh; it also hosts the only known breeding population of marsh wrens in the upper tidal Potomac (Johnston, 2000, p 248). Many of the fish species present (*e.g.*, striped bass, American shad, yellow perch, blueback herring) are important for commercial and recreational

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[118] For general information on the fauna of soft-sediment habitats see Chapter 6 in Bertness, 1999.

fisheries in the area (Mangold, 2004). A recent analysis of conditions at Dyke Marsh Preserve concluded that further study of the marsh's response to sea-level rise is needed to predict impacts and formulate restoration plans (Engelhardt *et al.*, 2005, p. 7).

Parklands on the Mason Neck Peninsula will be managed for conservation, but shoreline protection on adjacent lands may result in marsh loss and reduced abundance of key bird species. For instance, the Mason Neck National Wildlife Refuge hosts seven nesting bald eagle pairs and up to 100 bald eagles during winter. The refuge also has one of the largest great blue heron colonies in Virginia and provides nesting areas for hawks and waterfowl, as well as a stopover for migratory birds. Many of the resident and migratory birds are of high conservation priority. Studies in marshes of Virginia's Eastern Shore have found a direct relationship between marsh area and the abundance of bird species in the marsh (Watts, 1993).

Apart from conservation lands, much of the Upper Potomac shorefront is either beach and mudflat or is heavily developed. On the Virginia side, much of the Prince William County shoreline is developed with sandy beach (NOAA, 2005). On the Maryland side the beach at the Indian Head Naval Surface Warfare Center is likely to erode without nourishment, although plans are unclear. In developed parts of Maryland and D.C., narrow shoreline areas are likely to erode in front of hard structures.

F.1.4 Washington, D.C.

Elevations

As Figure F.11 shows, the Potomac River originally covered the area occupied today by East Potomac Park, Hains Point, Washington Channel, the Tidal Basin, and the Reflecting Pool. The plan was to put the president's residence just northeast of the mouth of Tiber Creek, which was near what is now 17th and Constitution; thus the White House grounds originally had a tidal shoreline (Figure F.8). To improve navigation between Georgetown and Bladensburg, George Washington and Pierre L'Enfant envisioned what became the Washington City Canal from Tiber Creek to the approximate vicinity of what later became the Washington Navy Yard. The canal eventually ran east from the Potomac River along what is now Constitution Avenue, with a lock at 6th Street, and a connection to James Creek, which flowed into the Anacostia[119].

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[119] For a brief history of the canal, see e.g. the web page for the Washington Canal Park: http://www.washingtoncanalpark.org/history.html (cited July 22, 2005).

Figure F.8 During the Presidency of John Tyler, the White House had waterfront property. Source: White House Historical Association (permission pending)

The White House and especially the Capitol were built on high ground immune from flooding, but much of the land between the two was quite low (Figures F.9 and F.10).

During the following decades, soil erosion from upstream farming led to the creation of wide mudflats below Georgetown. A large dredge-and-fill operation later excavated Washington Channel from the mudflats, and the extra material was used to create the shores of the Tidal Basin and the dry land on which the Lincoln Memorial, Jefferson Memorial, East Potomac Park, and Hains Point sit today (Bryan, 1914). These areas were bulkheaded from the start, because it was most efficient to construct a retaining wall and place material on one side of the wall. The canals were filled and replaced with drain pipes (see e.g. Farquhar, 2000).

Figure F.9 View of the City of Washington from Across the Anacostia River. The White House and Capitol are on high ground. The Potomac River is in the rear ground on left and right sides. Source: Library of Congress, "View of the City of Washington...from Arlington House..." Black and white lithograph by Fitz Hugh Lane after P. Anderson. Published by T. Moore's Lithography, Boston. Copyrighted 1838 by P. Anderson.

Figure F.10 City of Washington from Arlington House, looking east. A canal runs along the north side of the mall, which is very low-lying. The Potomac River occupies what later became Washington Channel, the Tidal Basin, and East Potomac Park. Source: Library of Congress, "City of Washington From beyond the Navy Yard." Color aquatint by William James Bennett after George Cooke. Published 1834 by Lewis P. Clover of New York.

Figure F.12 shows lands close to sea level, based largely on topographic information provided by the District of Columbia. Within the downtown area, most of the lowest land is the area filled during the 1870s, such as Hains Point and the location of the former Tiber and James Creeks, as well as the Washington City Canal that joined them. The largest low area is the former Naval Air Station, now part of Bolling AFB, just south of the mouth of the Anacostia River. A dike protects this area. Most of the low land between I-295 and the Anacostia River was open water when the District of Columbia was originally planned (compare Figures F.11 and F.12). The District of Columbia has between 2.8 and 4.1 square kilometers of land below 1 meter, an area roughly half the size of Rock Creek Park (NPS, 2008).

Vulnerable Habitat

The Upper Potomac River features a variety of sensitive wetland habitats potentially vulnerable to sea-level rise. Several major areas are managed for conservation or are the target of restoration efforts, making ultimate impacts uncertain.

The wetlands around the Anacostia River are an example. Local organizations have been working to reverse historical modifications and restore some of the wetlands around several heavily altered lakes. Restoration of the 32-acre Kenilworth Marsh was completed in 1993; restoration of the Kingman Lake marshes began in 2000 (USGS, date unknown). Other efforts to restore the river include conversion of some seawalls and bulkheads to woodland buffers. Given the planned buffers, marshes would be allowed to migrate in parts of Kingman Island; but shoreline armoring would also be required to protect the golf course. Monitoring of the restored habitats demonstrates that these marshes can be very productive. A recent survey identified 177 bird species in the marshes, including shorebirds, gulls, terns, passerines, and raptors as well as marsh nesting species such as marsh wren and swamp sparrow (Paul *et al.*, 2004, p. 11).

Roosevelt Island is another area where sea-level rise effects are uncertain. Fish in the Roosevelt Island marsh provide food for herons, egrets, and other marsh birds (NPS, not dated). The ability of the tidal marshes of the island to keep pace with sea-level rise will depend on the supply of sediment, and increased inundation of the swamp forest could result in crown dieback and tree mortality (Lippson and Lippson, 2006, p 218).

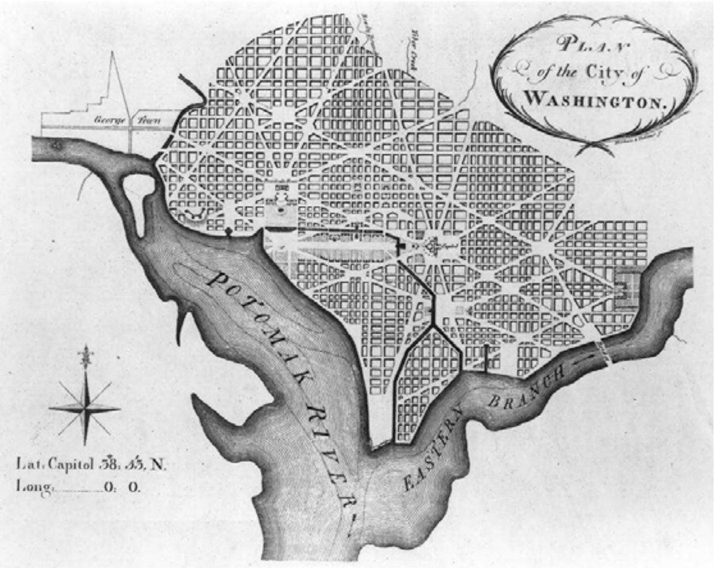

Figure F.11 L'Enfant's Plan for the City of Washington.
Source: Library of Congress.

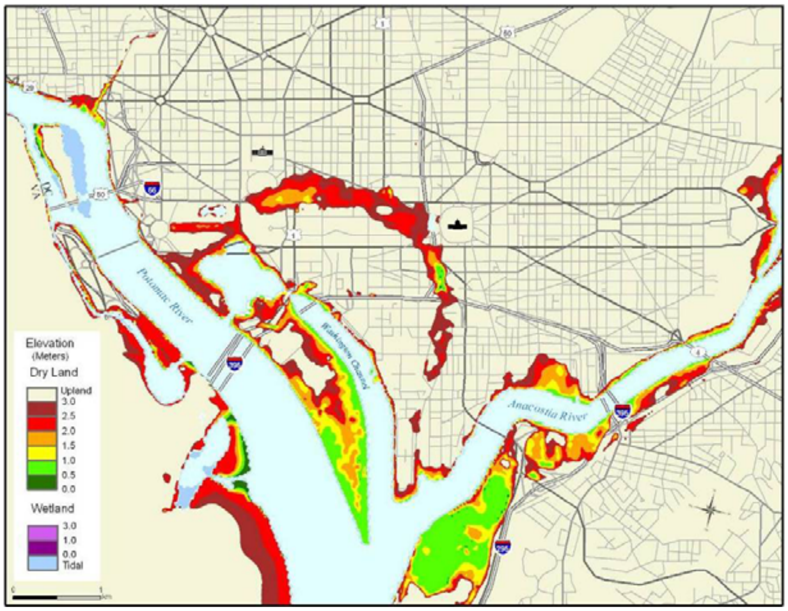

Figure F.12 Elevations of lands close to sea level in Washington, D.C.

F.1.5 Western Shore: Potomac River to Susquehanna River

Elevations

The Western Shore counties have relatively little low land, unlike the low counties across the Bay. As Figure F.13 shows, the Deal/Shady Side peninsula (Anne Arundel) and Aberdeen Proving Grounds (Harford) are the only areas with substantial amounts of land within 1 to 2 meters above spring high water. The block closest to the water, however, is similarly low in many of the older communities, including parts of Baltimore, downtown Annapolis, North Beach, and Chesapeake Beach.

Table F.4 suggests that the Maryland localities along the Western Shore (including the Patuxent River) have between 28 and 73 square kilometers of dry land within 1 meter above the tides. Most the low land is in Harford, Anne Arundel, and Baltimore Counties (all of whose planning departments provided EPA with local elevation data)[120]. Hurricane Isabel flooded many areas between 1 and 3 meters above spring high water, including downtown Annapolis, North Beach, Chesapeake Beach, and Fells Point. (See box: Baltimore)

Between the Potomac and the Patuxent Rivers, the bay shore is usually a sandy beach in front of a bank less than three meters high. Cliffs and bluffs up to 35 meters above the water dominate the shores of Calvert County. The shores north of Calvert County tend to be beaches — but these beaches become narrower as one proceeds north, where the wave climate is milder.

Vulnerable Habitat

A range of sea-level rise impacts are possible along the western shore of Chesapeake Bay, including potential loss of key habitats. First, partial or complete marsh loss is expected in many areas. Along the bay shorelines, marshes are expected to be marginal with mid-range increases in sea-level rise, and to be lost with high-range increases in sea-level rise. The ability to migrate is likely to determine coastal marsh survival as well as the survival of the crustaceans, mollusks, turtles, and birds that depend on the marshes. In upper reaches of tributaries, however, marsh accretion should be sufficient to counter sea-level rise (Reed *et al.*, 2008). Several key locations warrant attention:

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[120] The Harford data, however, did not include the Aberdeen Proving Grounds.

- In the upper Patuxent River, marsh areas have achieved minimal migration despite inundation. In the Jug Bay Sanctuary, marsh inundation is causing vegetation changes, compounding stress on local bird species (Shellenbarger Jones and Bosch, 2008b).
- Cove Point Marsh in Calvert County is a 150-acre freshwater, barrier-beach marsh. Numerous state-defined rare plant species are present, including American frog's-bit (*Limnobium spongia*), silver plumegrass (*Erianthus alopecuroides*), various ferns, and unique wetland communities (Steury, 2002, p 16 and 21), as well as populations of the Northeastern beach tiger beetle, the Puritan tiger beetle (both federally listed as threatened), and the rare leaf beetle *Glyptina maritima*. The marsh is continuing to migrate, but will soon hit the northern edge of local residential development.
- Saltwater intrusions may shift the fauna dependent on nontidal wetlands in Shady Side, particularly freshwater fish.
- The potential loss of the wide mudflats at Hart-Miller Island would eliminate major foraging and nesting areas for sandpipers, plovers, and terns, as well as several high conservation priority species such as the swamp sparrow (*Melospiza georgiana*), spotted sandpiper (*Actitis macularia*), and willow flycatcher (*Empidonax traillii*).
- Given the extent of development and shoreline armoring in Anne Arundel and Baltimore City/County, both intertidal areas and wetlands are likely to be lost with even a modest acceleration in sea level rise.

Beach loss, particularly in St. Mary's, Calvert, and Anne Arundel counties along Chesapeake Bay, may occur in areas without nourishment. The widespread presence of shoreline protection can interfere with longshore transport and prevent inland retreat of beach areas. In general, beach loss will lead to habitat loss for resident insects (including the Northeastern beach tiger beetle, federally listed as threatened) and other invertebrates, as well as forage loss for larger predators such as shorebirds (Lippson and Lippson, 2006)[121].

The Calvert County cliffs represent unique habitat that could be degraded by sea-level rise; however, the cliffs are not likely to be lost entirely. The Puritan tiger beetle and Northeastern beach tiger beetle, both federally listed, are present in the area. In particular, the Puritan tiger beetle depends on natural, moderate cliff erosion for habitat, both as larvae and as adults. While natural erosion processes are allowed to continue in the protected cliff areas in the southern portion of the county, shoreline protections in the more northern developed areas are increasing erosion rates (Wilcock *et al.*, 1998). If erosion occurs at rates high enough to shear off areas to a depth below larvae burrows, Puritan tiger beetles could be eliminated. In addition, in the northern areas where the cliffs are stabilized, the rocky and sandy toes to the cliffs will be lost to inundation, along with the invertebrate community (*e.g.*, burrowing amphipods and hermit crabs) that resides there.

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[121] For more detail on beach habitats and the species that occur in the mid-Atlantic region, see Shellenbarger Jones, 2008.

Other effects on nearshore communities may be observed. In the upper Patuxent River, the spread of SAV more tolerant of deeper depths and higher turbidity (*e.g.*, *Hydrilla*) may be accompanied by a decrease in larger fish, though its spread may be tempered by changes in salinity (Shellenbarger Jones, 2008).

F.1.6 Eastern Shore: Susquehanna River to Choptank River

Elevations

One hundred years ago, residents of the Baltimore-Washington-Annapolis area who wanted to go to the beach did not usually travel to Ocean City or Rehoboth on weekends. They went to bay beaches such as Bay Ridge (AAC, 2007) and resorts on the Eastern Shore such as Betterton Beach and Tolchester.

As Figure F.13 shows, the Eastern Shore above Rock Hall is dominated by bluffs and steep slopes rising to above 6 meters. Tolchester Beach, Betterton Beach, (Figures F.14 to F.16) and Crystal Beach (Figure 4.9, Chapter 4) are typical in that regard. From Rock Hall south to around the middle of Kent Island, all of the land within a few kilometers of the Chesapeake Bay or its major tributaries is within 6 meters above spring high water; with some areas less than 3 meters above the tides. Between Kent Island and the Choptank River, large areas are less than 3 meters above the tides.

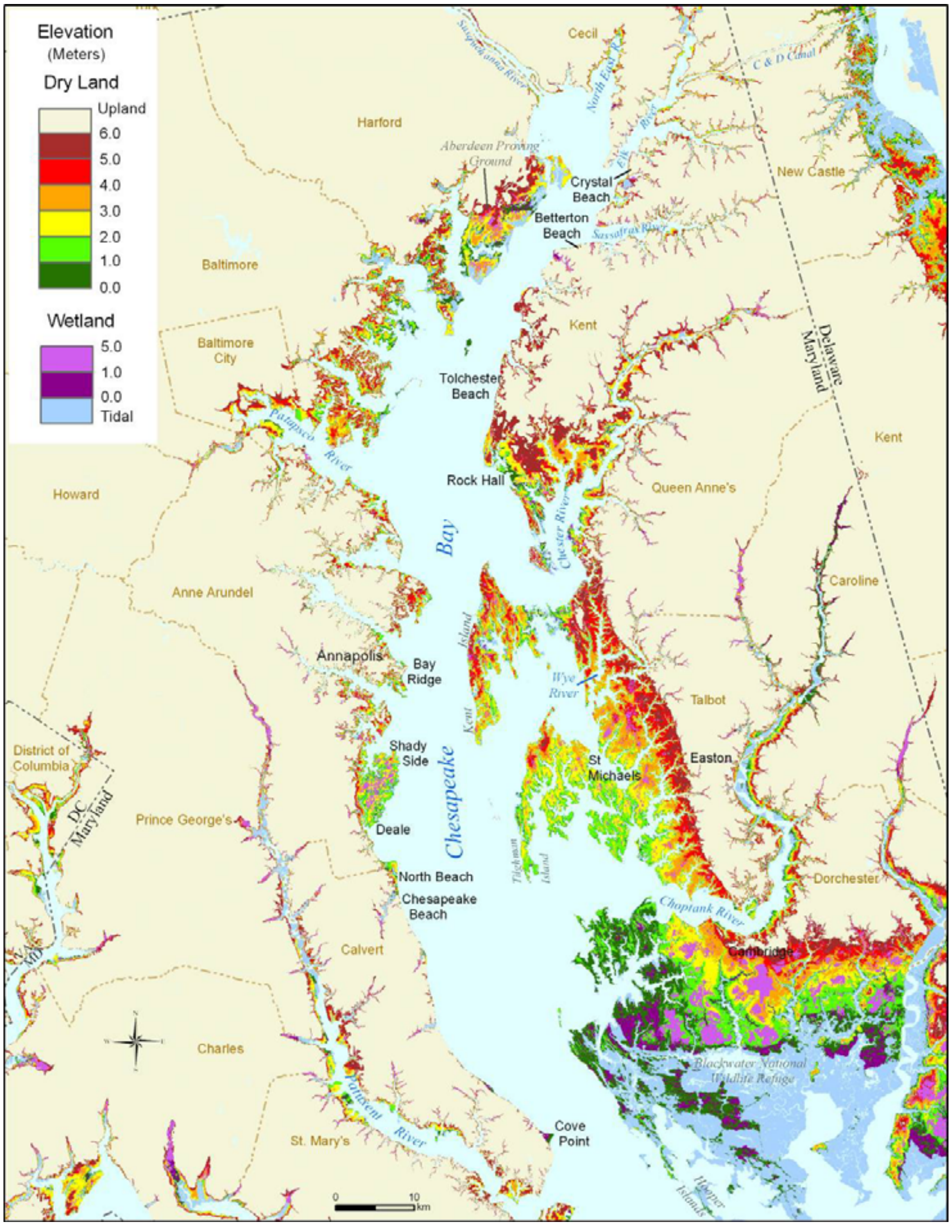


Figure F.13 Upper Chesapeake Bay. Elevations relative to spring high water.

Table F.4 Low and high estimates for the area of dry and wet land close to sea level, Chesapeake Bay, Maryland Western Shore (square kilometers).

	Tidal	**50 cm**		**1 meter**		**2 meters**		**3 meters**		**5 meters**	
		Low	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Locality	Cumulative (total) amount of Dry Land below a given elevation										
Prince George's		0.0	1.1	0.4	1.7	1.3	3.2	2.3	5.3	6.5	10.8
Charles		0.0	0.7	0.3	1.2	0.9	2.0	1.7	2.5	2.7	3.3
St. Mary's		0.8	3.8	2.5	8.0	8.8	18.8	18.2	30.6	38.5	48.4
Calvert		0.4	3.9	1.7	5.8	4.6	10.1	7.6	17.3	21.2	35.7
Anne Arundel		1.7	7.2	6.7	14.6	20.2	38.7	43.5	59.1	80.5	94.3
Howard		0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.2	0.3
Baltimore City		0.2	2.1	0.9	3.9	2.7	7.5	5.7	11.9	14.1	21.0
Baltimore		2.3	6.6	7.3	13.0	20.8	27.0	37.0	45.8	74.5	80.7
Harford		0.7	17.3	7.6	25.1	21.7	40.3	34.2	57.1	65.5	78.2
Total		**6.1**	**42.7**	**27.5**	**73.4**	**81.1**	**147.8**	**150.3**	**229.7**	**303.7**	**372.7**
	Cumulative (total) amount of wetlands below a given elevation										
Prince George's	12.3	0.0	0.5	0.2	0.9	0.7	1.8	1.3	2.9	3.5	5.1
Charles	1.3	0.0	0.2	0.1	0.2	0.2	0.4	0.3	0.4	0.5	0.6
St. Mary's	7.0	0.3	1.0	0.8	2.0	2.2	3.9	3.9	5.9	7.5	8.8
Calvert	14.6	0.1	0.9	0.4	1.3	1.1	2.2	1.7	3.8	4.7	7.5
Anne Arundel	12.1	0.2	0.7	0.6	1.6	3.1	8.1	9.5	12.4	15.3	17.1
Howard	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.1	0.1
Baltimore City	0.2	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.1	0.1
Baltimore	10.5	0.1	0.3	0.3	0.7	1.0	1.3	1.5	1.7	2.2	2.3
Harford	29.4	0.2	2.5	1.2	3.8	3.3	6.2	5.2	9.0	10.2	12.0
Total	**87.3**	**0.8**	**6.2**	**3.7**	**10.5**	**11.6**	**24.0**	**23.5**	**36.4**	**43.9**	**53.6**
Dry and Nontidal wetland		7	49	31	84	93	172	174	266	348	426
All Land	87	94	136	119	171	180	259	261	353	435	514
Source: Titus and Cacela, 2008. Uncertainty Ranges Associated with EPA's Estimates of the Area of Land Close to Sea Level. Section 1.3 in: Background Documents Supporting Climate Change Science Program Synthesis and Assessment Product 4.1: Coastal Elevations and Sensitivity to Sea-level Rise, J.G. Titus and E. Strange (eds.). EPA 430R07004. U.S. EPA, Washington, DC. The low and high estimates are based on the on the contour interval and/or stated root mean square error (RMSE) of the data used to calculate elevations. For more details, see Chapter 1.											

Vulnerable Habitat

Above Kent Island. The environmental implications of sea-level rise effects in the upper Chesapeake Bay are likely to be relatively limited. The Susquehanna River provides a large (though variable) influx of sediment to upper Chesapeake Bay, as well as almost half of Chesapeake Bay's freshwater input (CBP, not dated). This sediment generally is retained above the Chesapeake Bay Bridge and provides material for accretion in the tidal wetlands of the region (CBP, 2002). The other Upper Chesapeake Bay tributaries characteristically have large sediment loads as well, and currently receive sufficient sediment to maintain wetlands and their ecological function. As such, Upper Chesapeake Bay will continue to provide spawning and nursery habitat for crabs and fish, as well as nesting and foraging habitat for migratory and residential birds, including bald eagles and large numbers of waterfowl. Likewise, while some of the beaches may require nourishment for retention, the general lack of shoreline protections will minimize interferences with longshore sediment transport. Hence, beaches are likely to remain intact throughout much of the region.

Two areas in the Upper Bay — Eastern Neck and Elk Neck — appear most vulnerable to sea-level rise effects. First, Eastern Neck Wildlife Refuge lies at the southern tip of Maryland’s Kent County. Ongoing shoreline protection efforts seek to reduce erosion of habitats supporting many migratory waterfowl and residential birds, as well as turtles, invertebrates, and the Delmarva fox squirrel (*Sciurus niger cinereus*), federally listed as endangered. In many marsh locations, stands of invasive *Phragmites australis* are the only areas retaining sediment (Shellenbarger Jones and Bosch, 2008c). Local managers have observed *P. australis* migrating upland into forested areas as inundation at marsh edges increases, although widespread marsh migration of other species has not been observed (Shellenbarger Jones and Bosch, 2008c). The three-square bulrush marshes (*Scirpus americanus*) on Eastern Neck have been largely inundated, as have the black needle rush marshes (*Juncus roemerianus*) on Smith Island and other locations, likely causes of reductions in black duck counts (Shellenbarger Jones and Bosch, 2008c).

Likewise, loss of upland to open water is decreasing habitat for bald eagle and the Delmarva fox squirrel.

Other sea-level rise impacts are possible in Cecil County, in and around the Northeast and Elk Rivers. The headwaters of the rivers are tidal freshwater wetlands and tidal flats, spawning and nursery areas for striped bass and a nursery area for alewife (*Alosa pseudoharengus*), blueback herring (*Alosa aestivalis*), hickory shad (*Alosa mediocris*) and white perch, as well as a wintering and breeding area for waterfowl (USFWS, 1980). Accretion is expected to be sufficient in some areas due to the large sediment inputs in the Upper Bay. However, significant armoring in the developed headwaters could interfere with sediment transport. Where accretion rates are not sufficient, wetland migration would be difficult due to the upland elevation adjacent to the shorelines. These conditions increase the chances of large tidal fresh marsh losses.

Other sensitive Cecil County habitats exist. The cliffs at Elk Neck State Park and the Sassafras River Natural Resource Management Area will be left to erode naturally. The cliff swallows and Puritan tiger beetle (federally listed as threatened) will continue to use the unique habitat. Around Grove Point, Puritan tiger beetle populations may be impacted because shoreline stabilization may result in loss of beach areas.

Finally, marsh loss is possible in and around the Aberdeen Proving Ground in Harford County. The Proving Ground is primarily within 5 meters of sea level and contains a large concentration of tidal wetlands (20,000 acres). The prospects for future shore protection are poorly understood here, as well as along other secured installations along Chesapeake Bay and its tributaries. The wetlands may accrete sufficient sediment to meet moderate sea-level rise rates, but higher rates would result in loss of the tidal marshes and associated ecological functions. In particular, the large bird populations (*e.g.*, bald eagles, great blue herons, double-crested cormorants) that migrate through and nest in these marshes would be affected (MD DNR, not dated).

Kent Island to Choptank River. The central eastern shore region of Chesapeake Bay contains diverse habitats, and sea-level rise holds equally diverse implications, varying greatly between sub-regions. Large expanses of marsh and tidal flats are likely to be lost, affecting shellfish, fish, and waterfowl populations. Several subregions merit consideration:

- The Chester River forms the northern border of Queen Anne's County. Marshes along the river will be marginal with moderate sea-level rise rate increases, and topography will preclude migration in many areas (Reed *et al.*, 2008). Birds that breed or feed in the Chester River marshes (*e.g.*, Virginia rail, American black duck, great blue and green herons, osprey) will be negatively affected by the habitat and prey loss (Robbins and Blom, 1996).
- Large tidal flats exist at the mouth of the Chester River (Tiner, 1995). Unless sedimentation increases significantly tidal flats are likely to be inundated if sea-level rise accelerates. Loss of tidal flats may result in a decline in the resident invertebrates and fish that use the shallow waters as well as the birds that feed on the flats (*e.g.*, great blue and green herons) (Shellenbarger Jones and Bosch,

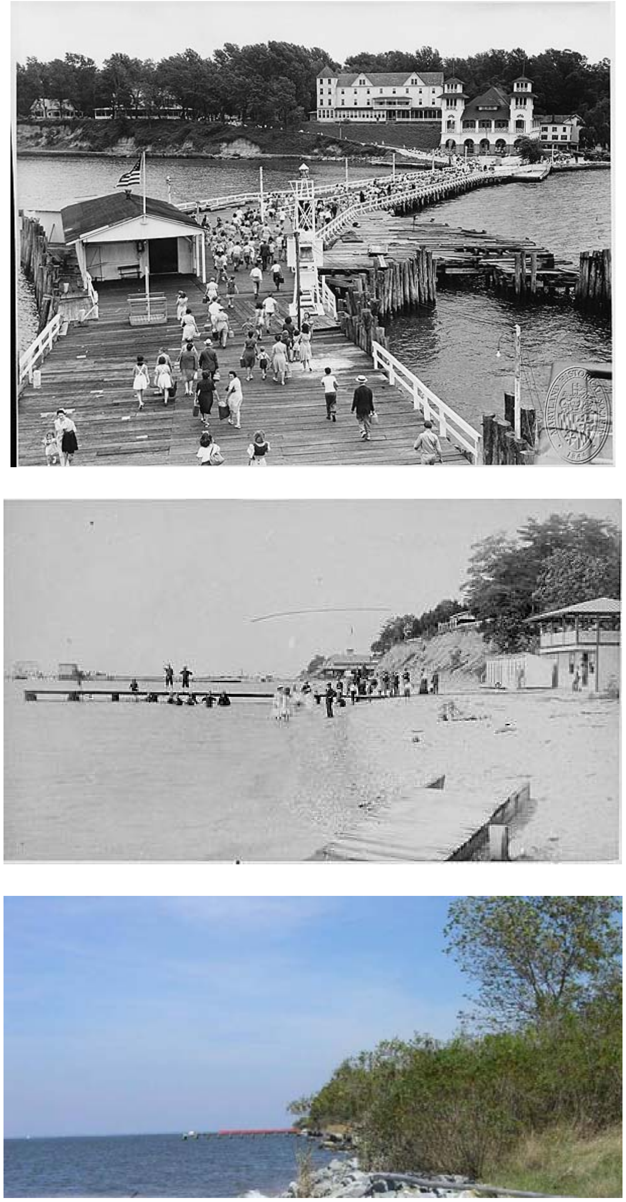
2008d; Robbins and Blom, 1996). Effects may extend to commercial and recreational fish species that spawn or feed in the area, including king and Spanish mackerel, cobia, red drum, flounder, and bluefish (NOAA, not dated).

- The Eastern Bay side of nearby Kent Island has several tidal creeks, extensive tidal flats, and wetlands. If shores are protected in this area, the marshes and tidal flats are likely to be lost (although some marsh may convert to tidal flat). Increasing water depths are likely to reduce — and eventually eliminate — the remaining SAV (largely a mix of *Ruppia maritima* and *Zannichellia palustris*); a landward migration onto existing flats and marshes will depend on sediment type and choice of shoreline structure (Shellenbarger Jones and Bosch, 2008). The loss of tidal wetlands and probable loss of SAV would cause losses to fish and birds (see Chester River discussion). Additionally, large shellfish beds in Eastern Bay may be affected by the habitat changes, with uncertain consequences.
- Portions of the Wye River shore are being developed. If these shores are protected and the marshes and tidal flats in these areas are lost, the juvenile fish nurseries will be affected and species that feed in the marshes and SAV (*e.g.*, wading birds, striped bass, blue gill, blue crabs, oysters, and soft-shell clams) will lose an important food source (MD DNR, 2004, p. 19).

Certain key marsh areas are likely to be retained. The upper reaches of tributaries, including the Chester and Choptank rivers, are likely to retain current marshes and the associated ecological services. Likewise, Poplar Island will provide a large, isolated marsh and tidal flat area. In addition, the marshes of the Wye Island Natural Resource

Management Area support a large waterfowl population, with a wintering waterfowl count of 20,000 birds such as mallard, canvasback, and ruddy ducks and Canada geese (MD DNR, 2004, p 18). Maryland DNR will manage Wye Island to protect its biological diversity and structural integrity, such that detrimental effects from sea-level rise acceleration are minimized (MD DNR, 2004, p 12).

Beach loss is also possible in some areas. The Chesapeake Bay shore of Kent Island historically had narrow sandy beaches with some pebbles along low bluffs, as well as some wider beaches and dune areas (*e.g.*, Terrapin Park). As development continues, however, privately owned shores are gradually being replaced with stone revetments. The beaches will be unable to migrate inland, leading to habitat loss for the various resident invertebrates, including tiger beetles, sand fleas, and numerous crab species. Shorebirds that rely on beaches for forage and nesting will face more limited resources (Lippson and Lippson, 2006). Likewise, on the bay side of Tilghman Island, the high erosion rates will tend to encourage shoreline protection measures, particularly following construction of waterfront homes (MDNR, date unknown). Beach loss, combined with anticipated marsh loss in the area, will eliminate the worms, snails, amphipods, sand fleas, and other invertebrates that live in the beach and intertidal areas and reduce forage for their predators (*e.g.*, oystercatchers, sandpipers, plovers, and glossy ibises).



Figures F.14 to F.16 Tolchester. 1883-2003. F.14 shows the Tolchester resort as seen from a steamship docked at the end of the peer. F.15 shows the beach looking north during 1883, before the steamship pier was constructed. F.16 shows the same beach today. Also, see Chapter 4,Figure 4.9 for a picture of bluffs overlooking Crystal Beach.

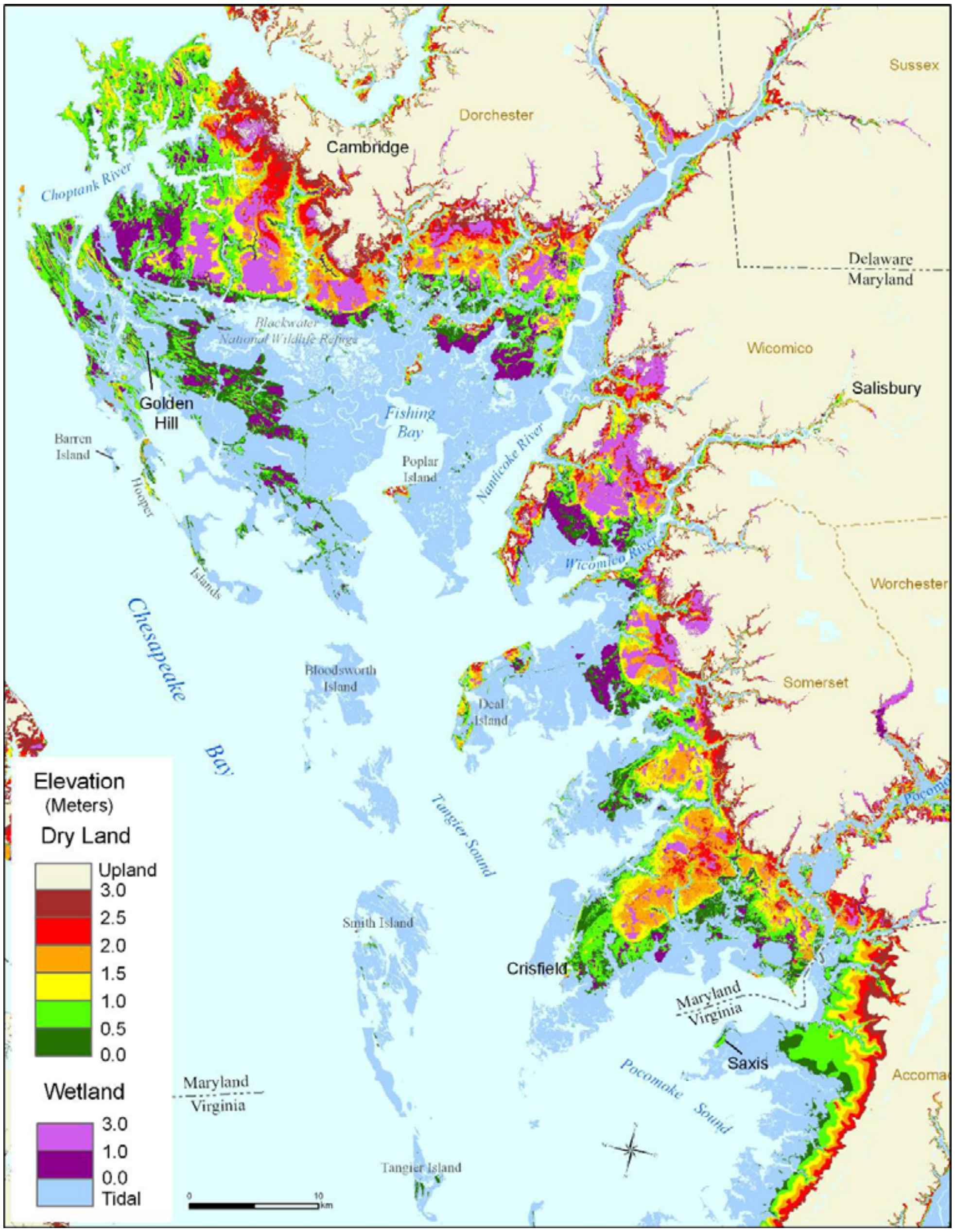


Figure F.17 Lower Eastern Shore: Lands close to sea level.

Table F.5 Low and high estimates for the area of dry and wet land close to sea level, Chesapeake Bay Eastern Shore (square kilometers).

		Tidal	**50 cm**		**1 meter**		**2 meters**		**3 meters**		**5 meters**	
			Low	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Locality	**State**	Cumulative (total) amount of Dry Land below a given elevation										
Cecil	MD		0.2	2.5	1.0	5.2	3.7	11.6	7.8	20.0	24.3	37.9
Kent	MD		0.2	8.4	4.8	15.9	16.3	32.9	28.8	56.1	71.4	105.2
Queen Anne's	MD		0.6	4.1	5.3	11.9	24.2	35.0	51.6	68.2	125.2	142.6
Caroline	MD		0.7	3.2	2.2	6.1	6.9	12.5	13.2	19.7	25.9	32.9
Talbot	MD		2.2	7.8	11.1	23.7	64.0	98.7	148.7	175.1	265.6	279.4
Sussex	DE		0.5	1.6	1.4	3.3	4.3	7.1	8.5	13.8	26.0	36.3
Dorchester	MD		30.1	120.0	150.4	214.9	281.9	312.9	358.4	386.2	461.6	474.0
Wicomico	MD		5.0	14.9	18.3	28.6	47.1	58.5	76.0	86.2	133.2	141.6
Somerset	MD		17.1	58.4	70.5	100.7	167.8	193.4	215.1	232.5	326.5	344.6
Worcester	MD		0.7	2.7	3.1	5.8	10.6	16.5	23.6	28.4	46.1	53.4
Accomack	VA		5.8	18.4	16.8	40.4	53.3	87.5	94.2	110.4	129.5	138.1
Northampton	VA		2.3	7.2	6.5	15.8	20.8	34.5	39.9	62.8	98.7	123.7
Total			**65.3**	**249.1**	**291.4**	**472.4**	**701.0**	**901.2**	**1065.8**	**1259.5**	**1734.0**	**1909.7**
		Cumulative (total) amount of wetlands below a given elevation										
Cecil	MD	12.6	0.0	0.2	0.0	0.7	0.4	1.7	1.2	2.8	3.5	5.5
Kent	MD	18.3	0.1	1.1	0.9	2.6	3.3	5.4	5.2	7.9	9.7	14.4
Queen Anne's	MD	21.4	0.2	1.1	1.5	3.0	4.9	6.5	7.9	9.6	14.6	17.9
Caroline	MD	14.4	0.3	1.4	0.7	2.6	2.5	5.3	4.4	7.5	8.0	11.7
Talbot	MD	26.1	0.1	0.3	0.5	1.0	2.5	4.2	6.8	8.5	17.9	19.6
Sussex	DE	6.7	0.6	1.8	1.6	2.7	3.1	4.4	4.8	6.4	10.1	13.1
Dorchester	MD	424.8	14.9	45.8	53.4	70.1	94.4	104.0	113.8	120.6	140.1	142.5
Wicomico	MD	67.0	5.4	9.9	10.7	13.5	24.2	29.2	37.0	44.4	67.0	70.2
Somerset	MD	265.4	6.6	15.7	17.3	21.3	34.8	39.8	45.1	51.5	80.6	90.1
Worcester	MD	23.7	0.3	0.9	1.0	1.6	2.7	4.0	6.3	8.8	18.2	20.8
Accomack	VA	156.4	5.3	16.7	15.3	34.6	44.8	71.8	76.5	88.2	103.2	111.1
Northampton	VA	25.5	0.1	0.4	0.4	1.2	1.9	3.7	4.2	6.2	8.8	10.1
Total		**1062.4**	**33.8**	**95.3**	**103.3**	**155.0**	**219.5**	**279.9**	**313.0**	**362.4**	**481.7**	**526.9**
Dry and Nontidal wetland			99	344	395	627	921	1181	1379	1622	2216	2437
All Land		1062	1162	1407	1457	1690	1983	2244	2441	2684	3278	3499

Source: Titus and Cacela, 2008. Uncertainty Ranges Associated with EPA's Estimates of the Area of Land Close to Sea Level. Section 1.3 in: Background Documents Supporting Climate Change Science Program Synthesis and Assessment Product 4.1: Coastal Elevations and Sensitivity to Sea-level Rise, J.G. Titus and E. Strange (eds.). EPA 430R07004. U.S. EPA, Washington, DC. The low and high estimates are based on the on the contour interval and/or stated root mean square error (RMSE) of the data used to calculate elevations. For more details, see Chapter 1.

F.1.7 The Lower Eastern Shore: Choptank River to Cape Charles

Between the Choptank River and Ocohannock Creek along the eastern shore of Chesapeake Bay lies the nation’s fifth largest concentration of land close to sea level (see Figure F.17). These four counties have approximately 256 to 385 square kilometers of dry land within 1 meter above the tides (see Table F.5). Water levels in roadside ditches rise and fall with the tides in the areas west of Golden Hill in Dorchester County and several necks in Somerset County. Many farms abut tidal wetlands, which are gradually encroaching onto those farms. Some landowners have responded by inserting makeshift tide gates over culverts, decreasing their own flooding but increasing it elsewhere. Throughout Hoopers Island, as well as the mainland nearby, one finds numerous abandoned driveways that once led to a home but are now ridges flooded at high tide, surrounded by low marsh or open water more recently abandoned homes surrounded by marsh, and dead trees still standing in areas where marsh has invaded a forest.

Elevations

Approximately halfway between Crisfield on the Eastern Shore and the mouth of the Potomac River on the Western Shore, are the last two inhabited islands in Chesapeake Bay unconnected by bridges to the mainland: Smith (Maryland) and Tangier (Virginia). Both islands are entirely below the USGS 5-foot contour.

Along the eastern shore of Northampton County, by contrast, elevations are higher, often with bluffs of a few meters. Nevertheless, several blocks of homes in the Town of Cape Charles are within 2 meters above spring high water.

Vulnerable Habitat

On the lower Eastern Shore of Chesapeake Bay in Maryland, habitats vulnerable to sea-level rise are diverse and include beaches, various types of tidal marsh, nontidal marshes, and upland pine forests.

Narrow sandy beaches exist along discrete segments of shoreline throughout the region, particularly in Somerset County. Given the gradual slope of the shoreline, these habitats could accommodate moderate sea-level rise by migrating upslope, assuming no armoring or other barriers exist. Many of the beaches provide critical nesting habitat for the diamondback terrapin (*Malaclemys terrapin*), and proximity of these nesting beaches to nearby marshes provides habitat for new hatchlings. Maryland lists the terrapin as a Species of Concern and it is protected across much of its geographic range (although it is commercially and recreationally harvested for food in Maryland). Because of increasing shoreline protection in areas to the north, the lower Eastern Shore region is responsible for supporting a growing portion of the diamondback terrapin population (Schweizer and Henry, 2004). Erosion control and shoreline stabilizing practices block access to the beach, forcing females to travel around the obstructions, or to deposit their eggs below the high tide line. Loss of prime nesting beaches remains a major threat to the diamondback terrapin population in Chesapeake Bay (see text box) (MD DTTF, 2001).

Of the 87,000 hectares of tidal marsh in the Chesapeake Bay, a majority is located in the three-county lower Eastern Shore region (Darmondy and Foss, 1979). The marshes are critical nursery grounds for commercially important fisheries (*e.g.*, crabs and rockfish); critical feeding grounds for migratory waterfowl; and home to furbearers (*e.g.*, muskrat and nutria). Tidal marshes will persist as sea level rises so long as they build vertically through accumulation of mineral and/or organic matter and as long as there are no shoreline barriers to migration[122]. The ability to build vertically in response to sea-level rise differs among the three tidal marsh types:

- Submerged Upland Tidal Marsh: Submerged upland tidal marsh is the predominant marsh type in the lower Eastern Shore region, with the majority located in Dorchester and Somerset counties (Darmondy and Foss, 1979). The drainage system in these marshes is poor, and limited tidal exchange and sediment influx means that vertical marsh development occurs primarily through the accumulation of plant organic matter. As a result, accretion rates in these marshes are typically less than the rate of sea-level rise (Stevenson and Kearney, 2001). In addition, studies in Blackwater NWR demonstrate that local land surface adjustments (*e.g.*, from groundwater withdrawal) can effectively increase sea-level rise, leading to more severe wetland loss (Stevenson *et al.*, 2001). The accretion deficits in these marshes lead not only to decreased marsh area and increased open water, but also to a change in the proportion of high and low marsh habitats.

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[122] Barriers to transgression are relatively few in Dorchester and Wicomico counties, being mostly associated with developed shorelines in the vicinity of towns and cities, although eroding shorelines on marsh islands are being more frequently stabilized to slow island loss (Kearney and Stevenson, 1991).

- Estuarine Meander Tidal Marsh: In estuarine meander tidal marshes, the dominant vegetation consists of cattails (*Typha* spp.), *Spartina cynosuroides*, and pickerel weed (*Pontederia cordata*), while more saline areas consist of the same species found in submerged upland marshes (*e.g.*, *Scirpus olneyi*, *Spartina patens*, and *Spartina alterniflora*). These marshes have better drainage and a greater influx of mineral sediments, especially during extreme high tides when the entire marsh surface is inundated with sediment-laden river waters. Accretion rates typically exceed the rate of sea-level rise (Kearney and Ward, 1986); therefore, these marshes are more capable of surviving future sea-level rise than submerged upland marshes, and will migrate upriver as sea level rises.
- Freshwater Tidal Marsh: Accretion rates in freshwater tidal marshes are relatively high because of the abundant source of riverine sediment (Kearney *et al.*, 1988). These marshes will tolerate the greatest increases in the rate of sea-level rise. However, the areal extent of tidal freshwater marshes will decrease once the entire river is influenced by tides and the turbidity maxima continue to migrate up the estuary. Salt water will intrude into the lower reaches of the tidal freshwater marsh zone, and that marsh will likely convert to estuarine marsh.

Freshwater riparian wetlands and swamps exist beyond the extent of tidal influence, in the upper reaches of the rivers. These habitats have unique ecological value for a wide array of plant and animal species, and function as freshwater reservoirs through the interaction of groundwater discharge/recharge processes and surface runoff. As sea level rises, tidal influences, and eventually salt water, will intrude into these habitats and convert them to tidal and estuarine habitats.

As submerged upland marshes migrate upslope, they encroach upon pine forests located immediately inland, causing inundation, saturation, and salinization of forest soils, and eventually tree mortality. For example, in the Beaverdam Creek area of Blackwater NWR, tidal marsh has transgressed > 100 m into the pine forest since about 1940, where trees of the leading edge of the forest are dead and decomposing (Guntenspergen and Cahoon, 2005). This forested area is habitat for the Federally endangered Delmarva Fox Squirrel.

Areas of Virginia's Eastern Shore are uniquely vulnerable to sea-level rise. Large portions of Northampton and Accomack counties (184.8 and 208.2 square miles, respectively) lie near sea level (Titus and Wang, 2008). Because most of the land in the two counties is undeveloped or agricultural, the area also has a high potential for wetland creation relative to other Virginia shorelines.

Most notably, the bay side of northern Accomack County is primarily tidal salt marsh, with low-lying lands (less than 2 feet above the wetlands) extending several miles inland. The county as a whole contains nearly a fifth of the state's dry land within 2 feet of mean spring high water. (Titus and Cacela 2008). Unprotected marshes are already migrating inland in response to sea-level rise, creating new wetlands in agricultural areas at a rate of 40 acres per year. Given the anticipated lack of shoreline protection and insufficient sediment input, the seaward boundaries of these tidal wetlands are likely to continue retreating (Reed *et al.*, 2008). The upland elevations are higher in southern than northern Accomack County (see Figure E.2), however, making wetland migration more difficult.

The salt marshes of Accomack County support a variety of species, including rare bird species such as the seaside sparrow, sharp-tailed sparrow, and peregrine falcon (VA DCR, date unknown). Growth and survival of these species may be reduced where shores are hardened, unless alternative suitable habitat is available nearby. Furthermore, long-term tidal flooding will decrease the ability of nekton (*i.e.*, free-swimming finfish and decapod crustaceans such as shrimps and crabs) to access coastal marshes. As the accessible area declines, a decrease in nekton production may occur.

The bay side of Northampton County is most notable for its beach/dune systems, including some wide sandy beaches near the town of Cape Charles (Varnell and Hardaway, 2005). Estuarine beach/dune systems occur in areas of stability and sand accretion (such as the mouths of tidal creeks), in front of older dune features (such as washovers or spits), and against structures like jetties and groins (Hardaway *et al.*, 2004). Beach nourishment to protect public beaches is likely. The beaches and associated maritime forests provide habitat for a variety of species, most notably neo-tropical songbirds and the federally listed threatened northeastern beach tiger beetle (Varnell and Hardaway, 2005, p 5).

F.2 BAYWIDE POLICY CONTEXT

Chesapeake Bay's watershed has tidal shores in Virginia, Maryland, the District of Columbia, and Delaware. Because the shores of the District and Delaware account for a small portion of the total, the policy context depends primarily on Virginia and Maryland This section focuses mainly on the coastal policies of these two states that focus on the Bay, but we also include some policies that apply to both ocean and bay.

Coastal management officials of Maryland have cooperated with EPA since the 1980s in efforts to learn the ramifications of accelerated sea-level rise for their activities (AP, 1985). Increased erosion from sea-level rise was one of the factors cited for the state's decision in 1985 to shift its erosion control strategy at Ocean City from groins to beach nourishment (AP, 1985). The state also developed a planning document for rising sea level (Johnson, 2000), and sea-level rise was a key factor motivating Maryland to become the second mid-Atlantic state to obtain LIDAR elevation data for the entire coastal floodplain.

Neither Maryland nor Virginia has adopted an explicit policy to address the consequences of rising sea level. Nevertheless, the policies designed to protect wetlands, beaches, and private shorefront property are collectively an implicit policy. Both states prevent new buildings within 100 feet of most tidal shores; Maryland also limits the density of new development in most areas to one home per 20 acres within 1,000 feet (300 meters) of the shore. Virginia allows most forms of shore protection. Maryland encourages shore protection[123], but discourages new bulkheads in favor of revetments or nonstructural measures (MD DNR, 2006a). Both states have programs to inform property owners of nonstructural options, although obtaining permits for structural options is easier (NRC, 2007; Johnson and Luscher, 2004). Both states work with the federal government to obtain federal funds for beach nourishment along their respective ocean resorts (Ocean City and Virginia Beach); Virginia also assists local governments in efforts to nourish public beaches along Chesapeake Bay and its tributaries. Summaries of these land use, wetlands, and beach nourishment policies follow.

F.2.1 Land use

The primary state policies related to land use are Maryland's Chesapeake Bay Critical Area Protection Act, Virginia's Chesapeake Bay Preservation Act, and Virginia's Coastal Primary Sand Dunes & Beaches Act.

Maryland Chesapeake Bay Critical Area Protection Act. The Maryland General Assembly enacted the Chesapeake Bay Critical Area Protection Act in 1984 to reverse the deterioration of the Bay[124]. The law seeks to control development in the coastal zone and preserve a healthy Bay ecosystem. The jurisdictional boundary of the Critical Area includes all waters of Chesapeake Bay, adjacent wetlands[125], dry land within 1,000 feet

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[123] Code of Maryland Regulations§ 27.01.04.02.02-03

[124] Chesapeake Bay Critical Areas Protection Act, Maryland Code Natural Resources §8-1807.

[125] I.e. all state and private wetlands designated under Natural Resources Article, Title 9 (now Title 16 of the Environment Article).

of open water[126], and in some cases dry land within 1,000 feet inland of wetlands that are hydraulically connected to the Bay[127].

The act created a Critical Areas Commission to set criteria and approve local plans[128]. The commission recognizes three land use management sub-districts within the Critical Area: intensely developed areas (IDAs), limited development areas (LDAs), and resource conservation areas (RCAs)[129]. Within the RCAs, new development is limited to an average density of one home per 20 acres[130], and the regulations encourage communities to "consider cluster development, transfer of development rights, maximum lot size provisions, and/or additional means to maintain the land area necessary to support the protective uses"[131] The program limits future intense development activities to lands within the IDAs, and permits some additional low-intensity development in the LDAs. However, the statute allows up to 5% of the RCAs in a county to be converted to an IDA[132].

The three categories were originally delineated based on the land uses of 1985. Areas that were dominated by either agriculture, forest, or other open space, as well as residential areas with densities less than 1 home in 5 acres, were defined as RCAs[133]. Thus, the greatest preservation occurs in the areas that had little development when the act was

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[126] Maryland Code Natural Resources §8-1807(c)(1)(i)(2).

[127] Lands more than 1000 feet from open water may be excluded if and only if highly functional wetlands are between the land and the open water. Maryland Code Natural Resources §8-1807(c)(1)(i)(2) and §8-1807(a)(2).

[128] Maryland Code Natural Resources §8-1808.

[129] Code of Maryland Regulations §27.01.02.02(A).

[130] Code of Maryland Regulations §27.01.02.05(C)(4).

[131] Code of Maryland Regulations §27.01.02.05(C)(4).

[132] Code of Maryland Regulations §27.01.02.06.

[133] Code of Maryland Regulations §27.01.02.05.

passed, typically lands that are far from population centers and major transportation corridors — particularly along tributaries (as opposed to the Bay itself).

The Critical Areas Program also established a 100-foot natural buffer adjacent to tidal waters[134]. No new development activities, with the exception of those supporting water-dependent facilities, are allowed within the buffer[135]. By limiting development in the buffer, the program prevents additional infrastructure from being located in the areas most vulnerable to sea-level rise. In some cases, the 100-foot buffer provides a first line of defense against coastal erosion and flooding induced by sea-level rise. But the regulations also encourage property owners to halt shore erosion[136]. Nonstructural measures are preferred, followed by structural measures[137], with an eroding shore the least preferable (Titus, 1998).

Virginia Chesapeake Bay Preservation Act. The Chesapeake Bay Preservation Act[138] seeks to limit runoff into the Bay by creating a class of land known as Chesapeake Bay Preservation Areas. The act also created the Chesapeake Bay Local Assistance Board to implement[139] and enforce[140] its provisions. Although the act defers most site-specific development decisions to local governments[141], it lays out the broad framework for the

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[134] Code of Maryland Regulations §27.01.00.01 (C)(1).
[135] Code of Maryland Regulations §27.01.00.01 (C)(2).
[136] Code of Maryland Regulations§ 27.01.04.02. 02
[137] Code of Maryland Regulations§ 27.01.04.02. 03.
[138] Code VA §10.1-2100 et seq. As of August 8, 2003, the Act was posted on the Virginia Legislative Information System website as part of the Code of Virginia at: http://leg1.state.va.us/cgi-bin/legp504.exe?000+cod+TOC10010000021000000000000.
[139] Code VA §10.1-2102.
[140] Code VA §10.1-2104.
[141] Code VA §10.1-2109.

preservation areas[142] and provides the Board with rulemaking authority to set overall criteria[143]. The Board has issued regulations[144] defining the programs that local governments must develop to comply with the act[145].

All localities must create maps that define the locations of the preservation areas, which are subdivided into resource management areas[146] and resource protection areas (RPAs)[147]. RPAs include areas flooded by the tides, as well as a 100-foot buffer inland of the tidal shores and wetlands[148]. Within the buffer, development is generally limited to water dependent uses, redevelopment, and some water management facilities. Roads may be allowed if there is no practical alternative. Similarly, for lots subdivided before 2002, new buildings may encroach into the 100-foot buffer if necessary to preserve the owner's right to build; but any building must still be at least 50 feet from the shore[149]. Property owners, however, may still construct shoreline defense structures within the RPA. The type of shoreline defense installed is not regulated (beyond certain engineering considerations). Consequently, hard structures can be installed anywhere along Virginia's shoreline.

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[142] Code VA §10.1-2107(B).

[143] Code VA §10.1-2107(A).

[144] Chesapeake Bay Preservation Area Designation and Management Regulations (9 VAC 10-20-10 et. seq.).

[145] 9 Virginia Administrative Code §10-20-50.

[146] The act also provides for Resource Management Areas (RMAs) which are lands that, if improperly used or developed, have the potential to diminish the functional value of RPAs. Finally, areas in which development is concentrated or redevelopment efforts are taking place may be designated as Intensely Developed Areas (IDAs) and become subject to certain performance criteria for redevelopment. Private landowners are free to develop IDA and RMA lands, but must undergo a permitting process as well to prove that these actions will not harm the RPAs.

[147] 9 Virginia Administrative Code §10-20-70.

[148] 9 Virginia Administrative Code §10-20-80 (B).

[149] 9 Virginia Administrative Code §10-20-130 (4).

Virginia Coastal Primary Sand Dunes & Beaches Act. Virginia's Dunes and Beaches Act preserves and protects coastal primary sand dunes while accommodating shoreline development. The act identifies eight counties and cities that can adopt a coastal primary sand dune zoning ordinance, somewhat analogous to a Tidal Wetlands ordinance: Accomack, Northampton, Virginia Beach, Norfolk, Hampton, Mathews, Lancaster, and Northumberland (Hardaway *et al.*, 2001); all but Hampton and Accomack have done so. The act defines beaches as (1) the shoreline zone of unconsolidated sandy material; (2) the land extending from mean low water landward to a marked change in material composition or in physiographic form (for example, a dune, marsh, or bluff); and (3) if a marked change does not occur, then a line of woody vegetation or the nearest seawall, revetment, bulkhead or other similar structure.

F.2.2 Wetlands and erosion control permits

Virginia. The Tidal Wetlands Act seeks to "…preserve and prevent the despoliation and destruction of wetlands while accommodating necessary economic development in a manner consistent with wetlands preservation" (VA Code 28.2-1302). It provides for a Wetlands Zoning ordinance that any county, city, or town in Virginia may adopt to regulate the use and development of local wetlands. Under the ordinance, localities create a wetlands board consisting of five to seven citizen volunteers. The jurisdiction of these local boards extends from mean low water (the Marine Resources Commission has jurisdiction over bottom lands seaward of mean low water) to mean high water where no emergent vegetation exists, and slightly above spring high water[150] where marsh is

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[150] The Act grants jurisdiction to an elevation equal to 1.5 times the mean tide range, above mean low water.

present. The board grants or denies permits for shoreline alterations within their jurisdiction (Trono, 2003).

The Virginia Marine Resources Commission has jurisdiction over the permitting of projects within state-owned subaqueous lands. It also must "… promulgate and periodically update guidelines which scientifically evaluate vegetated and non-vegetated wetlands by type and describe the consequences of use of these wetlands types" (Section 28.2-1301). The commission has guidelines for wetlands, subaqueous lands, and coastal primary sand dunes and beaches. The commission has also published a pamphlet of best management practices for shoreline development that might affect wetlands, beaches, and subaqueous lands. The commission also reviews proposed projects in localities that have no local Wetlands Board by virtue of not having adopted a Wetland Zoning ordinance.

The Virginia Coastal Program's web page recently posted a fairly detailed analysis of the process for issuing permits for erosion control structures (Trono, 2003), which is designed to avoid destruction of wetlands or other adverse environmental impacts. The focus of the regulations and the review processes, however, is on avoiding immediate damage to the environment. The long-term impact on the environment from preventing the landward migration of tidal habitats is not considered.

Maryland. The Wetlands and Riparian Rights Act[151] gives the owner of land bounding on navigable water the right to protect their property from the effects of shore erosion. For example, property owners who erect an erosion control structure in Maryland can

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[151] Maryland Environmental Code §16-101 to §16-503.

obtain a permit to fill vegetated wetlands152 and fill beaches and tidal waters up to 10 feet seaward of mean high water153. In addition, Maryland's statute allows anyone whose property has eroded to fill wetlands and other tidal waters to reclaim any land that the owner has lost since the early 1970s154. (The Corps of Engineers has delegated most wetland permit approval to the state155.) The state encourages the "living shorelines" approach to halting erosion (e.g., marsh planting and beach nourishment) over hard structures and revetments over bulkheads156. Few new bulkheads are built for erosion control, and existing bulkheads are often replaced with revetments.

Shore protection structures tend to be initially constructed landward of mean high water, but neither the state of Virginia nor Maryland[157] requires their removal once the shore erodes to the point where the structures are flooded by the tides. Nor has either state prevented construction of replacement bulkheads within state waters, although Maryland encourages revetments.

F.2.3 Beach nourishment and other shore protection activities

Virginia. Until 2003, the Board on Conservation and Development of Public Beaches promoted maintenance, access, and development along the public beaches of Virginia.

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152 See MD. CODE ANN., ENVIR. § 16-201 (1996); Maryland General Permit, previous note, app. at I-24, I-31. Along sheltered waters, the state encourages property owners to control erosion by planting vegetation. For this purpose, one can fill up to 35 feet seaward of mean high water. See MD. CODE ANN., ENVIR. § 16-202(a)(3)(iii) (Supp. 1997). Along Chesapeake Bay and other waters with significant waves, hard structures are generally employed.

153 MD. CODE ANN., ENVIR. § 16-202(a)(2).

154 MD. CODE ANN., ENVIR. § 16-201.

155 See Baltimore Dist., U.S. Army Corps of Engineers, Dep't of the Army, Maryland State Programmatic General Permit §§ 1-5 (May 6, 1996) [hereinafter Maryland General Permit].

156 Maryland General Permit at 56, section IV(A)(1)(g).

157 The Maryland/Virginia border along the Potomac River is the low water mark. Courts have not ruled whether Maryland or Virginia environmental rules would govern a structure in Maryland waters attached to Virginia land.

The largest beach nourishment projects have been along the 13 miles of public beach along the Atlantic Ocean in Virginia Beach. Annual fill projects have added 200,000 to 300,000 cubic yards of land along the shore between 1st and 59th Streets (VA PBB, 2000). A $100 million Hurricane Project was completed in 2001, including both a seawall and a major sand replenishment project. During the last 50 years, the State has provided 3% of the funding for beach nourishment at Virginia Beach, with the local and federal shares being 67% and 30% respectively (VA PBB, 2000).

Virginia has made a greater effort than Maryland to promote beach nourishment (and public use of beaches) along Chesapeake Bay and its tributaries. Norfolk's four guarded beaches serve 160,000 visitors each summer (VA PBB, 2000). When shore erosion threatened property, the tourist economy, and local recreation, the Beach Board helped the city construct a series of breakwaters with beachfill and a terminal groin at a cost of $5 million (VA PBB, 2000). Across the James River, the City of Newport News and the Beach Board split the cost of a $1 million beach restoration project at Anderson Park, Huntington Park, and King-Lincoln Beach Park. The City of Hampton's Buckroe Beach along Chesapeake Bay has had severe erosion problems. Throughout the Board's lifetime, it provided $1.3 million for headland breakwaters and beach nourishment. Immediately to the north at the Salt Ponds public beach, the Beach Board funded a geotube project with a small amount of sand covering the tubes. More recently, the Beach Board provided $300,000 for a breakwater and beach nourishment project along the public beach of the Town of Cape Charles on the Eastern Shore. Along the Potomac River, the Beach Board supported efforts by the Town of Colonial Beach to maintain its beach with a combination breakwater and beachfill project, contributing $274,000 to this effort. Farther up the river at Aquia Landing in Stafford County, the Board provided $235,000 and technical support for a headland breakwater system and beachfill project. The Board has also supported beach restoration efforts along the York River.

Maryland's primary effort to protect shores along the Bay is through the Department of Natural Resource's Shore Erosion Control Program. The program provides both financial and technical assistance to Maryland property owners to resolve erosion problems through both structural and nonstructural shore erosion control projects. The state program has focused on nonstructural projects using bioengineering methods for shoreline restoration.

Although beach nourishment has historically been less common along Maryland's bay shores than those of Virginia, the Department of Natural Resources has been involved in several small-scale beach restoration efforts. The most significant beach nourishment project along the Bay has been a small recreational beach at North Beach (which despite its name has replaced most of the beach with a boardwalk and revetment). Many parks and small recreational communities have also received beach nourishment, including Sandy Point, and Point Lookout state parks on the western shore, the historic resort community of Bay Ridge, Terrapin Beach State Park, and Clairborne Landing and the Choptank River Fishing Pier in Talbot County.

The state has also used dredge spoils to restore Poplar and Smith islands. The Maryland Port Administration’s Poplar Island Restoration Project is using dredge materials from the Port of Baltimore to restore the island to its approximate footprint in the mid-1800s (USACE, 2005). The Port and the Corps of Engineers are currently working at Smith Island to combat erosion through a program to place dredged material on portions of the island (USACE, 2001). Preliminary examinations are under way to see if dredged materials can be used to restore other Chesapeake Bay islands such as James and Barren Islands (Federal Register, 2006), or to protect valuable environmental resources such as the eroding lands of the USFWS Blackwater National Wildlife Refuge (USACE, 2005 and USFWS, 2008).

The preceding discussion presents a simplification of the policy context. Many of the counties have coastal policies that may further alter coastal development — and citizens sometimes intervene to prompt *ad hoc* policy adjustments. (Appendix E discusses a proposed development along the Blackwater River that was cancelled as a result of citizen opposition.)

F.3 DEVELOPMENT AND SHORE PROTECTION

Chapter 5 describes the basis for ongoing studies that are analyzing land use plans, land use data, and coastal policies to create maps depicting the areas where shores may be protected and where wetlands may migrate inland. Because the maps from those studies have not yet been finalized, this section describes some of the existing and evolving conditions that may influence decisions related to future shore protection and wetland migration

F.3.1 Hampton Roads

Hampton Roads is the southernmost coastal planning district in Virginia. Extending from the North Carolina border to the York River, the region has 16 localities whose combined population is over 1.5 million. Lands vulnerable to sea-level rise include beaches along the Atlantic Ocean and Chesapeake Bay, both sides of the lower James River, a barrier spit and back barrier bays near North Carolina's Outer Banks, and parts of the York River.

Norfolk is home to the central business district of the Hampton Roads region. Although the city's population dropped during the 1990s, the local government is taking measures to redevelop and revitalize the urban core. One example of such a measure has been the successful revitalization of the Ocean View area along the northern shore of Norfolk. Newport News has similar development to Norfolk along its southern shores, with bluffs giving rise to less dense residential areas further north along the coast. The city of Hampton is also highly developed, but overall has a much smaller percentage of commercial and industrial development than Norfolk or Newport News. Norfolk and Newport News are also home to a number of private naval shipyards and coastal military naval establishments. In Norfolk, these shipyards are located on the western shore near the central business district and served as the backbone of the local economy for nearly a hundred years. The Fort Eustis military reservation occupies Mulberry Island in northern Newport News.

Outside of the urban core, localities are more rural in nature. These localities find themselves facing mounting development pressures and their comprehensive plans outline how they plan to respond to these pressures. Isle of Wight, Surry, James City, and York counties all face development pressure. Overall, however, the makeup of these outlying localities is a mix of urban and rural development, with historic towns and residential development dotting the landscape. The Town of Poquoson is an exception, being both extensively developed and very vulnerable to sea-level rise: The town is approximately 50 percent wetland and is almost entirely within three meters above sea level.

Virginia Beach has sandy shores along both the Atlantic Ocean and the mouth of Chesapeake Bay. Dunes dominate the bay shore, but much of the developed ocean shore is protected by a seawall (Figures F.18a and b), and periodic beach nourishment has occurred since the mid-1950s (Hardaway *et al.*, 2005). As the state’s only ocean resort, this city has a combination of high-rise condominiums and hotels, low-rise motels, restaurants and shops, and single-family homes with high property values. The northern two thirds of the city’s ocean coast is heavily developed; the southern third is within a state park or Back Bay National Wildlife Refuge.

Along Chesapeake Bay, by contrast, the Virginia Beach shore has substantial dunes, with homes set well back from the shore in some areas. Although the ground is relatively high, beach nourishment has been required on the bay beaches at Ocean Park (Hardaway *et al.*, 2005). Norfolk has maintained its beaches along Chesapeake Bay mostly with breakwaters and groins. Shores along other bodies of water are being armored. Of Norfolk's 167 miles of shoreline, 70 miles have been hardened (Berman *et al.*, 2002).

Figures F.18 Virginia Beach. (a) Homes set well back behind the dunes along the north-facing Chesapeake Bay shoreline. (b) Seawalls along the east-facing Atlantic beaches (October 1998).

Outside of the urban core of Hampton Roads, many lands are still rural and shore protection is not widespread.. Since 1979, Virginia Beach has had a "Green Line"[158] south of which the city tries to maintain the rural agricultural way of life. Because development has continued, Virginia Beach has also established a "Rural Area Line," which coincides with the Green Line in the eastern part of the city and runs 3 miles south

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[158] "The Green Line has been the city's most formidable defense against sprawl since its inclusion in the first Comprehensive Plan. Designed in 1979 to separate that area of the city where facilities and services could be provided within a reasonable time period (and this where urban development would be appropriate) from that area where there is no reasonable expectation of providing such services within a reasonable time (and thus where urban growth is not appropriate) the Green Line has been rigidly adhered to by the Council in the formulation and implementation of the city's land use and capital improvement planning." City of Virginia Beach, Comprehensive Plan Policy Document, at 19.

of it in the western portion. Below the Rural Area Line, the city strongly discourages development and encourages rural legacy and conservation easements (VBCP, 2003). In effect, the city's plan to preserve rural areas will serve to preserve the coastal environment as sea level rises throughout the coming century and beyond. To the west, by contrast, the City of Chesapeake is encouraging development in the rural areas, particularly along major corridors. Comprehensive plans in the more rural counties such as Isle of Wight and James City tend to focus less on preserving open space and more on encouraging growth in designated areas (IWCP, 2001 and JCCP, 2003). Therefore, these more remote areas may present the best opportunity for long-range planning to minimize coastal hazards and preserve the ability of ecosystems to migrate inland.

F.3.2 York River to Potomac River

Gloucester County's land use policies also have a strong conservation ethic. A large portion of the necks along Mobjack Bay has a conservation zoning that allows only low-density residential development "in a manner which protects natural resources in a sensitive environment." The intent is to preserve contiguous open spaces and protect the surrounding wetlands159. The County also seeks to maintain coastal ecosystems important for crabbing and fishing. As a result, wetlands and beaches along Mobjack Bay may be able to migrate inland as sea level rises.

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159 Gloucester County Code of Ordinances, accessed through Municode Online Codes; http://livepublish.municode.com/22/lpext.dll?f = templates&fn = main-j.htm&vid = 10843. Accessed on August 22, 2003.

Gloucester County also has a suburban country side zoning, which allows for low density residential development, including clustered sub-developments[160] along part of the Guinea Neck and along the York River between Carter Creek and the Catlett islands. These developments often leave some open space that might convert to wetlands as sea level rises even if the development itself is protected. The county plan anticipates development along most of the York River. Nevertheless, a number of areas are off-limits to development. For example, the Catlett islands are part of the Chesapeake Bay National Estuarine Research Reserve in Virginia, managed as a conservation area[161].

Along the Northern Neck, shoreline armoring is already very common, especially along Chesapeake Bay and the Rappahannock Rivers shores of Lancaster County. (See Figure F. 19.) Above Lancaster County, however, development is relatively sparse along the Rappahannock River. Development is proceeding along the Potomac River, by contrast.

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[160] Definition of suburban countryside in Gloucester County Code of Ordinances, accessed through Municode Online Codes on August 22, 2003: http://livepublish.municode.com/22/lpext.dll?f = templates&fn = main-j.htm&vid = 10843: "The intent of the SC-1 district is to allow low density residential development….Cluster development is encouraged in order to protect environmental and scenic resources."

[161] See the Research Reserve's web page at http://www.vims.edu/cbnerr/about/index.htm; accessed on May 12, 2007.Virginia Institute of Marine Science. (date unknown). "About Chesapeake Bay National Estuarine Research Reserve in Virginia." http://www.vims.edu/cbnerr/about/index.htm. Accessed May 12, 2007.

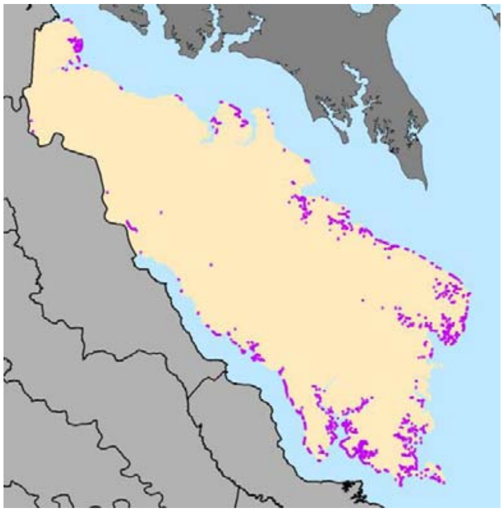

Figure F. 19 Location of shoreline armoring within the Northern Neck. Each dot indicates the presence of a bulkhead or revetment within about 1,000 feet. Therefore, the armoring is not necessarily as continuous as the map might appear to imply. The dots that appear to be inland are actually along tidal creeks. Source: Northern Neck Planning District.

F.3.3 Potomac River

West of Chesapeake Bay, the southwestern shoreline of the Potomac River is the border between Maryland and Virginia[162]. As a result, islands in the Potomac River, no matter how close they are to the Virginia side of the river, are part of Maryland or the District of Columbia. Moreover, most efforts to control erosion along the Virginia shore take place partly in Maryland (or DC) and thus could potentially be subject to Maryland (or DC) policies[163].

Development is proceeding along approximately two-thirds of the Potomac River shore. Nevertheless, most shores in Charles County (Maryland) are in the resource conservation

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[162] See Maryland v. Virginia, 540 US (2003), slip opinion at 2.

[163] The Virginia Shore across from the District of Columbia is mostly owned by the federal government, which would be exempt from DC policies.

area defined by the state's Critical Areas Act (and hence limited to one home per 20 acres) (MD DNR, 2007). A significant portion of Prince George's County's shoreline along the Potomac and its tributaries are owned by the National Park Service and other conservation entities that seek to preserve the coastal environment (MD DNR, 2000).

In Northern Virginia, parks also account for a significant portion of the shore. In Outside the park lands, several developers have set development back from low-lying marsh areas to avoid problems associated with flooding and poor drainage, or created developments with lot sizes greater than 10 acres. In Stafford County, the CSX railroad line follows the river for several miles, and is set back to allow shores to erode, but not so far back as to allow for development between the railroad and the shore[164].

F.3.4 Washington DC

The low land vulnerable to sea level rise in the District of Columbia includes portions of the downtown area, the monuments, Columbia Island, and the military lands along the Potomac River south of the mouth of the Anacostia. These facilities are unlikely to be given up to rising sea level; city officials are currently discussing the flood control infrastructure necessary to avoid portions of the downtown area from being classified as part of the 100-year floodplain. Nevertheless, natural areas in the city account a substantial portion of the city's shore, such as Roosevelt Island and the shores of the Potomac River within C&O National Historic Park.

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[164] Personal communication with Mark Remsberg, Community Development, King George County, December 17, 2004.

As part of the city's efforts to restore the Anacostia River, District officials plan have proposed a series of environmental protection buffers along the Anacostia River with widths between 50 and 300 feet. Bulkheads are being removed except where they are needed for navigation, in favor of natural shores in the upper part of the river and bioengineered "living shorelines" in the lower portion (see Figure F.20) (DCOP, 2003).

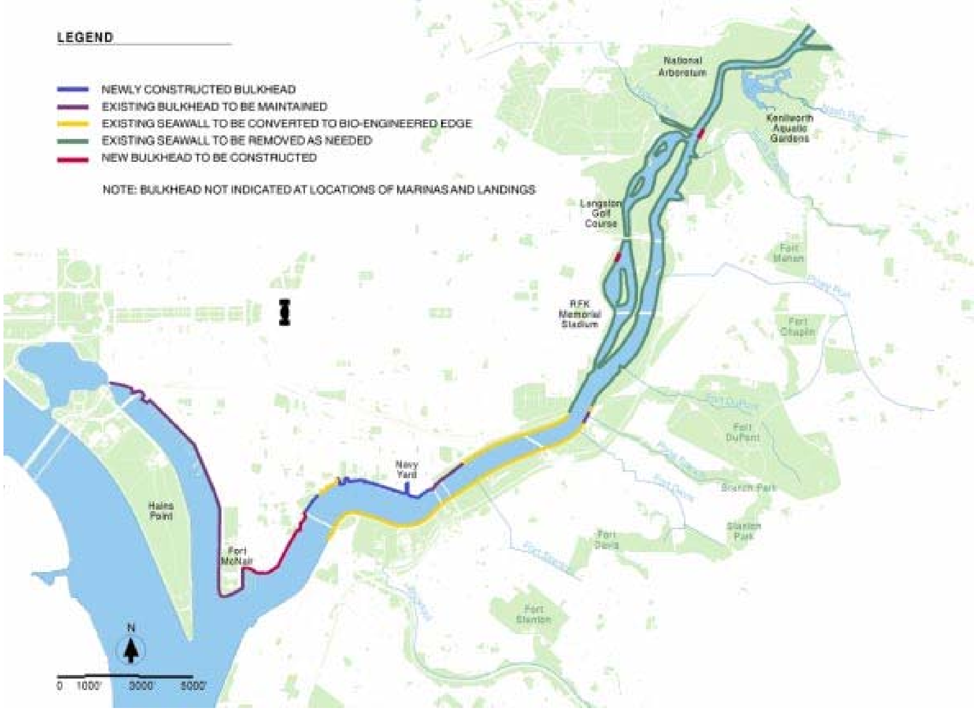

Figure F.20 District of Columbia Plans to restore natural shores along Anacostia River.
Source: DCOP, 2003.

F.3.5 Western Shore: Potomac River to Susquehanna River

Compared with the Potomac River, Maryland's Critical Areas Act is unlikely to preserve a major portion of the Western Shore, which was largely developed before the act was passed. Stone revetments are common along the mostly developed shores of Anne Arundel and Baltimore counties. .Yet the Western Shore also has one of the only shore protection policies in the nation that prohibits shore protection along an estuary, even when the prohibition means that homes will be lost. Calvert County's erosion policy is designed to preserve unique cliff areas that border Chesapeake Bay. They are a unique visual landmark and provide habitat to plants and wildlife, including endangered species.

The County allows erosion control structures in certain developed areas to protect property interests, but also bans structures in other areas to protect endangered species and the unique landscape. Cliffs in Calvert County are separated into three categories according to the priority for preservation of the land:

- Category 1 provides the greatest environmental protection. No shore protection is allowed and new development must be set back from the cliff edge by 300 feet.
- Category 2 allows limited shoreline armoring. Shore protection is allowed solely to protect built before 1997. A 200-foot setback for new development is also required.
- Category 3 comprises all remaining cliff areas on the Chesapeake Bay. Shore protection is allowed[165].

Although a county policy prohibiting shore protection would appear to run counter to the state law granting riparian owner the right to shore protection, to date no legal challenges to the cliff policy have been made. The state has accepted the County's policy, which is

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[165] Personal communication from Dr. David Brownlee to William Nuckols and Daniel Hudgens, December 14, 2000.

embodied in the County's critical areas plan submitted to the state under the Critical Areas Act.

Recognizing the potential environmental implications, living shoreline protection is becoming increasingly commonplace along the Western Shore.

F.3.6 Eastern Shore: Susquehanna River to Choptank River (Cecil, Kent, Queen Anne's, Caroline, and Talbot counties)

The decline of the bay beach resort has coincided with a decline in public demand for a bay beach. For those who have built or purchased homes near the ocean during the last few decades, one of the most important reasons for purchasing a home has been the amenity that one can walk to the beach — an amenity that would be lost if the beach were to disappear. Hence substantial expenditures have been devoted to beach nourishment to avoid having to choose between losing the beach and losing the first row of homes. Along Chesapeake Bay, by contrast, recent coastal development has not placed a high value on the beach. The new bayfront subdivisions often provide no public access to the beach, and as shores erode, people erect shore-protection structures that eventually eliminate the beach (Titus, 1998). Some traditional access points have been closed (Titus, 1998). Maintaining a beach remains important to some of the older bay resort communities where residents have long had a public beach — but even communities with "beach" in the name are seeing their beaches replaced with shore protection structures[166].

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[166] E.g. Chesapeake Beach, North Beach, Tolchester Beach all have more armored shores than beach.

Maryland's Critical Areas Act, however, is likely to restrict the extent of additional development along the Eastern Shore of Chesapeake Bay to a greater extent than along the Western Shore. The resource conservation areas where development is discouraged include half of the Chesapeake Bay shoreline between the Susquehanna and Choptank rivers. Among the major tributaries, most of the Sassafras, Chester, and Choptank rivers is similarly preserved; the Act did not prevent development along most of the Wye, Elk, and North East rivers. Existing development is most concentrated in the northern areas near I-95, Kent Island, and the various necks near Easton and St. Michaels. .

Extrapolating the recent bayfront model for development along Chesapeake Bay would lead one to expect beaches to be replaced with shoreline armoring. However, if bay beaches were to come back into vogue, then efforts to maintain them might involve either beach nourishment or allowing shores to erode naturally. Scientists are starting to recognize environmental value to bay beaches[167] and homeowners are starting to place value on environmental quality.

F.3.7 The Lower Eastern Shore: The Choptank River to Cape Charles

Along Chesapeake Bay, islands are threatened by a combination of erosion and inundation. Wetlands are taking over portions of Hoopers and Deal Islands, but shore erosion is the more serious threat. During the middle of the 19th century, watermen who made their living by fishing Chesapeake Bay made their homes on various islands in this region. Today, Bloodsworth and Lower Hoopers islands are uninhabitable marsh, and the

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[167] E.g., see Nordstrom, 1997 and NRC, 2007. Nordstrum "Estuarine Beaches". National Research Council. "Mitigating Shoreline Erosion".

erosion of Barren and Poplar islands led people to move their homes to the mainland. Smith Island is now several islands, and it has a declining population. Hoopers and Deal islands are becoming gentrified. Virtually all of the beaches along Chesapeake Bay are eroding. Shore erosion of beaches and clay shores along the Chester, Nanticoke, and Chester rivers is less — but enough to induce shoreline armoring along most developed portions.

The lower Eastern shore has a history of abandoning lowlands to shore erosion and rising sea level to a greater extent than other parts of the state.

Today Smith and Tangier are the only inhabited islands without a bridge connection to the mainland. Government officials at all levels are pursuing efforts to prevent the loss of these lands, partly because of their unique cultural status and — in the case of Tangier — a town government that works hard to ensure that the state continues to reinvest in schools and infrastructure. The Corps of Engineers has several planned projects for halting shore erosion, but to date, serious efforts to elevate the land are not under way. The replacement of traditional lifestyles with gentrified second homes may increase the resources available to preserve these islands.

The mainland of Somerset County vulnerable to sea-level rise is mostly along three necks. Until recently, a key indicator of the cost-effectiveness of shore protection was the availability of a sewer line[168]. As sea level rises, homes without sewer may be condemned as septic systems fail. The incorporated town of Crisfield, in the

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[168] The mounds systems have made it possible to inhabit low areas with high water tables.

southernmost neck, has long had sewer service, which has been recently expanded to nearby areas. The town itself is largely encircled by an aging dike. Deal Island, no longer the thriving fishing port of centuries gone by, still has moderate density housing on most of the dry land.

Wicomico County's low-lying areas are along both the Wicomico and Nanticoke Rivers. Unlike Somerset, Wicomico has a large urban/suburban population, with the Eastern Shore's largest city, Salisbury. Planners accept the general principals of the state's Critical Areas Act, which discourages development along the shore.

Much of coastal Dorchester County is already part of Blackwater Wildlife Refuge. The very low land south of Cambridge that is not already part of the refuge is farmland. A development of approximately 1000 acres was recently proposed and approved along Egypt Road south of Cambridge; but as a result of citizen opposition it was later cancelled and the state plans to buy most of the property. The County plan does not anticipate development in most of the low-lying lands west of Cambridge. On the higher ground along the Choptank River, by contrast, many waterfront parcels are being developed.

BOX F.1: The Diamondback Terrapin, *Malaclemys Terrapin*

The diamondback terrapin, *Malaclemys terrapin*, comprising seven subspecies, is the only turtle that is fully adapted to life in the brackish salt marshes of estuarine embayments, lagoons, and impoundments (Ernst and Barbour, 1972). Its range extends from Massachusetts to Texas in the narrowest of coastal strips along the Atlantic and Gulf coasts of the United States (Palmer and Cordes, 1988). Extreme fishing pressure on the species resulted in population crashes over much of their range so that by 1920 the catch in Chesapeake Bay had fallen to less than 900 pounds. The Great Depression put a halt to the fishery, and during the mid-20th century, populations began to recover (CBP, 2006). Although a modest fishery has been reestablished in some areas, stringent harvest regulations are in place in several states. In some instances, States have listed the species as endangered (Rhode Island), threatened (Massachusetts), or as a “species of concern” (Georgia, Delaware, New Jersey, Louisiana, North Carolina, and Virginia). In Maryland, the status of the northern diamondback subpopulation is under review (MD DNR, 2006b).

Effects of Sea-level Rise

The prospect of sea-level rise, along with land subsidence at many coastal locations, increasing human habitation of the shore zone and shoreline stabilization, places the habitat of terrapins at increasing risk. Because human infrastructure (*i.e.*, roadways, buildings, and impervious surfaces) leaves tidal salt marshes with little or no room to transgress inland, the ecosystem that terrapins depend on may be lost with concomitant extirpation of the species.

F.4 POPULATION OF LANDS CLOSE TO SEA LEVEL

F.4.1 Chesapeake Western Shore

Table F.6 estimates the population of lands close to sea level for each of the localities along the Western Shore of Chesapeake Bay or its tributaries. The greatest concentration of people living close to sea level is in the various localities around Hampton Roads. The uncertainty range reflects the lack of precision in the elevation data. Although Maryland now has LIDAR for most of the state, when our elevation data set was assembled it was unavailable; as Figure 1.1 shows (Chapter 1), we had better elevation data in the Hampton Roads area than most of the Western Shore.

Table F.6 Population of lands close to sea level: Western Shore.

Locality	**Low and high estimates of population below a given elevation (thousands)**					
	50cm		**1m**		**2m**	
	Low	**High**	**Low**	**High**	**Low**	**High**
Hampton Roads						
Chesapeake	3.4	13.9	3.4	19.8	12.5	50.2
Hampton	6.1	19.7	6.1	35.6	19.0	98.5
Isle of Wight	0.0	0.3	0.0	0.3	0.0	0.4
James City County	0.0	0.1	0.0	0.5	0.0	0.7
Newport News	4.1	6.8	4.1	7.7	6.8	17.9
Norfolk	9.2	30.6	9.2	40.1	29.8	166.8
Poquoson	0.5	5.1	0.5	8.4	4.9	11.6
Portsmouth	1.1	8.5	1.1	12.3	8.3	45.4
Suffolk	0.0	0.8	0.0	1.2	0.0	1.9
Surry	0.0	0.0	0.0	0.0	0.0	0.006
Virginia Beach	4.8	28.4	4.8	47.8	25.2	168.8
York	1.8	4.5	1.8	5.5	4.3	10.3
Total	**30.9**	**118.7**	**30.9**	**179.2**	**110.6**	**572.6**
Northern Neck/Middle Peninsula)						
Essex	0.0	0.2	0.0	0.2	0.0	0.4
Gloucester[a]	0.2	2.7	0.2	3.3	2.7	5.2
King and Queen	0.0	0.0	0.0	0.1	0.0	0.2
King William	0.0	0.3	0.0	0.9	0.0	1.3
Lancaster	0.0	0.6	0.0	0.6	0.1	1.6
Mathews	0.0	1.3	0.0	1.8	1.3	4.2
Middlesex	0.0	0.1	0.0	0.2	0.1	0.4
Northumberland[b]	0.0	0.1	0.0	0.1	0.0	2.8
Richmond County	0.0	0.0	0.0	0.1	0.0	0.2
Total	**0.2**	**5.3**	**0.2**	**7.3**	**4.2**	**16.3**

Table F.6 Population of lands close to sea level: Western Shore (cont.).

Locality	**Low and high estimates of population below a given elevation (thousands)**					
	50cm		**1m**		**2m**	
	Low	**High**	**Low**	**High**	**Low**	**High**
Maryland						
Anne Arundel	0.0	2.9	0.0	10.2	2.8	21.2
Baltimore City	0.0	0.3	0.0	1.5	0.0	6.3
Baltimore County	*	*	*	*	*	*
Calvert	0.0	1.3	0.0	1.8	1.0	3.3
Charles[2]	0.0	0.1	0.0	1.2	0.0	1.8
Harford	0.0	0.9	0.0	1.0	0.9	2.9
Prince George's[b]	0.0	0.3	0.0	0.5	0.1	1.6
St. Mary's[b]	0.0	1.3	0.0	2.7	0.8	5.6
Total	**0.0**	**7.1**	**0.0**	**18.9**	**5.6**	**42.7**

* Data unavailable.

a. Figures are for the entire county. County is split between Chesapeake and Delaware Bay Watersheds.

b. Figures are for the entire county. County is split between Chesapeake and Potomac River Watersheds.

F.4.2 Potomac River

Table F.7 estimates the population of lands close to sea level along for each of the counties along the Potomac River and the District of Columbia. The absence of good elevation data makes these estimates very uncertain. Because Lewisetta is below the USGS "5-ft" contour, the low estimate for Northumberland should include the population of that community for the 2-meter case. The "high estimates" are also partly an artifact of our data limitations. In Fairfax County, for example, the NOAA analysis found 1647 people living in Census blocks that are entirely below the lowest topographic contour (the 10-ft contour). However, tens of thousands of people live in Census blocks with some land below that contour, and hence the high estimate of 6000 people.

Table F.7 Population of lands close to sea level: Potomac River.

	Low and high estimates of population below a given elevation (thousands)					
	50cm		**1m**		**2m**	
County	**Low**	**High**	**Low**	**High**	**Low**	**High**
District of Columbia	0.0	0.2	0.0	0.2	0.2	5.6
Maryland						
Charles[a]	0.0	0.1	0.0	1.2	0.0	1.8
Prince George's[a]	0.0	0.3	0.0	0.5	0.1	1.6
St. Mary's[a]	0.0	1.3	0.0	2.7	0.8	5.6
Virginia						
Alexandria	0.0	3.1	0.0	7.6	0.0	11.0
Arlington	0.0	0.0	0.0	1.6	0.0	2.5
Fairfax	0.0	6.1	0.0	9.5	0.0	10.2
King George	0.0	0.4	0.0	0.4	0.0	0.4
Northumberland[a]	0.0	0.1	0.0	0.1	0.0	2.8
Prince William	0.0	2.2	0.0	2.4	0.0	2.5
Stafford	0.0	0.0	0.0	0.1	0.0	0.2
Westmoreland	0.0	0.4	0.0	0.8	0.0	2.2
Total	**0.0**	**14.2**	**0.0**	**27.1**	**1.1**	**46.3**

a. Figures are for the entire county. County is split between Chesapeake and Potomac River Watersheds.

The District of Columbia was able to provide better elevation data than Maryland and Virginia (See Figure 1.1 in Chapter 1). Approximately 200 people live in low-lying areas near Georgetown that are potentially vulnerable to sea-level rise.

F.4.3 Chesapeake Bay Eastern Shore

Table F.8 estimates the population of lands close to sea level for each of the counties along the Eastern Shore of Chesapeake Bay or its tributaries. Somerset, Dorchester, and Accomack counties have the largest populations living within one meter above spring high water[169]. These three counties have islands that have long been populated by watermen (Smith, Hoopers, and Tangier, respectively), as well as low-lying towns such

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[169] Worcester and Sussex Counties have substantial populations living in low lying areas along the Atlantic Coast. Their small areas close to sea level in the Chesapeake Bay watershed are lightly populated.

as Crisfield, Toddville, and Chesconessex. The uncertainty range reflects the lack of precision in the elevation data. Thus, the Maryland calculations are more accurate.

Table F.8 Population of lands close to sea level: Eastern Shore.

	Low and high estimates of population below a given elevation (thousands)					
	50cm		1m		2m	
County	**Low**	**High**	**Low**	**High**	**Low**	**High**
Delaware						
Sussex[1]	1.1	7.2	1.1	9.5	7.1	17.0
Maryland						
Caroline	0.3	0.6	0.3	0.6	0.4	0.9
Cecil	0.0	0.3	0.0	0.7	0.2	1.3
Dorchester	0.0	0.6	0.7	2.0	3.5	4.2
Kent	0.0	0.5	0.0	1.0	0.0	1.7
Queen Anne’s	0.0	0.1	0.1	0.2	0.7	2.2
Somerset	1.2	3.8	4.5	6.2	8.1	9.7
Talbot	0.0	0.1	0.1	0.3	0.9	1.7
Wicomico	0.1	0.1	0.1	0.4	0.9	1.2
Worcester[2]	0.0	1.1	0.6	3.2	6.4	12.6
Virginia						
Accomack[2]	0.8	7.0	0.8	7.6	6.9	9.3
Northampton[2]	0.0	0.3	0.0	0.6	0.2	1.1
Total	**7.3**	**30.7**	**12.3**	**45.1**	**42.5**	**86.0**

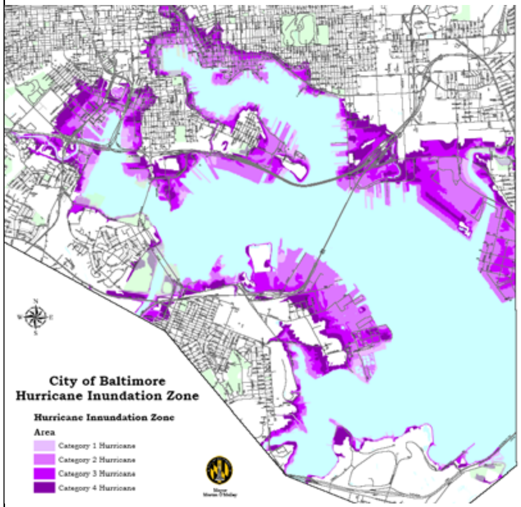
[1] Figures are for the entire county. County is split between Chesapeake and Delaware Bay Watersheds.

[2] Figures are for the entire county. County is split between Chesapeake and Atlantic Coast Watersheds.

BOX F.2: Planning for Sea-level Rise in Baltimore

Only 3.2% of the City of Baltimore's 210 square kilometers of land is currently within the coastal floodplain. This land, however, includes popular tourist destinations such as Inner Harbor and the Fells Point Historic District, as well as industrial areas, some of which are being redeveloped into mixed use developments with residential, commercial, and retail land uses. The map below depicts the areas that the city expects to be flooded by category 1, 2, 3 and 4 hurricanes, which roughly correspond to water levels of 1.75 meters (6 feet), 3 meters (10 feet), 4.2 meters (14 feet), and 5.5 meters (18 feet) above NAVD. Approximately 250 homes are vulnerable to a category 1, while 700 homes could be flooded by a category 2 hurricane. As Hurricane Isabel passed in September 2003, water levels in Baltimore Harbor generally reached approximately 8 feet above NAVD, flooding streets and basements, but resulting in only 16 flood insurance claims.

The city's All Hazards Plan explicitly includes rising sea level as one of the factors to be considered in land use and infrastructure planning.[170] The All Hazards Plan has as an objective to "develop up-to-date research about hazards" and a strategy under that objective to "study the threat, possible mitigation and policy changes for sea-level rise." As a first step toward accurate mapping of possible sea-level rise scenarios the city is exploring options for acquiring LIDAR. Policies developed for floodplain management foreshadow the broad methods the city is likely to use in its response.



Map: Inundation Zone under Category 1, 2, 3, and 4 hurricanes.

Property values are high, and there is a long-standing practice of armoring shores to facilitate port-related activities and more recently, protect waterfront structures from shore erosion. In most areas, there is not enough room between the harbor and waterfront buildings to fit a dike. Even where there is room, the loss of waterfront views would be unacceptable in tourist and residential areas. In addition, storm sewers, which drain by gravity into the harbor, would have to be fit with pumping systems.

Fells Point Historic District

This historic community has 60 acres within the 100-year flood plain. Fells Point is a Federal Historic District and pending approval as a Local Historic District. The row houses here were built predominantly in the early to mid-19th century and cannot be easily elevated. Elevating brick and stone structures is always more difficult than elevating a wood frame structure. But because row houses are, by definition, attached to each other, elevating them one at a time is not feasible. Many of these homes have basements, which already flood. FEMA regulations do not permit basements in new construction in the floodplain and treats existing basements as requiring mitigation. Possible mitigation for basements includes relocation of utilities, reinforcement of walls, and filling.

In theory, homes could be remodeled to add stairways and doors to convert what is now the second floor to a first floor and convert the first floors to basements. But doing so would reduce the livable space. Moreover, federal and local preservation laws, as well as community sensibilities, preclude adding third stories to these homes. Elevating streets is also problematic because below-grade utilities need to be elevated. In the last decade only one street was elevated specifically to reduce flooding.

FEMA Flood Hazard Mapping and Sea-level Rise

Baltimore City is a participating jurisdiction in the National Flood Insurance Program (NFIP) through its regulation of development in the floodplain and through overall floodplain management. The city is currently funded through the Cooperative Technical Partnership (CTP) to update its flood maps. Federal flood mapping policies require that Flood Insurance Rate Maps (FIRMs) be based on existing conditions. At the time the mapping agreement was created (2005), FEMA would not allow use of the CTP funds to include additional mapping of sea-level rise or the mapping of projected future BFE. As a result, the city will be permitting new structures with effective functional lifespan of 50 to 100 years but elevated only to current flood elevations. One strategy to surmount this limitation is to add “freeboard,” or additional elevation to the effective BFE. Baltimore already requires one additional foot of freeboard.

The City of Baltimore is concerned, however, that 1 to 2 additional feet of freeboard is inequitable and inefficient. If flood levels will be, for example, 1 meter higher than the flood maps currently assume, then lands just outside the current flood boundary are also potentially vulnerable. If the city were to add 1 meter of freeboard to property in the floodplain, without addressing adjacent properties outside the floodplain, then adjacent property owners would have divergent requirements that city officials would find difficult to justify.

Infrastructure
Baltimore has two regional sewerage plants. One of them, the Patapsco Wastewater Treatment Plant, sits on ground that is less than two meters above mean sea level and floods occasionally. The facility itself is elevated and currently drains by gravity into the Patapsco River. With a significant rise in sea level, however, pumping will be needed and possibly additional protections against storms. Numerous streets, with associated conduits and utility piping, are within the existing tidal floodplain and would potentially be impacted by sea-level rise.

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Appendix G. North Carolina

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The coast of North Carolina has shifted significantly during the last few centuries due to rising sea level and other factors. In the 16th century the Outer Banks separated Roanoke Island (the first English Colony in North America) from the Atlantic Ocean, as they do today. But directly east of Roanoke Island was Roanoke Inlet, which separated Bodie Island (now southern Nags Head) from the barrier island to the north. There were several other inlets between Cape Hatteras and Back Bay. (Riggs and Ames, 2003 p. 118; Collet and Bayly 1790). Sediment transport along the shore eventually closed all of those inlets. Today, the nearest inlet is Oregon Inlet, more than 20 km away.

Other shores have also changed substantially over the last four centuries. Croatan Island was split by the creation of Hatteras Inlet, leaving its northern and southern portions connected to what are now Hatteras and Ocracoke Islands, respectively. Roanoke Island was connected to the mainland of Dare County until the early 19th century by marshes. When Roanoke Inlet closed, the currents that drain Albemarle Sound eroded channels through the connecting marshes allowing Albemarle Sound and Currituck Sound to drain to the ocean through Oregon Inlet and inlets farther south. (Riggs and Ames, 2003 p. 69). Stumpy Point Bay was an inland freshwater lake until the 19th century, when shoreline erosion opened it to Pamlico Sound. Albemarle-Pamlico Peninsula, which is very low and flat, at one time held the largest continuous area of wetlands in North Carolina and one of the largest in the nation (Cummings, 1966; Riggs and Ames, 2003 p. 69) but many of those wetlands have been drained for agriculture and other purposes.

The North Carolina coast continues to evolve. Many ocean shores are gradually retreating, claiming shorefront homes and prompting officials to relocate the coastal highway (NC-12) and the Cape Hatteras lighthouse inland.

This appendix examines some of the possible implications of rising sea level for North Carolina, with a focus on the impacts examined in chapters 1-6 of this report. The lands along North Carolina's Albemarle Sound, Pamlico Sound, and their tidal tributaries (sometimes collectively called the Albemarle-Pamlico Sound) account for 70 percent of the nontidal wetlands, 40 percent of the dry land, and 55 percent of all the land in the Mid-Atlantic within 1 meter above spring high water (Jones and Wang, 2008). Most importantly, the land is mostly low and wet. This area has a diverse array of habitats which include barrier beaches and salt marshes found in the rest of the Mid-Atlantic, as well as cypress and pocosin swamps (defined below) that are rarely found elsewhere in the region.

The extent to which these habitats can adapt to sea-level rise is unclear. The unique hydrology of the Albermarle-Pamlico Sound particularly the low tide ranges and low salinity, may make the area's habitats particularly vulnerable if changes in the barrier islands expose the sounds to higher tide ranges and higher salinity water. With more than 60 percent of the land within the Mid-Atlantic that might realistically be allowed to become submerged as sea level rises, North Carolina may represent an important environmental planning opportunity (Titus and Wang, 2008).

G.1 LAND VULNERABLE TO INUNDATION

The third largest area of land vulnerable to rising sea level in the United States lies between Cape Lookout and the mouth of Chesapeake Bay. In North Carolina alone, between 1300 and 1800 square kilometers of dry land is within one meter above the tides (See Chapter 1)[171] — approximately half the total for the entire Mid-Atlantic. Another 3000 to 3400 square kilometers of nontidal[172] wetlands are within one meter above the tides — again approximately half the total for the entire Mid-Atlantic. Three counties are almost entirely within three meters above the tides.

North Carolina's coastal zone can be divided into two different geological zones, each with different characteristics (Riggs and Ames, 2003). The zone northeast of a line drawn between Cape Lookout and Raleigh is called the Northern Coastal Province. It has gentle slopes, four major rivers, and long barrier islands with a moderately low sediment supply, compared to barrier islands worldwide. The rest of the state's coastal zone has steeper slopes, an even lower sediment supply, short barrier islands, and many inlets.

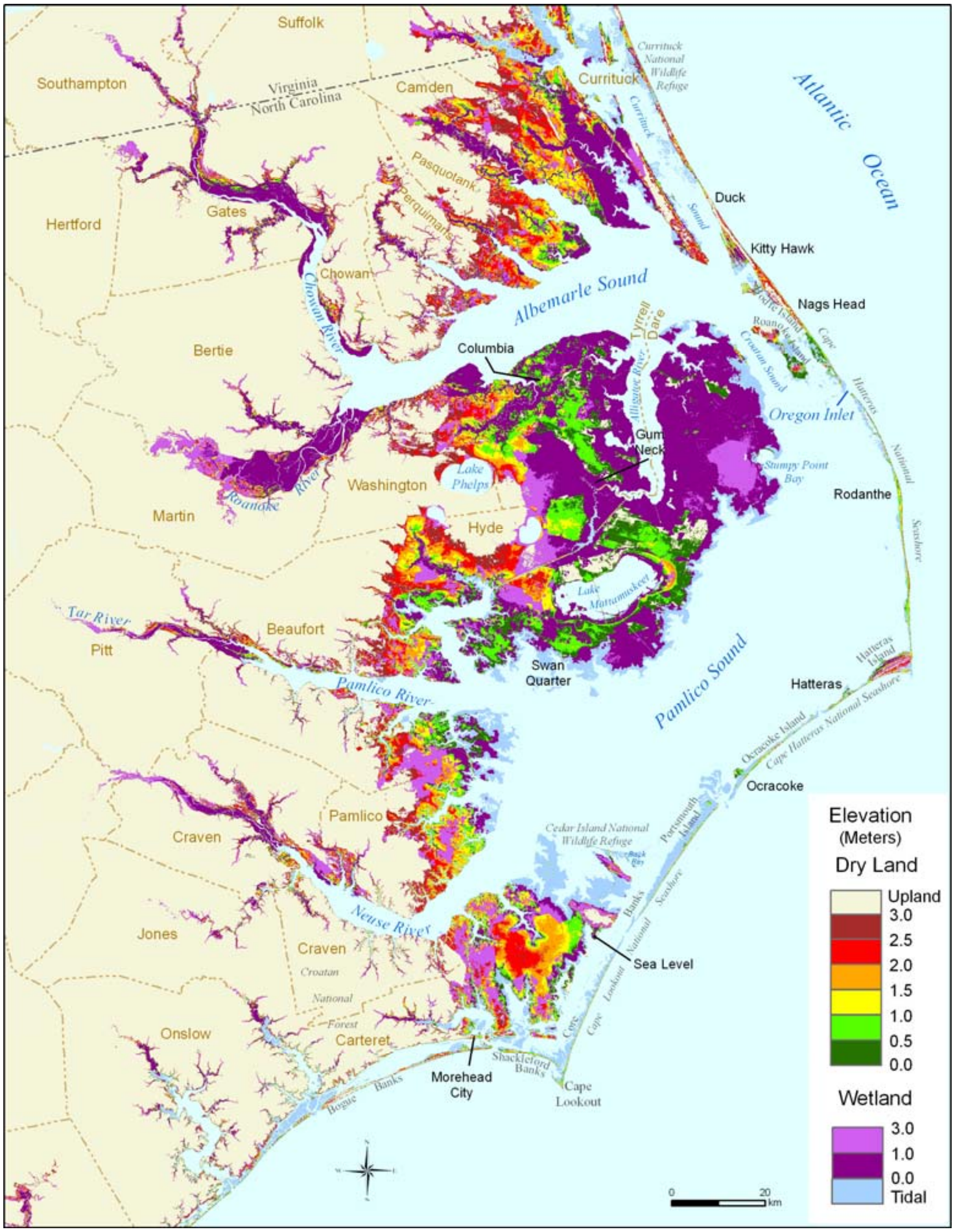

Figure G.1 Elevation of lands close to sea level: Cape Lookout to Virginia Beach.

Figures G.1 and G.2 show the elevations of lands close to sea level north and south of Cape Lookout, respectively, distinguishing between dry land and nontidal wetlands. Figure G.3 shows the northern portion of the coast, without distinguishing between dry land and wetlands[173]. Table G.1 provides low and high estimates of the area of dry and wet land, by county[174]. The entire state has between 700 and 1200 square kilometers of dry land within 50 cm above the tides, as well as approximately 2300 to 2900 square kilometers of nontidal wetlands. Hyde, Tyrrell, and Dare counties account for more than half of the nontidal wetlands within 50 cm of the tides (Titus and Wang, 2008; Titus and Cacela, 2008).

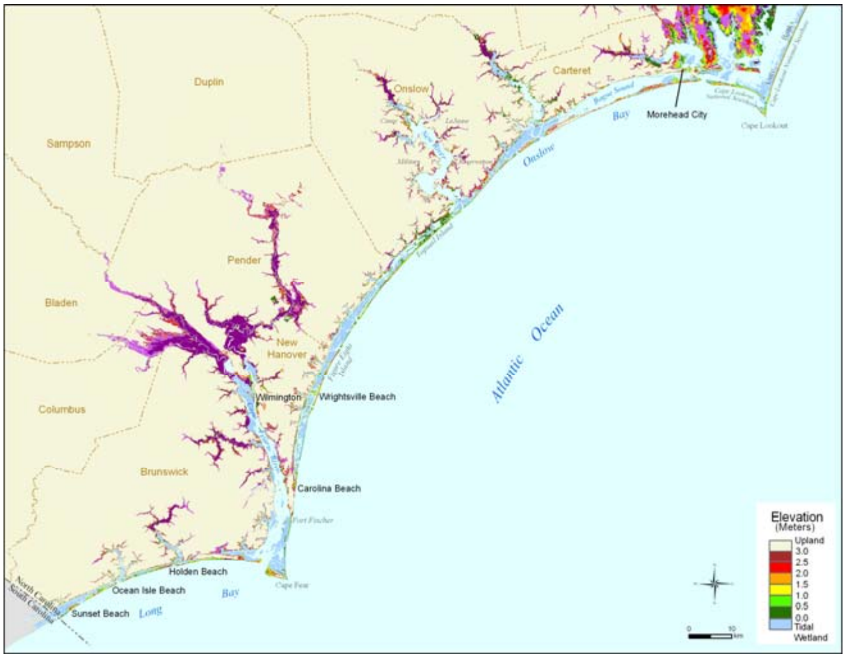

Figure G.2 Elevation of lands close to sea level: South Carolina border to Cape Lookout.

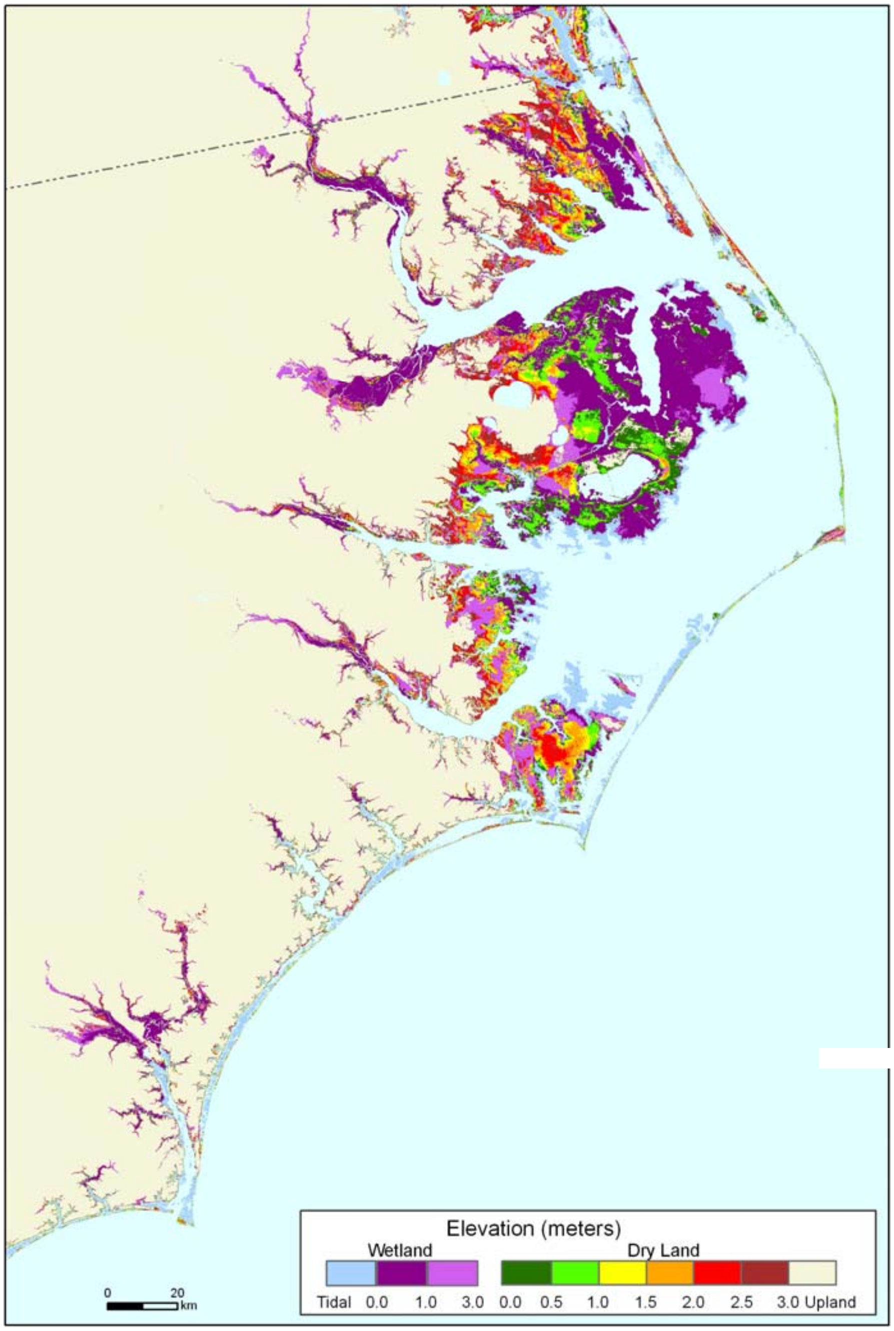

Figure G.3 Elevation of lands close to sea level: Cape Lookout to Virginia Beach.

Table G.1 Low and high estimates of the area of dry and wet land close to sea level (square kilometers).

	Tidal	**50 centimeters**		**1 meter**		**2 meters**		**3 meters**		**5 meters**	
		Low	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
County		Cumulative (total) amount of dry land below a given elevation									
Beaufort		48.6	93.1	109.4	156.4	257.2	317.2	422.2	481.8	722.2	744.0
Bertie		1.8	3.4	4.7	6.8	12.1	14.8	22.3	25.9	56.2	64.6
Brunswick		14.5	20.1	24.1	31.1	47.8	55.1	73.8	82.9	140.3	149.3
Camden		10.5	21.2	25.7	45.7	115.1	147.0	200.9	231.7	321.3	336.2
Carteret		56.0	95.5	126.9	179.4	326.4	379.3	427.4	436.8	489.9	495.5
Chowan		2.9	5.0	6.5	9.2	17.3	22.2	42.0	54.7	172.9	187.6
Craven		7.9	16.2	19.6	31.5	60.0	78.3	110.8	131.7	242.8	266.6
Currituck		22.9	37.9	49.6	70.6	143.4	177.8	251.7	273.3	321.7	325.5
Dare		47.0	65.2	71.5	86.1	106.2	117.5	133.4	140.4	153.7	154.8
Gates		5.3	10.5	11.3	16.1	22.3	27.1	36.3	49.6	106.6	130.2
Hertford		3.7	6.9	7.4	11.3	17.5	21.5	26.5	30.6	50.2	55.4
Hyde		280.5	410.4	433.5	482.0	548.3	586.4	640.9	659.5	703.9	707.4
New Hanover		8.3	13.0	14.9	20.5	29.9	35.1	45.2	52.0	83.5	89.6
Onslow		25.3	32.6	35.3	43.1	58.2	67.6	85.0	95.8	152.2	165.8
Pamlico		26.9	48.2	64.3	94.6	169.8	194.4	243.0	262.6	321.6	325.1
Pasquotank		11.0	26.1	39.6	64.9	131.4	161.2	220.7	259.4	457.3	460.0
Pender		5.9	9.9	11.6	16.8	28.0	36.3	55.2	68.9	135.9	148.6
Perquimans		5.0	8.8	11.7	18.1	51.9	79.1	144.7	189.4	427.1	432.0
Tyrrell		130.6	235.5	269.3	321.1	357.8	369.1	375.1	377.5	380.3	380.3
Washington		5.6	13.7	22.4	38.4	80.9	106.2	191.6	238.1	534.8	555.7
North Carolina[1]		**724**	**1179**	**1368**	**1757**	**2609**	**3030**	**3803**	**4208**	**6124**	**6349**
		Cumulative (total) amount of wetlands below a given elevation									
Beaufort	35.1	64.9	94.6	105.4	131.0	171.1	202.2	252.5	272.3	322.9	329.8
Bertie	0.3	110.2	123.1	127.0	132.4	146.9	152.6	171.0	176.9	224.8	233.6
Brunswick	109.2	38.4	44.0	47.2	51.9	60.8	64.6	73.2	76.7	94.6	97.8
Camden	7.1	137.2	146.3	148.7	154.6	167.7	174.7	186.8	194.2	243.1	258.0
Carteret	334.3	33.9	66.5	86.6	117.1	180.0	201.6	236.5	243.3	286.4	292.5
Chowan	0.0	29.1	32.5	34.0	36.6	41.7	43.9	51.2	55.8	95.9	104.3
Craven	12.1	58.9	74.3	79.7	94.4	121.1	136.8	158.7	169.7	216.6	227.5
Currituck	124.6	129.3	144.4	150.1	158.6	177.9	183.8	196.3	199.3	218.7	220.6
Dare	167.8	376.3	525.3	552.6	604.0	658.6	663.5	665.5	665.9	666.4	666.4
Gates	0.0	78.5	88.6	89.3	93.1	98.7	102.3	107.8	113.7	129.4	132.0
Hertford	0.0	44.8	53.0	53.8	57.6	61.8	65.4	68.9	70.8	79.7	81.2
Hyde	199.3	324.7	461.1	488.4	538.2	577.9	592.2	619.5	633.6	684.6	688.7
New Hanover	55.7	27.7	34.7	36.0	39.0	43.3	45.4	49.1	51.0	59.1	60.5
Onslow	68.8	24.7	29.6	31.1	35.1	41.3	44.7	50.5	54.0	69.4	71.7
Pamlico	111.6	51.6	66.7	73.1	81.0	106.3	123.1	148.4	161.0	221.1	231.6
Pasquotank	0.3	50.0	58.2	62.4	68.2	78.6	84.0	96.3	101.9	123.5	124.1
Pender	38.2	82.7	107.4	113.4	127.7	149.8	160.7	178.8	188.8	231.7	238.9
Perquimans	0.0	38.1	43.7	46.8	52.0	65.8	73.6	90.5	97.8	167.0	180.2
Tyrrell	3.8	421.7	502.3	522.5	554.1	571.5	578.9	593.3	601.5	622.5	622.5
Washington	0.3	70.0	78.2	85.5	92.5	105.5	112.0	134.5	145.5	191.8	197.1
North Carolina[1]	**1272**	**2280**	**2879**	**3048**	**3354**	**3794**	**3992**	**4347**	**4509**	**5273**	**5405**
Dry +		3004	4059	4415	5112	6404	7021	8150	8717	11397	11754

Nontidal wetland											
All Land	1272	4276	5331	5687	6384	7676	8293	9422	9989	12669	13026

Source. Adapted from Titus and Wang (2008) and Titus and Cacela (2008) .
[1] Includes Bladen, Columbus, Duplin, Edgecombe, Greene, Halifax, Jones, Lenoir, Martin, Northampton, Pitt, and Sampson Counties which were omitted to fit table on a single page.

More than half the dry land below 50 cm is in either Hyde or Tyrrell County. But Carteret, Beaufort, and Dare counties also have approximately 50 to 100 square kilometers of dry land below the 50-cm contour. All of these counties have populated areas close to sea level. In the case of Dare County, some of the low-lying areas are on the sound side of the Outer Banks.

The data on coastal elevations probably understate the vulnerability of North Carolina relative to the rest of the Mid-Atlantic. Because the land is flat, areas a few meters above sea level drain slowly — so slowly that most of the lowest land is nontidal wetland. Because rising sea level decreases the average slope between nearby coastal areas and the sea, it may also slow the speed at which these areas drain. Some of the dry land a few meters above the tides could convert to wetland from even a small rise in sea level; and nontidal wetlands at these elevations would be saturated more of the time. Wetland loss could occur if dikes and drainage systems are built to prevent dry land from becoming wet.

The very low tide range in some of the sounds is another possible source of vulnerability. Albemarle Sound, Currituck Sound, and much of Pamlico Sound have a very small tide range, because inlets to the ocean are few and far between (NOAA, 2005). Some are narrow and shallow as well. Although Oregon and Ocracoke inlets are more than 10 meters deep (over 30 feet), the inlets are characterized by extensive shoals on both the ebb and flood sides, and the channels do not maintain depth for long distances before they break into shallower finger channels[175]. Like narrow channels, this configuration slows the flow of water between the ocean and sounds. Thus, although the astronomic tide range at the ocean entrances is approximately 90 cm, it decreases to 30 cm just inside the inlets, and a few centimeters in the centers of the estuaries.

The water-level variations are driven by local and regional wind and barometric pressure changes rather than astronomical tides. NOAA estimates that most of the estuary is about 15 cm above sea level (although the average water level in parts of these estuaries may be below the ocean sea level). Figure G.4 shows estimated mean tide level, compared with the reference elevation known as NAVD88, which is 13 cm above the ocean sea level (NOAA 2008). Therefore, even areas with no dikes have substantial dry land and nontidal wetlands within (for example) 30 cm above the estuary's mean tide level (45 cm above ocean sea level). But it is possible that rising sea level combined with storm-induced erosion will cause more, wider, and/or deeper inlets in the future (Zhang *et al.*, 2004; see chapter 2). If creation of more extensive inlets caused the astronomical tide range to increase to (for example) 60 cm, then the dryland and nontidal wetlands lands that are 30 cm above the estuary's mean level today would be inundated by the tides even if mean sea level did not rise[176]. For the same reason, if sea level continues to rise or accelerates, the average high tide could rise by 30-60 cm more than the rise in mean sea level.

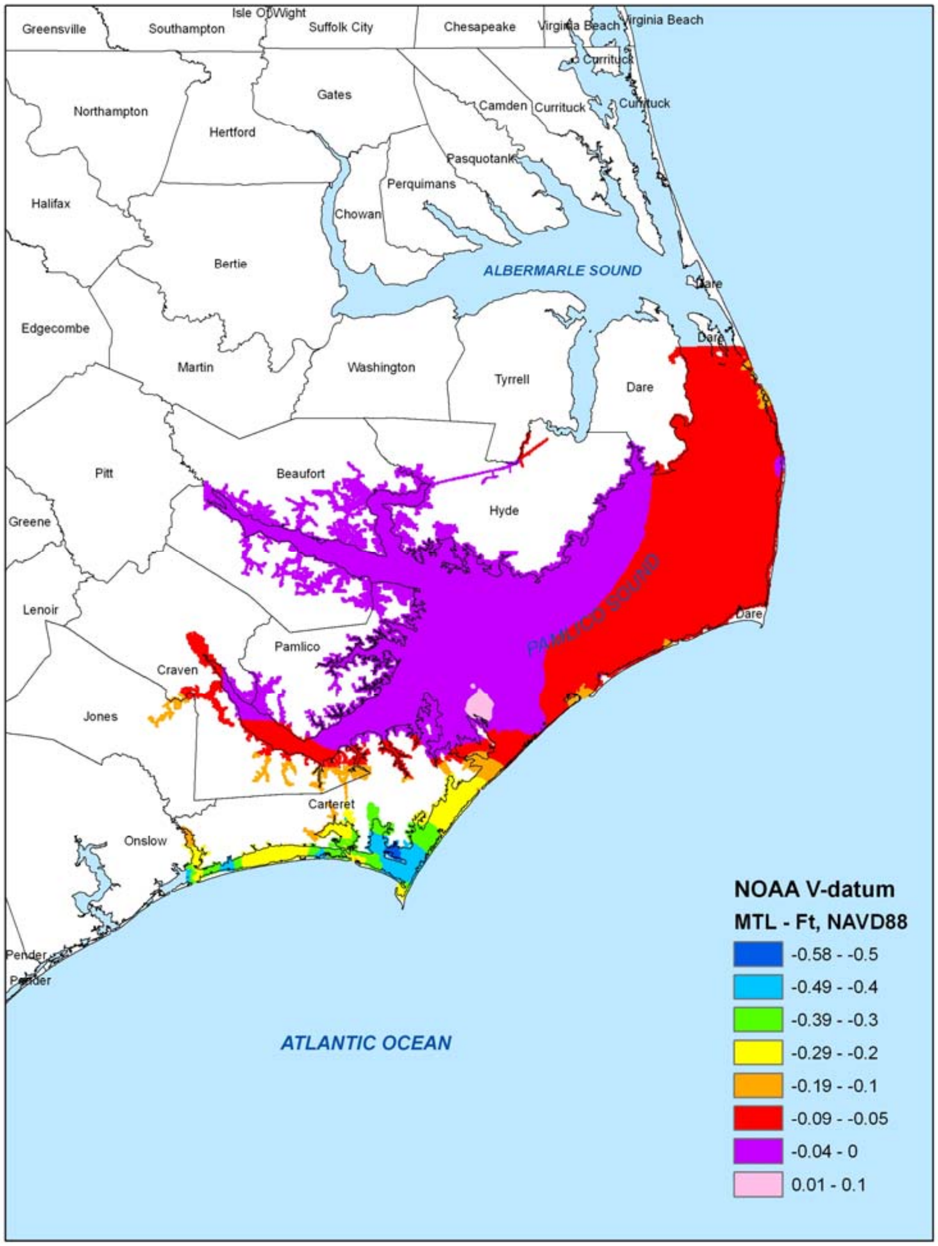

Figure G.4 Estimated Mean Tide Level in North Carolina Estuaries. Elevation compared with NAVD88. Source: Adapted from NOAA 2004.

The reduced tidal flushing also keeps salinity levels relatively low in most of the estuaries within the Northern Coastal Province (Riggs and Ames, 2003 p.9). Salinity is relatively high at the inlets, but declines as one proceeds upstream. Also, there is a strong seasonal variation with lower salinities during the periods of maximum river discharge and higher salinities during periods of drought. The salinity in Albemarle-Pamlico Sound can generally range from 0 parts per thousand (ppt) to 20 ppt, with the salinity in the upper reaches of the Neuse and Pamlico Rivers, Albemarle Sound and Currituck Sound having salinities usually below 5 ppt (Calwell, 2001; Tenore, 1972). Some tidal marshes (which are irregularly flooded by the winds rather than the regularly flooded by astronomical tides) are thus unable to tolerate salt water. In some areas, the flow of shallow groundwater to the sea is also fresh, so the soils are also unaccustomed to salt water.

More than other areas in the Mid-Atlantic, the Albemarle-Pamlico Sound region appears to be potentially vulnerable to the possibility that several impacts of sea-level rise might compound to produce an impact larger than the sum of the individual effects (Poulter and Halpin, 2008). If a major inlet opened, increasing the tide range and salinity levels, it is possible that some freshwater wetlands that are otherwise able to keep pace with rising sea level would be poisoned by excessive salinity and convert to open water. Similarly, if a pulse of salt water penetrated into the groundwater, sulfate reduction of the organic-rich soil and peat that underlays parts of the region could cause the land surfaces to subside (Portnoy and Giblin, 1997; Mitsch and Gosselink, 2000 p.10; Henman and Poulter, 2008).

Thus the land surrounding the Pamlico and Albemarle sounds faces the triple threat in which rising sea level (a) directly threatens low-lying areas with erosion and tidal inundation (Chapter 1) and might also create larger or more inlets (Chapter 3), which could (b) further increase tidal flooding, and (c) increase salinity levels, which could induce additional erosion and land subsidence[177]. Moreover, as we saw in Chapter 2, a substantial acceleration in the rate of sea-level rise could cause barrier islands to disintegrate. Pamlico Sound (and potentially Albemarle Sound) could be transformed from a protected estuary into a semi-open embayment with saltier waters, regular astronomical tides, and larger waves (Riggs, 2006).

G.2 SHORE PROCESSES

G.2.1 Ocean Coasts

North Carolina receives the highest wave energy along the entire east coast of the United States. When Hurricane Isabel cut a 1,700-foot-wide gap in Hatteras Island in September 2003, the North Carolina Department of Transportation and Army Corps of Engineers were able close the breach within two months at a cost of about $6.2 million (Schmitt, 2003; Beavers and Bruner, 2003). However, there are at least five sections of Hatteras Island that transportation planners refer to as “hot spots,” narrow, highly dynamic areas where the highway is at risk from storm surges at any time.

The North Carolina Division of Coastal Management (NCDCM) has calculated long-term erosion rates along the coastline adjacent to the ocean by comparing the location of shorelines in 1998 with the oldest available maps of shoreline location, mostly from the

1940s. The average erosion rate was 0.8 m (4.3 ft) per year. Approximately 18% of the ocean coastline retreated by more than 1.5 m/yr (5 ft/yr), and approximately 61% retreated by at least 0.6 m/yr (2 ft/yr). But 32% of the coastline accreted (NC DCM, 2003)[178]. The NCDCM recalculates long-term erosion rates about every five years to better track the dynamic shoreline trends and establish the setback line that determines where structures may be permitted on the oceanfront (NCDCM, 2005).

Several authors have estimated future shoreline erosion as sea level rises. One analysis of statewide erosion rates over the past 100 years led researchers to estimate that a one meter sea-level rise would cause the shore to retreat an average of 88 m, in addition to the erosion caused by other factors (excluding inlets) (Leatherman, Zhang and Douglas, 2000a)[179]. Another study estimated that a rise in sea level of 0.52 m between 1996 and 2050 would cause the shoreline at Nags Head to retreat between 33 and 43 m (Daniels, 1996).

Some researchers also believe that the barrier islands themselves may be in jeopardy if sea-level rise accelerates. According to Riggs and Ames, about 40 km (25 miles) of the Outer Banks are so sediment-starved that they are already in the process of "collapsing"[180]. Within a few decades, they estimate, portions of Cape Hatteras National Seashore could be destroyed by (1) sea-level rise (at current rates or higher), (2) storms of the magnitude experienced in the 1990s, or (3) one or more Category 4 or 5 hurricanes hitting the Outer Banks (Riggs and Ames, 2003). If several breaches were to open simultaneously, Pamlico Sound (and potentially Albemarle Sound) could be transformed from a protected estuary into a "semi-open embayment" with saltier waters, regular astronomical tides, and larger waves (Riggs, 2006).

Considering these and other studies, a panel of shoreline experts organized by USGS concluded that most of the Outer Banks between Nags Head and Ocracoke is vulnerable to barrier island disintegration over the next century if the rate of sea-level rise accelerates 2 mm/yr — and portions may be vulnerable even at the current trend. (See Chapter 3). The state of North Carolina alone has as much vulnerable ocean shore as all of the shores from Virginia to New York combined. (See Chapter 3).

G.3 VULNERABLE HABITATS AND SPECIES

Chapter 3 presents an assessment of the potential for wetland accretion from Virginia to New York, which excludes North Carolina. Nevertheless, authors in North Carolina appear to have reached a similar qualitative result. Some wetland systems are already at the limit of their ability to vertically keep pace with rising sea level, such as the remnants of the tidal marshes that connected Roanoke Island to the mainland of Dare County until the 19th century. The pocosin wetlands can vertically accrete by about 1-2 mm per year with or without rising sea level—when they are in their natural state (Craft and Richardson, 1998; Moorhead and Brinson, 1995). The altered drainage patterns, however, appear to be limiting their vertical accretion—and saltwater intrusion could cause subsidence and conversion to open water. Rather than helping the ecosystem respond to rising sea level, human activities appear to be disabling the processes that could otherwise allow these wetlands to stay ahead of the rising sea.

This section examines the types of wetlands in this area and the landscapes where they are found, followed by shoreline erosion and some of the rates at which it has been measured in different settings. We then discuss how wetlands affect the position of the shoreline and ways wetlands can respond to sea-level rise. Some wetlands, particularly marshes and swamps, can migrate landward as sea level rises, particularly if the slope of the land is gradual. Finally, we discuss some of the environmental effects of wetlands loss.

G.3.1 Distribution of Wetland Types

The Albemarle-Pamlico Sound system includes most of the major estuaries in North Carolina. The Albemarle Sound receives drainage from the Chowan and Roanoke Rivers (as well as Currituck Sound and Back Bay in Virginia Beach) and the Pamlico Sound receives drainage from the Tar and Neuse Rivers. All of these rivers deliver substantial quantities of sediments that are either deposited on adjacent floodplains or are carried into the Albemarle Sound and the Pamlico River and Neuse estuaries. Deposition rates of these sediments in the estuaries approximate 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 there is little or no astronomic tide to carry them to wetland surfaces. Storms that generate high water levels, especially ‘northeasters’ that raise water levels in the southern portions of Pamlico Sound, deposit sediments on storm levees adjacent to marsh shorelines. Most tributaries that drain the coastal plain are a minor supply of suspended sediment to the estuaries (Riggs, 1996).

While many wetlands in coastal North Carolina formed in similar geologic settings, different types of wetlands emerged. Poorly drained flat plains between streams (known as inter-stream divides) typify the Albemarle-Pamlico Peninsula. Portions of these areas are locally known as "pocosins," which refers to a plant community of evergreen shrubs and wetland tree species occupying peat deposits[181]. Rising sea level has now reached some peatlands, particularly those at lower elevations, *e.g.*, in Dare County, on the extreme eastern end of the Albemarle-Pamlico peninsula. As a result, scarped peat shorelines (*i.e.*, peat shorelines with steep vertical drop-offs created by waves) are extensive (Riggs and Ames, 2003).

Other types of wetlands, including large areas of marshes and forested wetlands, are also influenced by sea level. Many are classified as fringe wetlands because they occur along the periphery of estuaries that flood them irregularly. Salinity is the major control that determines the dominant vegetation type. In the fresh to slightly brackish (oligohaline) Albemarle Sound region, forested shrub-scrub wetlands dominate. Forested wetlands also occur on floodplains of the major rivers (Chowan, Roanoke, Tar, and Neuse), as well as tributaries draining pocosins and other areas of the coastal plain. As the shoreline erodes in areas with forested wetlands, bald cypress trees become stranded in the permanently flooded zone. They eventually die and fall down, which creates a zone in shallow water with a complex habitat structure, including fallen trees and relic "knees" cypress trees once sprouted for support. Landward, one finds a "storm levee" (coarse sand deposited during storms) bordering the swamp forest in areas exposed to waves. These forests are described as "tidal cypress-gum swamp." (Shafale and Weakley, 1990) They can range from gum-maple swamps on mineral soils to evergreen shrub bogs (pocosins) growing on peaty deposits.

Salinity is an important factor that affects the types of vegetation found in a given area. Trees are killed by extended exposure to salinity above 10 ppt (approximately 1/4 -1/3 the salinity of sea water), and the growth of most trees and shrubs is restricted at much lower salinities (Conner *et al.*, 1997; Poulter *et al.*, 2008). In brackish water areas, marshes consisting of plants that are saltwater-tolerant replace forested wetlands. Along the Pamlico Sound, a large area consists of brackish marshes. 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. It is only the lower reaches of the Chowan, Roanoke, Tar, and Neuse rivers that are affected by rising sea level. Along small tributaries of the Neuse and Pamlico River estuaries, there are brackish marshes at estuary mouths and forested wetlands in regions further upstream, where the salinity is low (Brinson *et al.*, 1985).

Sea level influences the location of the boundaries between wetlands and uplands, in part because estuarine water levels can drive poor drainage of coastal wetlands. These boundaries are commonly found where brackish water from storm surges has created a transition between salt-tolerant marshes and upland forest. Sea level also may influence the zones different plant communities occupy. For example, where waves have raised the elevation of wetlands by depositing sediment on “storm levees” on the shore of marshes, the elevation tends to be higher than in adjacent areas, and therefore different types of plants tend to be found there.

G.3.2 Estuarine Shoreline Erosion

Rising sea level is not the primary cause of shoreline retreat along estuarine shores in North Carolina. Storm waves cause shorelines to recede whether or not the sea is rising. Nevertheless, rising sea level can indirectly increase the erosive power of storm waves, and decrease the ability of shores to advance between storms. (See Chapter 2). A study of 21 sites estimated that shoreline retreat — caused by “the intimately coupled processes of wave action and rising sea level” — is already eliminating wetlands at a rate of about 3.2 square kilometers (800 acres) per year, mostly in zones of brackish marsh habitat, such as on the Albemarle-Pamlico Peninsula (Riggs and Ames, 2003).

Riggs and Ames (2003) compiled data collected across North Carolina shorelines, both those that are adjacent to wetlands and those that are not. These data show that the vast majority of estuarine shores in the region are eroding, except for the sound sides of barrier islands (which one might expect to advance toward the mainland). Shores have retreated almost 2 m per year, over periods as long as 30 years. Annual averages for most shoreline types are less than 1 m per year, (Table G.2) but annual maxima exceed the average many-fold and can reach 8 m per year where the shoreline is characterized by sediment bluffs or high banks. One or a few individual storm events contribute disproportionately to average annual shoreline recession rates (Riggs and Ames, 2003). Variables that affect erosion rates include number and pattern of seasonal storms, fetch (the distance waves travel over open water), shoreline type, composition of soil, presence and type of vegetation, and depth of water near the shore.

Table G.2 Estuarine shoreline erosion rates by shoreline type and the percent of total shoreline for each type. From Riggs and Ames (2003), Table 9-1-5, at 145.

Shoreline type	Percent of shoreline	Maximum rate per year (m)	Average rate per year (m)
Sediment Bank			
Sediment low bank	30	2.7	1.0
Sediment bluff/high bank	8	8.0	0.8
Back-barrier strandplain	?	0.6	-0.2*
Organic Shoreline			
Mainland marsh	55	5.6	0.9
Back-barrier marsh	?	5.8	0.4
Swamp forest	7	1.8	0.7
Total			2.7

G.3.3 Will Wetlands Keep Pace With Rising Sea Level?

Although wetlands are retreating at their seaward boundaries, away from the shore, most marshes and swamps in North Carolina appear to be keeping pace with rising sea level. As we look into the future, three scenarios seem possible:

Continuation of current trends. If sea level continues to rise approximately 3 mm/year, most wetlands are unlikely to drown, although some wetland will be lost as shores retreat.

Wetland drowning, however, may result if rates of sea-level rise increase by 2 mm/yr, and is likely if rates increase by 7 mm/yr[182]. Under the drowning scenario, the low-lying wetlands of the lower coastal plain would convert to aquatic ecosystems, and the large, low, and flat pocosin would transform from forest to aquatic habitat (Poulter, 2005). In areas of pocosin peatland, shrub and forest vegetation first would be killed by brackish water. In contrast to fringe wetlands, swamp forest wetlands along the piedmont-draining rivers are likely to sustain themselves under the drowning scenario. This is due to the general abundance of mineral sediments when rivers overflow their banks. This applies to regions within the floodplain, but not at river mouths. Also, pocosin swamp forest peatlands at higher elevations in the coastal plain will continue to grow vertically, independently of sea-level rise and of mineral sediment supplies since they are disconnected from the riverine and estuarine systems.

Barrier islands are breached. Chapter 6 suggests that more inlets are likely, and that disintegration of some of the barrier islands is possible if sea-level rise accelerates. This would cause a state change from a non-tidal to tidal regime as additional inlets open, causing the Albemarle and Pamlico Sounds to have a significant tide range and increased salinity. Poulter (2005) estimated that conversion from a non-tidal to tidal estuary might expose hundreds of square kilometers of nontidal wetlands to tidal flooding. In theory, it is possible that this transformation might increase the ability of wetland to keep pace with rising sea level by increasing the supply of sediment. The conversion of Pamlico Sound to a tidal system would likely re-establish tidal channels where ancestral streams were located. 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 former uplands.

As sea level rises further and waters with higher salt content reach the peninsula, the ability of peat-based wetlands to keep up is doubtful (Riggs, 2006). In peatlands, shrub and forest vegetation first would be killed by brackish water. It is unlikely that pocosin and swamp forest areas would convert to tidal wetlands, for two reasons. First, the root mat within them would collapse due to plant mortality and decomposition, causing a rapid subsidence of several centimeters[183]. Second, brackish water may accelerate decomposition of peat. When seawater reaches peat soils, a group of sulfate-metabolizing bacteria begin to digest the soil at a much faster rate than the normal methane-producing bacteria that inhabit freshwater peat soils (Portnoy and Giblin, 1997). Further, the death of woody vegetation and fact that wetland plants can no longer become established results in the exposure of organic-rich soils directly to decomposition, erosion, suspension, and transport, without the stabilizing properties of vegetation (Henman and Poulter, 2008; IPCC, 2007).

G.3.4 Environmental Implications of Habitat Loss and Shore Protection

North Carolina's coastal wetlands provide important habitat for many species. Human activities to control shoreline erosion and flooding, however, are already harming wetlands. Nontidal wetlands account for more than 69 percent of the land within one meter above spring high water.

Ecological/habitat processes and patterns. Some wetland functions are proportional to size. Other functions depend on the wetland's edges, that is, the borders between open water and wetland. Because of the large size of many irregularly flooded marshes in the region, their interior portions are effectively isolated from the aquatic portions of the estuary.

In the absence of tidal creeks and astronomic tidal currents, pathways for fish and invertebrate movement are severely restricted. In contrast, the twice-daily inundation of tidal marshes increases connections across the aquatic-wetland edge, as does the presence of tidal creeks, which allow fish and aquatic invertebrates to exploit intertidal areas (Kneib and Wagner, 1994). Mobility across ecosystem boundaries is less prevalent in irregularly flooded marshes, where some fish species become marsh "residents" because of the long distances required to navigate from marshes to subtidal habitats (Marraro *et al.*, 1991). Where irregularly-flooded marshes are inundated for weeks at a time, little is known about how resident species adapt. These include, among other species, several types of fish (*e.g.*, killifish and mummichogs), brown water snakes, crustaceans (various species of crabs), birds (yellowthroat, marsh wren, harrier, swamp sparrow, and five species of rails), and several species of mammals (nutria, cotton rat, and raccoon). North Carolina's coastal marshes are also home to a reintroduced population of red wolves (see Box G.1).

BOX G.1: Reintroduced population of red wolves in North Carolina

Red Wolf *(Canus rufus)*

Photograph credit: U.S. Fish and Wildlife Service. Red Wolf Recovery Project. Photos. Accessed at: http://www.fws.gov/alligatorriver/redwolf/rwpics.html on March 12, 2007. Photo: Greg Koch

Habitat: The red wolf (*Canus rufus*) is federally listed as endangered and was formerly extinct in the wild. Red wolves were hunted and trapped aggressively in the early 1900s as the southeast became increasingly developed, and the remaining wolves then suffered further declines with the extensive clearing of forest and hardwood river bottoms that formed much of the prime red wolf habitat (USFWS, 1993; USFWS, 2004). The last wild red wolves were found in coastal prairie and marsh habitat, having been pushed to the edges of their range in Louisiana and Texas. The red wolf is elusive, and most active at dawn and dusk. It lives in packs of five to eight animals, and feeds on white-tailed deer, raccoon, rabbit, nutria, and other rodents. In addition to food and water in a large home range area (25 to 50 square miles), red wolves require heavy vegetation cover (USFWS, 1993).

Locations: Through a captive breeding program and reintroduction of the species, there are now an estimated total of 100 red wolves living in the wild in coastal areas of North Carolina. In the wild, the red wolf currently occupies approximately 1.7 million acres on three national wildlife refuges and other public and private lands in eastern North Carolina. Principal among these areas is the Alligator River National Wildlife Refuge (NWR), the site of the red wolf's reintroduction to the wild in 1987 (USFWS, 2006). The refuge is surrounded on three sides by coastal waters and connected to the mainland by a largely developed area. Red wolves have also been reintroduced to the Pocosin Lakes NWR, slightly inland from Alligator River NWR, and are occasionally sighted on the Mattamuskeet NWR. The last wild red wolves were found in Louisiana and Texas coastal marsh areas, but their historic range extended from southern Pennsylvania throughout the southeast and west as far as central Texas (USFWS, 2004). Despite their potential for survival in numerous habitat types throughout the southeastern United States, the small current population faces serious threats from sea level rise.

Impact of Sea Level Rise: Alligator River National Wildlife Refuge (NWR), the red wolf's primary population center is at risk due to sea level rise. Developed areas inland of the peninsular refuge limit habitat migration potential. In a 2006 report, the Defenders of Wildlife (an environmental advocacy organization) characterized Alligator River NWR as one of the ten NWRs most gravely at risk due to sea level rise. The effects of sea level rise can already be seen on the habitat in Alligator NWR, where pond pine forest has transitioned into a sawgrass marsh in one area, and the peat soils of canal banks are eroding near the sounds (Stewart, 2006). Areas of hardwood forest and pocosin will be replaced by expanding grass-dominated freshwater marshes currently occupying the edges of the sounds. Bald cypress and swamp tupelo forests will also replace the hardwood areas (USFWS, 2006). The red wolf is not likely to adapt to the marsh habitat in the short amount of time that these processes are already taking place (Stewart, 2006).

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Effects of human activities. Human alterations, including bulkheads and other shore protection structures, have served mostly to stabilize the position of coastal wetlands and thus resist effects of both rising sea level and erosion.

Levees associated with waterfowl impoundments have isolated large marsh areas in southern Pamlico Sound from any connection with estuarine waters. Impoundments were built to create a freshwater environment conducive to migratory duck populations and thus eliminate most other habitat functions mentioned above for brackish marshes. Further, isolation from sea level influences has likely disconnected the impoundment from pre-existing hydrologic gradients that would promote vertical accretion of marsh soil. If the impoundments were opened to an estuarine connection after decades of isolation, they would likely become shallow, open-water areas incapable of reverting to wetlands (Day *et al.*, 1990).

Drainage ditches, installed to drain land so that it would be suitable for agriculture, are prevalent in North Carolina. By the 1970s, on the Albemarle-Pamlico Peninsula, there were an estimated 20 miles of streams and artificial drainage channels per square mile of land, while the ratio in other parts of North Carolina ranged from 1.4–2.8 to 1 (Heath, 1975). In many cases, ditches, some of which were dug more than a century ago to drain farmland (Lilly, 1981) now serve to transport brackish water landward, a problem that could become increasingly prevalent as sea level rises. Saltwater intrusion to agricultural soils is a major consequence of this process. A number of tide gates have been installed on the Albemarle-Pamlico Peninsula to reduce brackish water intrusion. Numerous canals and ditches in the Alligator River and Pocosin Lakes National Wildlife Refuges likewise carry brackish water inland, reversing intended flow directions. Brackish water may not only alter vegetation type in an area, but peat can collapse from the intrusion of sulfate-rich, brackish water. Studies are ongoing to understand the current and future effects of drainage networks (Poulter , Goodall and Halpin, in review).

Potential effects of human activities at the marsh-forest boundary on overland migration of wetlands are more subtle. The conversion of marsh into forest is an ongoing process that can expand or maintain marsh surface area that would otherwise be diminished by shoreline retreat. Existing structures can interfere with these processes, and new ones are being constructed in association with increasing shoreline and shore zone development. Highway and railroad beds directly impede wetland migration. Even those with culverts would hinder overland flow of water and slow wetland migration. Levees constructed to protect property from storm surges, dense housing developments with extensive bulkheads, and new highways and streets have similar effects.

G.4 DEVELOPMENT AND SHORE PROTECTION

G.4.1 Statewide Policy Context

Several North Carolina laws and regulations have an impact on response to sea-level rise within the state. First, setback rules encourage retreat by requiring buildings being constructed or reconstructed to be set back a certain distance from where the shoreline is located when construction permits are issued. Second, North Carolina does not allow shore protection structures such as seawalls and revetments on oceanfront shorelines,[184] preventing property owners from employing one possible method of holding back the sea to protect their property.[185]. Adding sand to beaches (*i.e.*, beach nourishment) is the preferred method in North Carolina to protect buildings near the ocean coastline. In addition, the State requires coastal counties to adopt land use plans to guide future development, and these plans are supposed to take into account sea-level rise[186]. In most county land use plans, this component does not explicitly address how the county will address sea-level rise, but land use plans are updated regularly (Feldman, 2007, pp. 64-65; Feldman, 2008, p. 5). The requirement could encourage counties to give more thought to how the areas most likely to be impacted by sea-level rise should respond in the future. Finally, the North Carolina Division of Coastal Management analyzes information and educates the public about shoreline change and coastal hazards in the state, and its efforts could heighten public awareness about sea-level rise vulnerability in North Carolina's coastal counties (Feldman, 2008).

North Carolina's Coastal Area Management Act and Dredge and Fill Law authorizes the Coastal Resources Commission (CRC) to regulate certain aspects of development within North Carolina's 20 coastal counties[187]. For example, the CRC issues permits for development and classifies certain regions as Areas of Environmental Concern (*e.g.*, ocean hazard zones and coastal wetlands) where special rules governing development apply. In response to the threat of damage to coastal structures from the waves, North Carolina has required since 1980 new development to be set back from the oceanfront. The setbacks are measured from the first line of stable natural vegetation[188]. Single-family homes of any size—as well as multi-family homes and non-residential structures with less than 5,000 square feet of floor area--must be set back by 60 feet or 30 times the long-term rate of erosion as calculated by the state, whichever is greater. Larger multi-family homes and non-residential structures must be set back by 120 feet or the erosion-based setback distance, whichever is greater. The setback distance for these larger structures is calculated as either 60 times the annual erosion rate or 105 feet plus 30 times the erosion rate, whichever is less[189]. North Carolina is considering changes to its oceanfront setback rules, including progressively larger setback factors for buildings with 10,000 square feet of floor area or more (NC CRC, 2007, p.1). Along estuarine shorelines, North Carolina has a 30-foot setback[190] and restricts development between 30 and 75 feet from the shore[191]. As the shore moves inland, these setback lines move inland as well.

As of 2000, the U.S. Army Corps of Engineers participated in beach nourishment projects along more than 32 miles of North Carolina’s shoreline (including some nourishment projects that occurred as a result of nearby dredging projects), and nourishment along an additional 85 miles of coastline had been proposed (USACOE, 2000)[192]. If necessary, property owners can place large (geotextile) sandbags in front of buildings to attempt to protect them from the waves. Standards apply to the placement of sandbags, which is supposed to be temporary (to protect structures during and after a major storm or other short-term event that causes erosion, or to allow time for relocation)[193]. Buildings are supposed to be moved or removed within two years of becoming “imminently threatened” by shoreline changes[194]. Furthermore, there is no ban on hardened structures along estuarine shorelines, as long as they are built landward of wetlands[195]. State guidelines for siting and constructing estuarine hardened structures are under review by the Coastal Resources Commission (see, *e.g.*, Feldman, 2008, p. 5).

The Coastal Area Management Act also requires that coastal counties develop and periodically update land use plans, which are binding in Areas of Environmental Concern. One of the hazards that these land use plans are supposed to take into account is sea-level rise, but most plans either do not include policies tailored to areas threatened by sea-level rise, address it only in passing, or defer to the state to take action.

North Carolina officials are in the process of reassessing certain state policies in light of the forces of shoreline change and climate change. Policy considerations have been affected by numerous studies that researchers have published on the potential effects of sea-level rise on North Carolina (Poulter *et al.*, in review). The state legislature appointed a Legislative Commission on Global Climate Change to study and report on potential climate change effects and potential mitigation strategies, including by providing recommendations that address impacts on the coastal zone (see the “North Carolina Global Warming Act,” Session Law 2005-442. The Commission’s recommendations have not yet been finalized, but a draft version offered such suggestions as creating a mechanism to purchase land or conservation easements in low-lying areas at great risk from sea-level rise; providing incentives for controlling erosion along estuarine shorelines using ecologically beneficial methods; creating a commission to study adaptation to climate change and make recommendations about controversial issues; and inventorying, mapping, and monitoring the physical and biological characteristics of the entire shoreline (Feldman, 2007, pp. 42-42; Feldman, 2008, p. 8; Riggs, Stephenson, and Clark 2007). The Coastal Resources Commission is also considering the potential effects of sea-level rise and whether to recommend any changes to its rules affecting development in coastal areas (Feldman, 2008, p.6). In addition, NCDCM is developing a Beach and Inlet Management Plan to define beach and inlet management zones and propose preliminary management strategies given natural forces, economic factors, limitations to the supply of beach-quality sand, and other constraints (Moffatt and Nichol, 2007).

G.4.2 Current Land Use

As discussed in Chapter 5, ongoing studies have combined land use data, regulations, and planner expectations for future development to create alternative scenarios of shore-protection and wetland migration. Because those studies have not yet been published in peer review journal articles, we describe some of the aspects of land use that would influence whether people hold back the sea or allow wetlands and beaches to migrate inland.

Ocean Coast. North Carolina's ocean coast, like the coasts of most states, includes moderate and densely developed communities, as well as undeveloped roadless barrier islands. Unlike other mid-Atlantic states, North Carolina's coast also includes a roadless coastal barrier that is nevertheless being developed, densely populated areas that nevertheless have been yielding homes to the sea, and a major lighthouse that has been relocated landward.

The northern 23 kilometers of the state's coastline is a designated undeveloped coastal barrier and hence ineligible for most federal programs (USFWS, not dated). This stretch of barrier island includes two sections of Currituck National Wildlife Refuge, each about 2 kilometers long, which are both off-limits to development and make it infeasible for the County to even consider a road along the barrier island (NC DOT, not dated). Nevertheless, the privately owned areas are gradually being developed, even though they are accessible only by boat or four-wheel drive vehicles traveling along the beach. The roadless areas are ineligible for federal beach nourishment and flood insurance.

Along the Dare County coast from Kitty Hawk to Nags Head, federal legislation has authorized shore protection, provided that it is cost-effective. Homes have been falling into the water as shores erode; but now that the through streets parallel to the shore are at risk, small sand replenishment projects have been undertaken to protect these roads. The beaches in some of the communities north of Kitty Hawk are not yet open to the public, and hence they are currently ineligible for beach nourishment.

From Nags Head to Hatteras Island, most of the coast is part of Cape Hatteras National Seashore, with a coastal highway running the entire length, from which one can catch a ferry to Ocracoke Island. Congress appropriated $9.8 million to move the Cape Hatteras Lighthouse 1,600 feet inland (NPS, 2000). The National Park Service generally allows shores to retreat, and the road has been relocated inland in places. Nevertheless, the coastal coastal highway is essential infrastructure, the protection of which would require maintaining the barrier island. A possible exception is that part of Hatteras Island between Rodanthe and Oregon Inlet. The federal and state governments are considering the possibility that when a new bridge is built over Oregon Inlet, that it would run over Pamlico sound just west of Hatteras Island, as far as Rodanthe.

Southwest of Cape Lookout, the coast consists mostly of developed barrier islands, , conservation lands that will not be protected, and designated “undeveloped coastal barriers” that are nevertheless being developed. The undeveloped Portsmouth Island and Core Banks constitute Cape Lookout National Seashore., and lack road access. Cape Lookout is located on Core Banks. Shackleford Banks, immediately adjacent to the southwest, is roadless and uninhabited. To its west, Bogue Banks includes five large communities with high dunes and dense forests (Pilkey *et al.*, 1998). The island also receives fill to widen its beaches regularly.

To the west of Bogue Banks are the barrier islands of Onslow County and then Pender County. Some islands are only accessible by boat, and most of these are undeveloped. North Topsail Beach, on Topsail Island, has been devastated by multiple hurricanes, in part due to its low elevation and the narrow width of Topsail Island. Erosion has forced multiple roads on the island to be moved. While some parts of North Topsail Beach are part of a unit under the Coastal Barrier Resources Act (CBRA) system, making them ineligible for federal subsidies, development has occurred within them nonetheless (Pilkey *et al.*, 1998).

Further to the west are the barrier islands of New Hanover County. An exclusive residential neighborhood is located on Figure Eight Island. Wrightsville Beach, like many other communities southwest of Cape Lookout, has an inlet on each side. It is the site of a well-known battle to protect a hotel from being washed away due to inlet migration. The U.S. Army Corps of Engineers has committed, over the long term, to regular beach renourishment to maintain the place of the shoreline in Wrightsville Beach and Carolina Beach (USACOE, 2006 p.38). An exception to North Carolina's rules forbidding hardened structures has been granted in Kure Beach, west of Carolina Beach, where rock rip-rap has been placed on the oceanfront to protect Fort Fisher (which dates back to the Civil War) (Pilkey *et al.*, 1998). The rip-rap also protects a highway that provides access to the area. Most of the beach communities in New Hanover County are extensively developed.

Some of the barrier islands in Brunswick County are heavily forested with high elevations, making them more resilient to coastal hazards (Pilkey *et al.*, 1998). Holden Beach and Ocean Isle Beach, however, contain many dredge-and-fill finger canals. Historically, at least two inlets cut through Holden Beach; and storms could create new inlets where there are currently canals (Pilkey *et al.*, 1998).

Estuarine Shores. Significant urbanization was slow to come to this region for many reasons. Most of the area is farther from population centers than the Delaware and Chesapeake estuaries. The Outer Banks were developed more slowly than the barrier islands of New Jersey, Delaware, and Maryland. And most importantly, the land is mostly low and wet. With more than 60 percent of the land within the Mid-Atlantic that might realistically be allowed to become submerged as sea level rises, this area represents an environmental planning opportunity that is of national importance.

The lands along the Albemarle and Pamlico sounds account for 70 percent of the nontidal wetlands, 40 percent of the dry land, and 55 percent of all the land in the Mid-Atlantic within 1 meter above spring high water.(Titus and Wang, 2008) They include about 50 percent of the dry land where protection is precluded or unlikely, and 63 percent of all land within the Mid-Atlantic that is likely to be submerged, assuming that nontidal wetlands are also allowed to flood (See Chapter 1).

Unlike the Delaware Estuary, communities in North Carolina do not have a long history of diking tidal wetlands to reclaim land from the sea for agricultural purposes[196]. But they are starting to gain experience with dikes to protect agricultural lands from flooding. In Tyrrell County, the Gum Neck has been protected with a dike for four decades. A dike is now planned for the town and farms around Swan Quarter, the county seat of Hyde County (which includes Ocracoke Island). Especially in Tyrell County, shore protection is a matter of self-preservation to this county. Hurricane Floyd led Pamlico County to encourage people to gradually abandon the eastern portion of the county, by working with FEMA to relocate people rather than rebuild damaged homes (Barnes, 2001). In parts of Carteret County, by contrast, people learned the opposite lesson and elevated homes. Hyde County is building a dike around its county seat and many farms nearby.

G.5 POPULATION OF LANDS CLOSE TO SEA LEVEL

Approximately 900,000 people live in the 20 coastal counties in North Carolina. The economies of these counties are dependent on agriculture, forestry, and tourism. Tourism is associated with coastal development and beach visits, as well as recreational sports and fishing. Bin *et al.*, (2007) estimated the economic costs of climate change in coastal North Carolina by evaluating impacts on tourism (beach visits and fishing), private property, and the business sector. They considered losses of beach width and fishing locations due to increased shoreline erosion from sea-level rise, loss of property value from direct inundation, and business interruptions from increased frequency of hurricanes associated with increasing sea surface temperatures.

In just four coastal counties (representing a cross-section of economic characteristics and vulnerability to sea-level rise), between 2 and 12% of properties were at risk from an 81 cm rise in sea level by the year 2080. The value of lost residential and nonresidential property in these four counties was estimated at $6.9 billion in 2080 (adjusted for a 2% discount rate) (Bin *et al.*, 2007). Impacts of sea-level rise on tourism, including recreational fishing, were based on the assumption that wider beaches are more frequently visited than narrower beaches. The study estimated that the lost recreational value ranged up to $3.5 billion for the southern North Carolina beaches, while lost fishing opportunities ranged up to $430 million (both estimates assumed a 2% discount rate) (Bin *et al.*, 2007).Lastly, business interruptions from changes in hurricane frequency and intensity were estimated, however the uncertainty regarding the relationship between climate change and hurricane characteristics is highly uncertain. The authors estimated that business impacts could increase 150% if hurricane intensity increases from Category 2 to 3 (Bin *et al.*, 2007).

BOX G.2: Vulnerability of the Albemarle-Pamlico Peninsula and Emerging Stakeholder Response

Vulnerability to sea level rise on the diverse Albemarle-Pamlico Peninsula is very high: about two-thirds of the peninsula is less than 5 feet above sea level (Heath, 1975), and approximately 30 percent is less than 3 feet above sea level (Poulter, 2005). Erosion rates in parts of the peninsula are already high. For example, along bluffs, erosion rates up to 25 feet per year have been measured (Riggs and Ames, 2003). The ecosystems of the Albemarle-Pamlico Peninsula have long been recognized for their biological and ecological value. The peninsula is home to four national wildlife refuges, the first of which was established in 1932. In all, about a fourth of the peninsula has been set aside for conservation purposes.

The Albemarle-Pamlico Peninsula is among North Carolina's poorest areas. Four of its five counties are classified as economically distressed by the state, with high poverty and unemployment rates, along with low wages. However, now that undeveloped waterfront property on the Outer Banks is very expensive and very scarce, developers have discovered the small fishing villages on the peninsula and begun acquiring property in several areas—including Columbia (Tyrell County), Engelhard (Hyde County) and Bath (Beaufort County). The peninsula is being marketed as the "Inner Banks." Communities across the peninsula are planning infrastructure, including wastewater treatment facilities and desalination plants for drinking water, to enable new development. Columbia and Plymouth (Washington County) have become demonstration sites in the North Carolina Rural Economic Development Center's STEP (Small Towns Economic Prosperity) Program, which is designed to support revitalization and provide information vital to developing public policies that support long-term investment in small towns (NC REDC, 2006).

There are already signs that sea level rise is causing ecosystems on the Albemarle-Pamlico Peninsula to change. For example, at the Buckridge Coastal Reserve, an 18,650-acre area owned by DCM, dieback is occurring in several areas of Atlantic white cedar. Other parts of the cedar community are beginning to show signs of stress. Initial investigations suggest the dieback is associated with altered hydrologic conditions, due to canals and ditches serving as conduits that bring salt and brackish water into the peat soils where cedar usually grows. Storm or wind events have pushed estuarine water into areas that are naturally fresh, affecting water chemistry, peatland soils, and vegetation intolerant of saline conditions (Poulter and Pederson, 2006).

There is growing awareness on the part of residents of the Albemarle-Pamlico Peninsula and local officials about potential vulnerabilities across the landscape. Many farmers acknowledge that salt intrusion and sea level rise are affecting their fields. Researchers at North Carolina State University are using Hyde County farms to experiment with the development of new varieties of salt-tolerant soybeans (NC SGA, 2002). Hyde County is building a dike around Swan Quarter, the county seat.

A variety of evidence has suggested to some stakeholders that the risks to the Albemarle-Pamlico Peninsula merit special management responses. In fact, because so much of the landscape across the peninsula has been transformed by humans, some have expressed concern that the ecosystem may be less resilient and less likely to be able to adapt when exposed to mounting stresses (Pearsall et al. 2005). Thus far, no comprehensive long-term response to the effects of sea level rise on the peninsula has been proposed. In 2007, The Nature Conservancy, Environmental Defense, Ducks Unlimited, the North Carolina Coastal Federation and others began working to build an Albemarle Conservation Partnership to develop a long-term strategic vision for the peninsula. Although this initiative is only in its infancy, sea level rise will be one of the first and most important issues the partnership will address.

The Nature Conservancy and others have already identified several potential responses to sea level rise on the Albemarle-Pamlico Peninsula. These approaches require community participation in conservation efforts, land protection, and adaptive management (Heath, 1975). Specific management strategies that the Nature Conservancy and others have recommended include: plugging drainage ditches and installing tide gates in agricultural fields so that sea water does not flow inland through them, establishing cypress trees where land has been cleared in areas that are expected to become wetlands in the future, reestablishing brackish marshes in hospitable areas where it is absent and areas that are likely to become wetlands in the future, creating corridors that run from the shoreline inland (which could facilitate habitat migration), reducing habitat fragmentation, banning or restricting hardened structures along the estuarine shoreline, and establishing submerged aquatic vegetation beds offshore (Pearsall and DeBlieu, 2005).

Table G.3 estimates the population of lands close to sea level in North Carolina. Because Census data for population is based on year-round residents, the estimates for many of the ocean coastal counties--especially Dare--would be greater if summer residents were included. The calculations assume that population is proportionately allocated in census blocks with high densities that are not along the open water. Therefore, the estimates for New Hanover County include residents of multifamily units on a census block that might have some low land along a historic or ancient creek. (See Chapter 6.)

Table G.3 Population of lands close to sea level: North Carolina.

County	Low and high estimates of population below a given elevation (thousands)					
	50cm		1m		2m	
	Low	High	Low	High	Low	High
North Carolina						
Beaufort	0.1	1.5	0.6	3.8	4.9	9.2
Brunswick	0.1	0.3	0.2	0.8	1.2	1.8
Camden	0.0	0.1	0.0	0.2	0.5	2.5
Carteret	0.4	2.1	1.2	5.3	8.4	14.6
Chowan	0.0	0.2	0.1	0.2	0.3	0.4
Craven	0.3	0.7	0.4	2.7	4.1	8.3
Currituck	0.0	0.2	0.1	0.7	1.2	3.2
Dare	0.0	1.9	1.1	5.1	7.3	11.9
Hyde	0.0	1.5	1.0	3.0	3.3	4.8
New Hanover	0.1	4.5	3.8	7.4	8.3	11.2
Onslow	0.3	0.8	0.7	1.1	1.3	2.8
Pamlico	0.0	0.3	0.3	0.7	1.3	2.7
Pasquotank	0.2	2.8	2.3	5.7	9.7	17.1
Pender	0.0	0.1	0.1	0.3	0.6	1.0
Perquimans	0.2	0.2	0.2	0.2	0.4	1.1
Tyrrell	0.0	1.4	0.9	2.3	3.1	3.6
Washington	0.0	0.1	0.1	0.2	0.3	1.2
Total	**1.6**	**18.6**	**12.9**	**39.7**	**56.2**	**97.5**

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Appendix H. Basic Approaches for Shoreline Change and Land Loss Projections: Application to Fire Island, New York

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While the factors that influence coastal change in response to sea-level rise are well known, our ability to incorporate this understanding into quantitative approaches that can be used to assess land loss over long time periods, such as 50-100 years, is limited. Part of the reason for this is the complexity of quantifying the influence of a range factors on shoreline change (*e.g.*, geologic framework, sediment supply, and hydrodynamic climate). In many settings, the human action to control the coast also adds to the complexity. This appendix reviews some of the basic approaches that have been applied to predict shoreline changes over 50-100 year time scales. One method which examines the vulnerability of a region to inundation (EPA, 1989; Titus and Richman, 2001; Rowley *et al.*, 2007) is used described previously in this report (See Chapter 1). This appendix is divided into two parts. First, three approaches that are used to predict shoreline change and land loss are reviewed. Next, three of the methods are applied to the shores of Fire Island, New York to provide examples of how these techniques are used and their limitations.

H.1 REVIEW OF SHORELINE CHANGE/SEA-LEVEL RISE IMPACT MODELS

The Bruun Model. One of the most widely known models developed for predicting shoreline change driven by sea-level rise on sandy coasts was formulated by Bruun (1962; 1988). This model is often referred to as the 'Bruun rule' and considers the two dimensional shoreline response (vertical and horizontal) to a rise in sea level (Schwartz, 1967). A fundamental assumption of this model is that the cross-shore shape of the beach, or beach profile, assumes an equilibrium shape that translates upward and landward as sea level rises. Four additional assumptions of this model are that:

- The upper beach is eroded due to landward translation of the profile
- The material eroded from the upper beach is transported offshore and deposited so that the volume eroded from the upper beach equals the volume deposited seaward of the shoreline
- The rise in the nearshore seabed as a result of deposition is equal to the rise in sea level, maintaining a constant water depth
- Gradients in longshore transport are negligible.

Mathematically, the model is depicted as:

$$R = \frac{L_*}{B + h_*} \cdot S \qquad \text{(Eqn H.1)}$$

where R is the horizontal retreat of the shore, h is the depth of closure or depth where sediment exchange between the shore face and inner shelf is assumed to be minimal, B is the height of the berm, and S is the vertical rise in sea level. This relationship can also be evaluated based on the slope of the shore face, Θ, as:

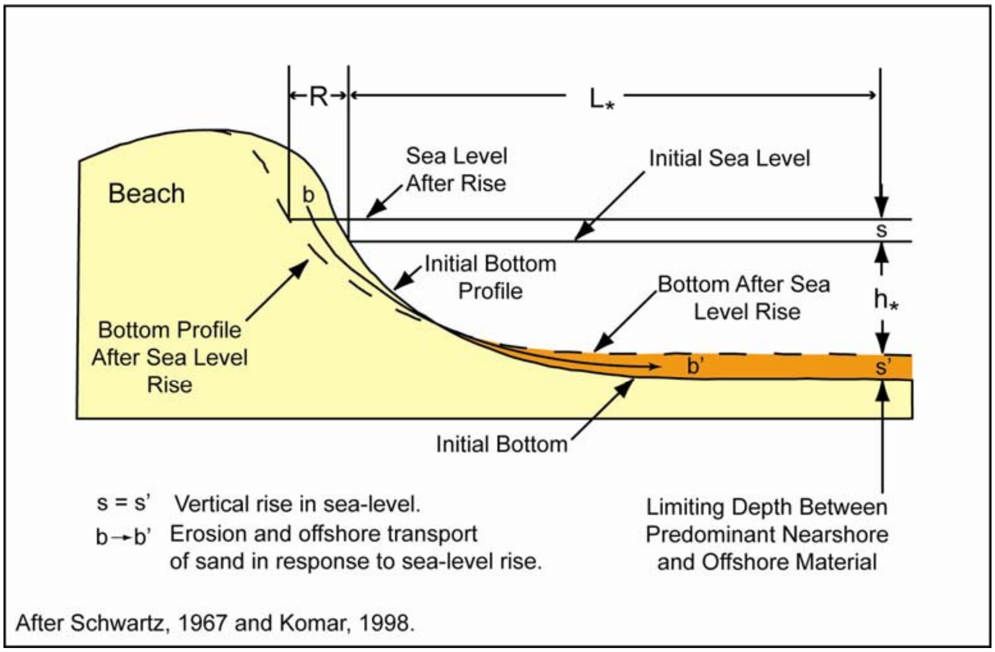
$$R = \frac{1}{\tan \Theta} \cdot S \qquad \text{(Eqn H.2)}$$

For most sites, it has been found that general values of Θ and R are approximately 0.01-0.02 and 50S–100S respectively (Wright, 1995; Komar, 1998; Zhang, 1998).

A few studies have been conducted to verify the Bruun Model to actual beach settings (Schwartz, 1967; Hands, 1980; also see SCOR, 1991; Komar, 1998; and Dean and Dalrymple, 2002 for a review). In other cases, some have advocated that there are several uncertainties with this approach which limit its use in practical application (Thieler *et al.*, 2000; Cooper and Pilkey, 2004). Field evaluations have also shown that the assumption of profile equilibrium can be difficult to meet (Riggs *et al.*, 1995, List *et al.*, 1997). Moreover, the Bruun relationship neglects the contribution of longshore transport which is a primary mechanism of sediment transport in the beach environment (Thieler *et al.*, 2000) and there have been relatively few attempts to incorporate longshore transport rates into this approach (Everts, 1985).

Even though the Bruun model has been in use for the last four decades no clear consensus exists regarding its validity as a quantitative predictive tool. Some studies have validated the approach (Bruun, 1962; Dubois, 1976; Hands, 1983; See review in SCOR, 1991; and Komar, 1998) while others have questioned several aspects of this method (Thieler *et al.*, 2000; Cooper and Pilkey, 2004).

A number of investigators have expanded upon the Bruun rule or developed other models that simulate sea-level rise driven shoreline changes. Dean and Maurmeyer (1983) adapted and modified the Bruun rule to apply to barrier islands (*e.g.*, the Generalized Bruun Rule). Cowell *et al.* (1992) developed the Shoreline Translation Model (STM) which incorporated several parameters that characterize the influence of geological framework to sea-level rise driven shoreline change. Stolper *et al.* (2005) developed a rules-based geomorphic shoreline change model (GEOMBEST) that simulates barrier island evolution in response to sea-level rise. While these models can achieve results consistent with our general understanding of sea-level rise driven changes to barrier island systems there is still the need for more research and testing against both the geologic record and present-day processes are needed to advance scientific understanding and inform management.



After Schwartz, 1967 and Komar, 1998.

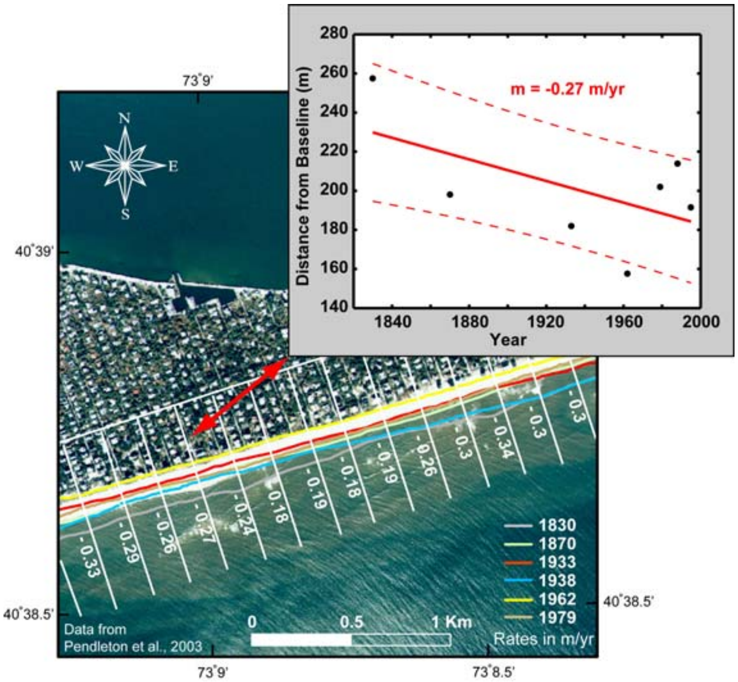
Figure H.1 Illustration showing the Bruun Model and the basic dimensions of the shore that are used as model inputs.

Historical Trend Extrapolation. Another commonly used approach to evaluate potential shoreline change in the future relies on the calculation shoreline change rates based on changes in shoreline position over time. The shoreline change rates can then be used to extrapolate future shoreline positions at a specific location. In this approach a series of shorelines is assembled from maps for a particular area. In most cases these maps are either National Ocean Service T-sheets, aerial photographs, or derived from GPS surveys (Shalowitz, 1964; Leatherman, 1983; Dolan *et al.*, 1991; Anders and Byrnes, 1991). The historical shorelines are then used to estimate rates of change over the time period covered by the different shorelines. Several statistical methods are used to calculate the shoreline change rates with the most commonly used being end-point rate calculations or linear regression (Dolan *et al.*, 1991; Crowell *et al.*, 1997). End-point rate calculations are simply the rates determined based on the change in position between the oldest and most recent shorelines in a given dataset. Linear-regression rates are the result of estimating the average rate of change using a number of shoreline positions over time. The shoreline change rates can then be used to extrapolate future changes in the shoreline (Crowell *et al.*, 1997).

Because past shorelines positions are readily available from maps that have been produced through time and the relatively straightforward approach, the extrapolation of historical trends to predict future shoreline position has been applied widely for coastal management and planning (Crowell and Leatherman, 1999). In particular, this method is used to estimate building set-backs (Fenster, 2005). Estimation of future shoreline positions is often the result of multiplying the observed rate of change by the number of years to of the projection. More specific assumptions can be incorporated that address the rate of sea-level rise or geological characteristics of an area (Leatherman, 1990; Komar *et al.*, 1999).

Historical trend analysis has evolved over the last few decades based on earlier efforts to investigate shoreline change (described in Crowell *et al.*, 2005). Since the early 1980s computer based GIS software has been developed to digitally catalogue shoreline data and facilitate the quantification of shoreline change rates (May *et al.*, 1982, Leatherman, 1983, Thieler *et al.*, 2005). At the same time, thorough review and critique of the procedures that are employed to make these estimates have been conducted (Dolan *et al.*, 1991; Crowell *et al.*, 1991; 1993; 1997; Douglas *et al.*, 1998, Douglas and Crowell, 2000; Honeycutt et al, 2001; Fenster *et al.*, 2001; Ruggiero *et al.*, 2003; Moore *et al.*, 2006; Genz *et al.*, 2007).

Recently, national scale assessment of shoreline change has been carried out by the U.S. Geological Survey (Gulf Coast: Morton *et al.*, 2004; southeastern U.S. coast: Morton and Miller, 2005; the California coast: Hapke *et al.*, 2006). In addition, efforts are ongoing to complete similar analyses for the Northeastern, mid-Atlantic, Pacific Northwest, and Alaskan coasts.



Data from Pendleton et al., 2003

Figure H.2 Aerial photograph of Fire Island, New York showing former shoreline positions and how they are used to calculate long-term shoreline change rates using linear regression. The inset box shows the shoreline positions at several points in time over the last 170 years. From the change in position with time, an average rate of retreat can be calculated. This is noted by the slope of the line, *m*. The red line in the inset box indicates the best fit line while the dashed lines specify the 95% confidence interval for this fit. Photo source: State of New York GIS.

The Sediment Budget. Another approach to shoreline change assessment involves evaluating the sediment mass balance, or sediment budget, for a given portion of the coast (Bowen and Inman, 1966; Komar, 1996; List, 2005). In this method, the gains and losses of sediment to a portion of the shore, often referred to as a control volume, are quantified and evaluated in based on estimates of beach volume change. Changes in the volume of sand for a particular setting can be identified and evaluated with respect to adjacent portions of the shore and to changes in shoreline position over time.

One challenge related to this method is obtaining precise measurements that minimize error since small vertical changes over these relatively low gradient shoreline areas can result in large volumes of material (NRC, 1987). To apply this approach, accurate measurements of coastal landforms such as beach profiles, dunes, or cliff positions, are needed. Collection of such data, especially those on the under-water portions of the beach profile are difficult. In addition, high-density measurements are needed to evaluate changes from one section of the beach to the next. While the results can be useful to understand where sediment volume changes occur, the paucity of quality data and the expense of collecting it limit the application of this method in many areas.

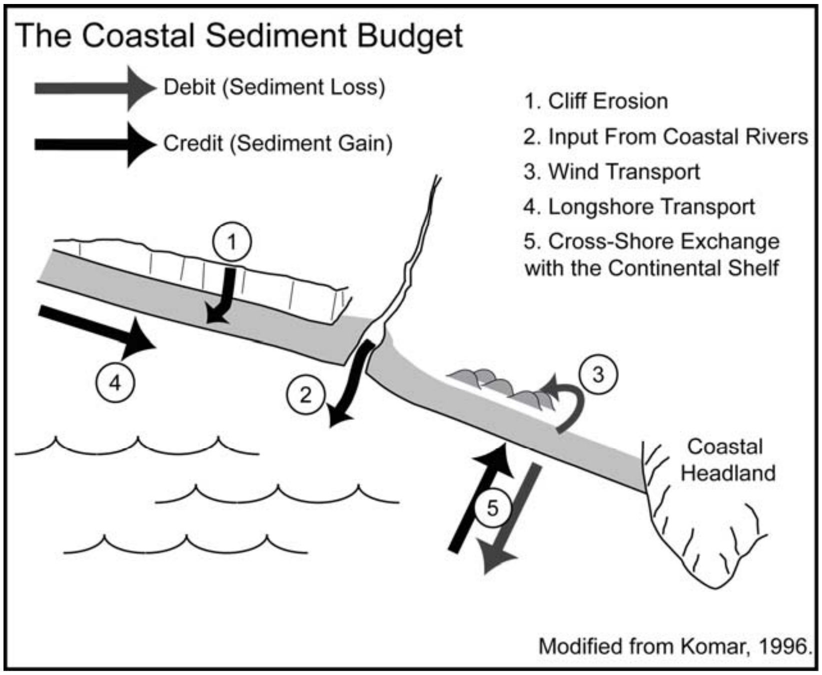


Figure H.3 A schematic of the coastal sediment budget (modified from Komar, 1996). In this approach the gains and losses of sediment from the beach and nearshore regions are evaluated to identify possible underlying causes for shoreline changes. In this schematic the main sediment sources are: 1) cliff erosion, 2) coastal rivers, 3) alongshore transport, and 4) cross-shore sediment transport from the continental shelf. The main sediment sinks are: 1) offshore transport from the beach to the shelf and 2) wind transport from the beach to coastal dunes.

Monte Carlo Simulation. One approach that has been applied to simple shoreline change models is the use of Monte Carlo simulations (Vrijling and Meijer, 1992, Reeve and Fleming, 1997). In this approach, a probability density function of some measure of shoreline change or position can be generated from a simple shoreline change model. A random number generator is used to generate a wide range of values for the respective input variables that are used to calculate the results. This approach is commonly applied using straightforward one-line models that relate shoreline change to wave height and sediment characteristics such as Pelnard-Considere's (1956) shoreline evolution equation or the U.S. Army Corps of Engineers CERC equation (CERC, 1984). This approach has been applied to address shoreline changes over time spans of 5 years (Dong and Chen, 1999), 12 years (Reeve and Fleming, 1997) and 25 years (Ruggiero *et al.*, 2006) but has not been attempted over longer scales approaching centuries and incorporated changes in sea level.

The Coastal Vulnerability Index. One approach to parameterize the potential for coastal changes is through the development of a Coastal Vulnerability Index (CVI). This technique was first applied by Gornitz *et al.* (1989; 1990; 1994) to evaluate coastal hazards along portions of the United States coast. In this approach, 13 variables that influence coastline change and morphology were identified. Each risk factor is ranked according to a numerical scheme. The magnitude of the combined factors is then computed to determine the CVI for a given section of coast. The resulting index provides a qualitative measure of potential vulnerability at a particular location.

Recently, the U.S. Geological Survey (USGS) used this approach to evaluate the potential vulnerability of the U.S. coastline on a national scale (Thieler and Hammar-Klose, 1999) and on a more detailed scale for the U.S. National Park Service (Thieler *et al.*, 2002). The USGS approach reduced the index to include six variables (geomorphology, shoreline change, coastal slope, relative sea-level change, significant wave height, and tidal range) which were considered to be the most important in determining a shoreline's susceptibility to sea-level rise (Thieler and Hammar-Klose, 1999). The CVI is calculated as:

$$CVI = \sqrt{\frac{a \times b \times c \times d \times e \times f}{6}} \qquad \text{(Eqn H.3)}$$

where a = geomorphology, b = rate of shoreline change, c = coastal slope, d = relative sea-level change, e = mean significant wave height, and f = mean tidal range.

The CVI provides a relatively simple numerical basis for ranking sections of coastline in terms of their potential for change that can be used by managers to identify regions where risks may be relatively high. The CVI results are displayed on maps to highlight regions where the physical effects of coastal change may be the greatest.

H.2 CASE STUDY: PROJECTING POTENTIAL FUTURE SHORELINE CHANGE, FIRE ISLAND, NEW YORK

H.2.1 Introduction

The southern coast of Long Island, including the offshore continental shelf, exhibits complex geomorphology and geology due to several factors including: the underlying glacial geology, mobile sandy deposits comprising Long Island, characteristics of waves and tides in the region, and frequent impacts by major storms. The result is that Long Island beaches and dunes are dynamic landforms constantly changing due to complex physical forcing agents. Fire Island, which forms the central portion of the southern Long Island coast (Figure H.4), is a barrier island system where shoreline changes and the processes driving, including the vulnerability to sea-level rise, them have been studied for the last several decades (See reviews in Leatherman and Allen, 1985; Pendleton *et al.*, 2004; Psuty, 2005). Shoreline retreat due to the long-term effects of diminished sand supply and storm erosion has threatened residential development and coastal habitat. In addition, rising relative sea level is also influencing shoreline and dune changes on Fire

Island (McCormick *et al.*, 1984; Leatherman and Allen, 1985; Zhang, 1998; Psuty, 2005). At the same time, these processes are natural phenomena inherent to barrier islands such as Fire Island. Even with the scientific knowledge gained from the research that has been conducted, it remains difficult to predict quantitatively with high confidence how the Fire Island system is likely to change in response to future sea-level rise over the next century and beyond. In addition, human action to control shoreline changes, tidal inlets, and rare storm related breaches of the barrier island system have had an impact on the barrier island's behavior. The following discussion reviews briefly the three basic methods that are currently used to assess potential shoreline changes driven by sea-level rise. The goal of this discussion is to illustrate the limitations of these shoreline change approaches that arise due to their simplicity and inability to capture the dynamic nature of the system.

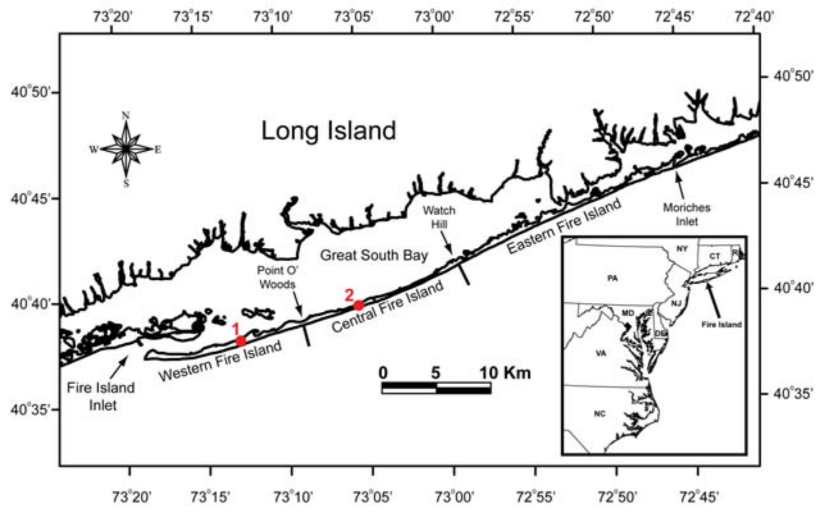


Figure H.4 Map of Fire Island, NY showing the three sections (western, central, eastern) that are discussed in this assessment. Red circles 1 and 2 denote the locations in Figures H.5 and H.6.

H.2.2 Potential Future Sea-level Rise Impacts: Established Concepts

Current scientific understanding suggests that Fire Island should migrate landward and upward over the long term through the process of ‘barrier island roll-over’ in response to rising sea level, the effects of storms, and sand feeding the barriers from a combination of erosion of the adjacent coast and the inner shelf (Hoyt and Henry, 1967; McCormick and Toscano, 1981; Leatherman and Allen, 1985; Williams and Meisburger, 1987; Schwab *et al.*, 2000). For this process to continue in the future, the evolution of the Fire Island system will depend on the continuing availability of sand to the barrier system from erosion of the adjacent coast as well as offshore areas. In addition, future storms will alter the Fire Island barrier. Some of these events could be large resulting in overwash and shoreline erosion whose effects may persist for a number of years. The formation of breaches and inlets during the most severe events is also possible, but it is difficult to predict when and where storm breaches might occur and how they might evolve (Williams and Foley, 2007). Historical records indicate that inlet formation and overwash have had large influences on these portions of the barrier and such risks are likely to remain in the future (Allen *et al.*, 2002 and Psuty, 2005). While there are some numerical models have been developed to predict barrier island migration and evolution in response to sea-level rise (Dean and Maurmeyer, 1983; Cowell *et al.*, 1992, 1995; Stolper *et al.*, 2005; Moore *et al.*, 2007), modeling approaches are still being developed and generally not yet suitable to inform management and policy decisions. Instead, the simpler approaches discussed in this case study are often used.

H.2.3 Projection of Future Shoreline Change Due to Sea-Level Rise Using Simple Quantitative Approaches

Three simple, commonly-used approaches are considered to predict future shoreline change and land loss due to sea-level rise along Fire Island. The three methods are: 1) the Bruun Rule model 2) extrapolation of historical shoreline change rates and 3) assessment of areas susceptible to inundation based on land elevation. The future shoreline changes were predicted for four sea-level rise scenarios which assumed that global sea levels would increase by 0.25 m, 0.5 m, 1 m, and 2 m by 2100. Long-term observations from a nearby tide gauge at the Battery in southern Manhattan indicated that relative sea level has risen at a rate of 2.88 mm/yr while the global rate over the last century was 1.7 mm/yr (Bindoff *et al.*, 2007). Based on this difference it is assumed that the local subsidence will occur at the same rate over the remainder of this century such that the total rise by 2100 is expected to be 0.11 m greater than the global rise. As a result, the future relative sea-level rise targets for this Fire Island assessment are: 0.36 m, 0.61 m, 1.11 m, and 2.11 m. In the following examples, the 1995 shoreline was used as a starting point for all of the projections and serves as a reference point from which all projections are discussed.

It is important to note that these three approaches are typically applied to different applications. While Bruun model is often applied to academic problems where researchers are either attempting to prove the validity of the concept (*e.g.*, Schwartz, 1967; Hands, 1983) or attempting to quantify the relationship between sea-level rise and shoreline change (Zhang *et al.*, 2002), it has also been used in coastal management applications (Komar, 1998). Historical shoreline change rate extrapolations are used most often in coastal management to inform coastal managers and as a basis for setback calculations (Crowell and Leatherman, 1999; Fenster, 2005). Inundation susceptibility assessments have been used for statewide or national scale assessment of sea-level rise impacts to provide estimates of land areas at risk from a specific rise in sea level (EPA, 1989; Najjar *et al.*, 2000).

The Bruun Model. The input parameters for this model, *L*, *B*, and *h* (See Figure H.1) were determined from a data base of beach profiles from the U.S. Army Corps of Engineers and State of New York between 1979 and 2003. The berm height, *B,* was determined from average profile estimated for each beach profile location. The depth of closure, *h*, was determined as the depth at which the standard deviation of beach profile change became constant following Morang *et al.*, (1999).

Historical Trend Extrapolation. In the second approach, shoreline change rates were used to extrapolate future shoreline positions to the year 2100. For this projection, shoreline change data were taken from Pendleton *et al.*, 2004. These shoreline change rates were calculated based on 10 historical shorelines spanning 1830 to 1995. The shoreline change rates were computed every 200 m along the shoreline and then averaged alongshore in 1 km bins. To extrapolate a future shoreline positions for the year 2100, the historical shoreline change rates calculated at the 200 m spacing were multiplied by 105; the number of years between the most recent shoreline (1995) and 2100. In taking this approach, it is assumed that all processes that contribute to long-term shoreline changes are reflected in the historical rate, including the effect of sea-level rise, and will remain more or less constant over the period of interest.

It is important to note that while the other two shoreline change methods are used to depict potential shoreline changes due to sea-level rise, extrapolation of shoreline change rates may not apply to sea-level rise scenarios that exceed those that occurred in the time periods corresponding to the historical shorelines that are used. During time span of the shorelines that were used in these calculations, relative sea level rose between 30-40 cm in the vicinity of Fire Island. These shoreline change projections, therefore, are best considered for the 0.36 m sea-level rise scenario. In some instances, a ratio can be established between sea-level rise and shoreline change such that an increased rise in sea-level can be considered (See Leatherman, 1990). Yet for these cases, the roll of sediment losses from the shore should also be considered carefully.

Inundation Susceptibility. The other approach which is used to evaluate potential land loss due to sea-level rise involves quantifying or specifying which land areas lie below a given elevation which corresponds to a particular rise in sea level. This approach is straight forward and can be determined using a variety of data (*e.g.,* Lidar elevations) to depict the topography of the landscape, however it does not consider any dynamic processes (*e.g.,* erosion, accretion, barrier rollover). Here, the elevation contours corresponding to the four sea-level rise scenarios were determined. The elevation contours used in this example were based on Lidar elevations acquired in the year 2000.

Using these data, elevation contours corresponding to the four sea-level rise scenarios were identified (Figures H.5 and H.6).

H.2.4 Comparison of Shoreline Change Results

The application of these three methods is discussed below based on the following figures (Figures H.5 and H.6).

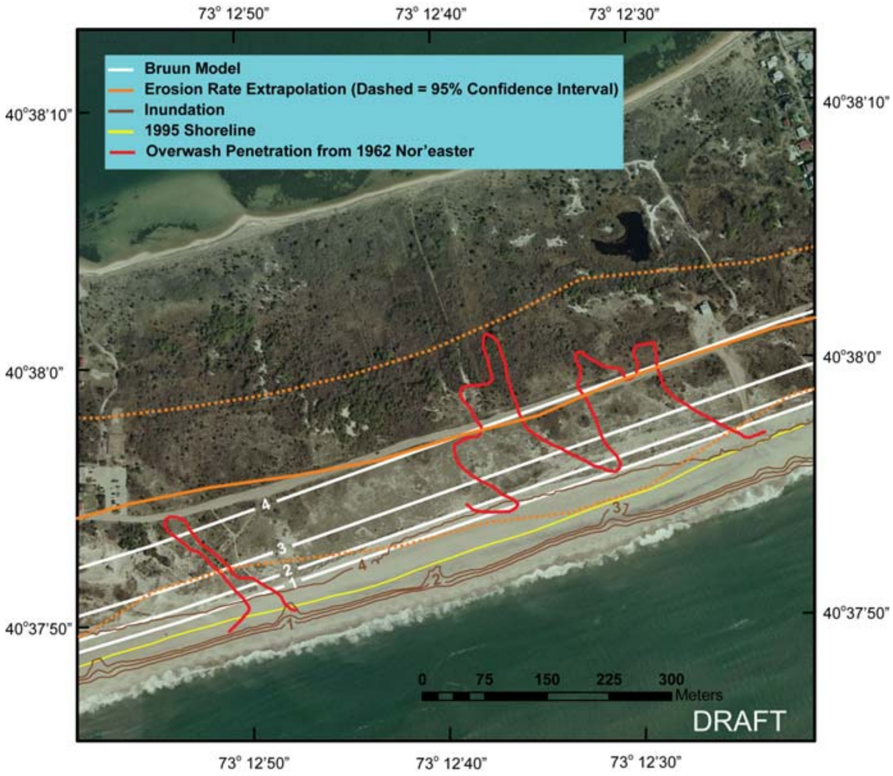


Figure H.5 Site 1 comparison of shoreline change projections for a portion of Fire Island, NY (See Figure H.1 for location). Aerial photograph obtained from the state of New York.

Inundation. Here, the contours corresponding to the first three sea-level rise cases occupy a narrow portion of the barrier where the slope of the shoreface is relatively steep. Only the elevation corresponding to the 2.11 m rise scenario clearly occurs landward of the 1995 shoreline. At site 1, the elevation contours corresponding to the first three sea-level rise scenarios (0.36, 0.61, and 1.11 m) occur seaward of the 1995 shoreline (starting point for the projections) and the results for the Bruun model and historical extrapolations. At site 2, elevation contours corresponding to the first three sea-level rise scenarios (0.36, 0.61, and 1.11 m) occur both landward and seaward of the 1995 shoreline (starting point for the projections).

These results indicate the difficulty in attempting to apply this approach to a barrier island setting. First, the elevation data that were used for this example were acquired in 2000-five years after the 1995 shoreline that was used as a baseline and as part of the historical shoreline data set. Second, the geological understanding of barrier island systems indicates that barrier islands can be expected to migrate upward and landward in response to sea-level rise, so it cannot be assumed that the Lidar based topography of the barrier island will remain static as sea level rises.

Historical rate extrapolation. At Site 1, the historical extrapolation, depicted by the orange line, occurs farther inland than most of the scenarios displayed here even though this applies only to the smallest sea-level rise scenario (0.36 m). Here, the shoreline extrapolated based on shoreline change rates is 100-150 m landward of the position estimated using the Bruun Rule for the 0.36 m scenario (Figure H.5). At Site 2, the historical extrapolation occurs either even with or slightly offshore of the 1995 shoreline indicating that the shoreline position would remain static or migrate offshore by the end of this century (Figure H.6).

The differences in the projected shoreline changes rates between the two locations may be related to differences in the sediment budget between locations. At site 1, analyses of the sediment budget and shoreline change trends suggest that there has been a net loss of material from the beach leading to net erosion of the shoreline (Allen *et al.*, 2002; Psuty, 2005). On the other hand, site 2 occurs in a region where it has been suggested that the sediment budget is balanced or even augmented by accumulation of material transported onshore from the continental shelf (Williams and Meisburger, 1987; Kana, 1995; Rosati *et al.*, 1999; Schwab *et al.*, 2000).

Bruun Model. Results based on the Bruun model project a landward migration of the shoreline for each respective sea-level rise scenario. Given that sediment budget analyses indicate a long-term loss of material from the shore at site 1 and a possible abundance of sediment at site 2, it is likely that the sediment budget at each site is not balanced. Because of this, a simple application of the Bruun model neglects the sediment budget contribution to long-term shoreline change and may underestimate the magnitude and direction of future shoreline changes.

Storm Overwash. Lastly, at site 1 historical evidence has shown that storm surges from severe storms can penetrate up to 300 m inland. In Figure H.5, based on overwash maps complied by Johnson (1982) it can be seen that overwash from the Ash Wednesday 1962 Nor’easter penetrated nearly 250 m inland. It is difficult to predict when or in some cases where these incursions may occur in the future, but it is clear that the penetration distance of these events, which occurred over 40 years ago, exceeded the shoreline changes projected in this case study (*e.g.* Douglas *et al.*, 1998). Historically, storm overwash has been most prevalent along the eastern and western portions of Fire Island where dune heights are lower than those of the central portion of the island.

Figure H.6 Site 2. Comparison of shoreline change projections for a portion of Fire Island, NY (see Figure H.1 for location). Aerial photos from the state of New York.

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Glossary

Access, Lateral
the right to walk or otherwise move *along* a shore, once someone has reached the shore.

Access, Perpendicular
a legally permissible means of reaching the shore from dry land.

Access Point
a place where anyone may legally gain access to the shore; usually a park, the end of a public street, or a public path. A place where perpendicular access is provided.

Accretion, Lateral
the gradual or imperceptible increase or extension of land by natural forces acting over a long periods of time, as on a beach by the washing-up of sand from the sea or on a floodplain by the accumulation of sediment deposited by a stream.

Accretion, Vertical
the vertical accumulation of a sedimentary deposit; the increase in thickness of a sediment body as a result of vertical sediment accumulation.

Active Margin
type of continental margin coinciding with the edge of a lithospheric plate where two plates are colliding. Because these margins are largely confined to the rim of the Pacific, this type of margin is also referred to as a pacific margin.

Armoring
the placement of fixed engineering structures, typically rock or concrete, on or along the shoreline to mitigate the effects of coastal erosion and protect structures. These structures include seawalls, revetments, bulkheads, and rip-rap (loose boulders).

Astronomical Tides
tides that result from the gravitational forces of the moon and sun on ocean waters.

Avulsion
the loss of lands bordering on the seashore by sudden or violent action of the elements, perceptible while in progress; a sudden and rapid change in the course and channel of a boundary river. Neither of these changes works a change in the riparian boundary.

Barrier Island
a long, narrow coastal landform composed of sand that is essentially parallel to the shore and is usually separated by wetlands; protects inland areas from ocean waves and storms.

Barrier Island Roll-Over
the landward migration or landward transgression of a barrier island, accomplished primarily over geologic time through the process of storm overwash.

Barrier Migration
refers to the whole scale movement of a barrier island or barrier spit in response to sea-level rise, changes in sediment supply, storm surges or waves, or some combination of each of these factors.

Barrier Raising
the equivalent of a beachfill operation in the area landward of the beach. This is rarely done as a large-scale operation. Individual lot owners sometimes import fill to raise their lots, especially if they are prone to flooding.

Barrier Spit
an elongate, wave-built accumulation of sand that built through longshore sediment transport and attached to the mainland or a larger sediment accumulation at the updrift end. A barrier island or barrier beach that is connected at one end to the mainland.

Beach
the unconsolidated material that covers a gently sloping zone, typically with a concave profile, extending landward from the low water line to the place where there is a definite change in material or physiographic form (such as a cliff), or to the line of permanent vegetation (usually the effective limit of the highest storm waves); a shore of a body of water, formed and washed by waves or tides, usually covered by sand or gravel, and lacking a bare rocky surface.

Beachfills
a technique in which sediment from an external source is placed on a beach to restore the beach back to an earlier condition, but they can also raise the terrain as well. Putting sand where there is none necessarily raises the elevation, but engineered beaches can be designed to have a volume and a height that a natural beach would never attain. Also known as beach nourishment.

Beach Nourishment
the addition of sand, usually dredged from offshore, to an eroding shoreline to enlarge or create a beach area, offering both temporary shore protection and recreational opportunities.

Berm
a geomorphic feature usually located at mid-beach and characterized by a sharp break in slope, separating the backshore from the seaward sloping foreshore.

Bluff
an elevated landform, such as a cliff, composed of partially consolidated and unconsolidated sediments, typically sands, gravel, and/or clays.

Breakwater
an offshore structure (such as a wall or jetty) that, by breaking the force of the waves, protects a harbor, anchorage, beach or shore area.

Breaching
formation of a channel through a barrier spit or island by storm waves, tidal action, or river flow. Usually occurs after a greater than normal flow, such as during a hurricane.

Bulkhead
a vertical wall along the shore designed either to create a vertical shore for navigation purposes, or to prevent erosion in areas with minor wave action.

Coastal Plain
any lowland area bordering a sea or ocean, extending inland to the nearest elevated land, and sloping very gently seaward it may result from the accumulation of material.

Coastal Squeeze
the narrowing, potentially to the point of failure or elimination, of an environmental system (typically a beach or marsh) that is trapped between the transgressing sea on one side and an impassable barrier (e.g., a sea wall or bulkhead) on the other.

Coastal Zone
the area extending from the ocean inland across the region directly influenced by marine processes.

Coastline
the line that forms the boundary between the coast and the shore or the line that forms the boundary between the land and the water.

Continental Shelf
the gently sloping surface at the edge of the continent that extends from the beach to where the steep continental slope begins, usually at depths greater than 300 ft.

Contour Interval
the difference in elevations of adjacent contours on a topographic map. The smaller the contour interval, the more precise the map.

Delta
a low relief landform resulting from sediments deposited from rivers over time at the coast.

DEM (Digital Elevation Model)
a set of elevation estimates corresponding to a grid with a given cell size, usually 10 or 30 meters. The term often refers to the output of an interpolation model, not the model itself.

Deposition

the process of sediment settling out of the water column and being deposited.

Depth of Closure

a theoretical depth below which sediment exchange between the nearshore (beach and shoreface) and the continental shelf is deemed to be negligible.

Dike

a wall generally of earthen materials designed to prevent the permanent submergence of lands below sea level, tidal flooding of lands between sea level and spring high water, or storm-surge flooding of the coastal floodplain.

Downdrift

the direction of net longshore sediment transport at the coast over time.

Dredge and Fill

used extensively before the 1970s to elevate estuarine shorelines to a height that allows construction for homes. Commonly known as lagoon development, channels are dredged through tidal wetlands to allow small boat navigation, and dredge spoil is placed on the remaining marsh to raise the marsh high enough to allow development. Also known as "canal estates" in some locations.

Dredge Spoil Disposal

similar to sediment broadcasting but is a way of disposing of spoils from the dredging of navigation channels onto nearby salt marshes in a way that also achieves environmental benefits of helping nearby salt marshes to survive.

Dune

a landform characterized by an accumulation of wind-blown sand, often vegetated, along the coast.

Ebb Current

the tidal current that occurs when the tide is going out.

Ebb-Tide Delta

Curved to elongate-shaped shoal on the seaward side of an inlet formed by ebb-tide currents (resulting from a falling tide) and modified by waves and flood-tide currents (associated with a rising tide).

Erosion

the loss of sediment, sometimes indicated by the landward retreat of a shoreline indicator such as the water line, the berm crest, or the vegetation line. The loss occurs when sediments are entrained into the water column and transported from the source.

Erosion-based setback
a setback equal to an estimated annual erosion rate multiplied by a number of years set by statute or regulation (e.g. 30 years).

Eustatic Sea-Level Rise
results from changes in global sea level relative to a vertical datum. Eustatic changes represent global sea level. The causes can be complex, such as ice sheet melting, increasing temperature of surface waters, and increasing volume of seafloor due to tectonic processes. – worldwide change in sea level resulting from a change in the volume of the oceans or the size of the ocean basins.

Extra-Tropical Storm
a cyclonic weather system that travels northward along the east coast of the United States and Canada producing strong winds and waves from the northeast; see nor'easter.

Fetch
the distance that a wave travels from the point of origin to the shore where it breaks. In sheltered areas, the fetch corresponds to the distance across a span of water over which wind-generated waves may grow before breaking on the opposing shore.
Distance over which the wind blows.

Flood Current
the tidal current that occurs when the tide is rising.

Flood-Tide Delta
horseshoe to multilobate shaped sand shoal located landward of a tidal inlet, formed by flood tide currents (associated with rising tide) and modified by ebb-tide currents (associated with falling tide). Some flood tide deltas are a product of storm processes.

Geologic Framework
refers to the underlying geological setting, structure, and lithology (rock/sediment type) in a given area.

Glacial Rebound
uplift of land following deglaciation due to the mass of the ice being removed from the land surface; an isostatic response of the lithosphere.

Global Sea Level Rise
the worldwide average rise in mean sea level.

Groins
an engineering structure normal to the coast, used to accumulate littoral sand by interrupting longshore transport processes. A groin is often constructed of concrete, timbers, steel, or rock.

Hydrodynamic Climate

refers to the characteristics of nearshore or continental shelf currents in an area that typically result from waves, tides, and weather systems.

Inlet

the narrow waterway between two barrier islands that connects the sea and a lagoon.

Inundation

refers to the submergence of dry lands when there is a rise of the sea surface.

Isostacy

equilibrium condition whereby portions of the Earth's crust are compensated (floating) by denser material below.

Jetty

an engineering structure extending into the ocean, designed to prevent shoaling of a channel by littoral materials and to direct and confine the stream or tidal flow. Jetties are built at the mouths of rivers or tidal inlets to help stabilize a channel for navigation.

Lagoon

shallow coastal body of seawater that is separated form the open ocean by a barrier or coral reef. The term is commonly used to define the shore-parallel body of water behind a barrier island or barrier spit.

Levee

a wall generally of earthen materials designed to prevent riverine flooding after periods of exceptional rainfall.

LIDAR (Light Detection and Ranging)

a remote sensing instrument that is able to measure the elevation of the land surface with a high degree of accuracy and precision. LIDAR relies on laser-based instruments that are flown over the land surface from planes. LIDAR have been very useful in producing high-quality data of regions surrounding the shoreline.

Littoral Cell

sections of coast for which sediment transport processes can be isolated from the adjacent coast. Within each littoral cell, a sediment budget can be defined that describes sinks, sources, and internal fluxes (sediment transport).

Littoral Drift

the sedimentary material moved in the littoral zone under the influence of waves and currents.

Littoral Transport

the movement of littoral drift in the littoral zone by waves and currents. Includes movement parallel and perpendicular to the shore.

Littoral Zone
used as a general term for the coastal zone influenced by wave action, or, more specifically, the shore zone between high and low water marks.

Living Shoreline
a type of shore protection that retains some or all of the environmental characteristics of a natural shoreline.

Longshore Current
an ocean current in the nearshore zone produced by waves approaching the coast at various angles.

Longshore Transport
sediment transport parallel to the shoreline, caused by longshore currents driven by waves approaching obliquely to the shoreline. Movement of sediment along the coast in the surf and breaker zones by wave suspension and the longshore current.

Marsh
low-lying vegetated wetlands occurring in the upper intertidal to supratidal zone. Salt marshes occur in protected environments such as behind barriers. In these regions salt grasses and succulent plants colonize them.

Mean High Water
a tidal datum. The average height of all high water heights observed over a 19-year period.

Mean Sea Level
average water level position measured over a 19-year period, which takes into account natural tidal oscillations. Often computed by the arithmetic mean of observed hourly heights over a 19-year period. Local mean sea level is determined relative to the local land at a tide station. Global mean sea level is the average level of the global ocean.

Metes and Bounds
the boundary lines and limits of a tract that is described and characterized by placing all data in the tract description as opposed to other references such as maps or plats.

Mixed Energy Coast
coast in which the morphology has developed through a combination of wave and tidal processes.

Moral Hazard
a circumstance in which insurance, lending practices, or subsidies designed to protect against hazard induces people to take measures that increase the hazard.

Mudflat

a level area of fine silt and clay along a shore alternately covered or uncovered by the tide or covered by shallow water.

Nanotidal Wetlands

wetlands that are irregularly flooded by wind-generated tides in estuaries with little or no astronomic tides. These wetlands are often classified as nontidal wetlands; but like tidal wetlands, their frequency of inundation is controlled directly by sea level.

National Geodetic Vertical Datum of 1929 (NGVD29)

a fixed reference adopted as a standard geodetic datum for elevations determined by leveling networks across the U.S. and sea-level measurements at 26 coastal tide stations. Now superseded by North American vertical Datum (NAVD88).

National Tidal Datum Epoch (NTDE)

the latest 19-year time period over which NOAA computes and publishes official tidal datums and local mean sea-level elevations from tide station records. The latest NTDE is 1983-2001.

Nearshore Zone

zone from the shoreline seaward to a point just beyond the breakers.

Nontidal wetlands

wetlands that are not flooded by astronomic tides.

North American Vertical Datum of 1988 (NAVD88)

a fixed reference for elevations determined by geodetic leveling, derived from a general adjustment of the first-order terrestrial leveling networks of the United States, Canada, and Mexico. NAVD88 supersedes NGVD29.

Northeaster (Nor'easter)

type of extra-tropical cyclone that travels northward along the east coast of the United States and Canada producing strong winds and waves from the northeast.

Ordinary High Water Mark

a demarcation between the publicly owned land along the water and privately owned land. Generally based on mean high water, the definition varies by state. Along beaches with significant waves, it may be based on the line of vegetation, the water mark caused by wave runup, surveys of the elevation of mean high water, or other procedures.

Overwash

sediment that is transported from the beach across a barrier, and is deposited in an apron-like accumulation along the backside of the barrier. Overwash usually occurs during storms when waves break through the frontal dune ridge and flow toward the marsh or lagoon.

Outwash plain
braided stream deposit beyond the margin of a glacier. It is formed from meltwater flowing away from the glacier, depositing mostly sand and fine gravel in a broad plain.

Passive Margin
type of continental margin occurring in the middle of a lithospheric plate, and hence no tectonic plate interaction and little tectonic activity. Because these margins are found rimming the Atlantic Ocean, this type of margin is also termed an Atlantic margin.

Pocket Beach
a beach usually small in a coastal re-entrant or between two littoral barriers.

Public Trust Doctrine
a legal principle derived from English Common Law. The essence of the doctrine is that the waters of the state are a public resource owned by and available to all citizens equally for the purposes of navigation, hunting, fowling, and fishing, and that this trust is not invalidated by private ownership of the underlying land.

Relative Sea-Level Rise
the rate of sea-level change measured with respect to a specified vertical datum relative to the land, which may also be changing elevation over time.

Revetment
a sloped facing of stone, concrete, etc., built to protect a scarp, embankment, or shore structure against erosion by wave action or currents.

River Diversions
used to reestablish the floodplain of rivers that once supplied sediment to marshes. Usually a river is not “diverted” to flow into the marsh; instead it is allowed to once again flow onto the marsh as it used to. This is usually accomplished by breaching levees that were once used to train the river or by allowing floodwaters to get onto the marshes in another controlled way.

Riverine Flooding
flooding of lands caused by the elevation of nontidal or tidal waters resulting from the drainage of upstream areas, usually after periods of exceptional rainfall.

Roll Over
see “barrier island roll-over.”

Rolling Easement
an interest in land (by title or interpretation of the public trust doctrine) in which a property owner’s interest in preventing real estate from eroding or being submerged yields to the public or environmental interest in allowing wetlands or beaches to migrate inland.

Root Mean Square Error
a measure of statistical error calculated as the square root of the sum of squared errors, where error is the difference between an estimate and the actual value. If the mean error is zero, it also equals the standard deviation of the error.

Saltwater Intrusion
increases in salinity of groundwater or surface water.

Sand Bypassing
hydraulic or mechanical movement of sand from the accreting updrift side to the eroding downdrift side of an inlet or harbor entrance. The hydraulic movement may include natural movement as well as movement caused by man.

Sand Dunes
mounds or ridges of sand. They are formed from sand this is transported and deposited by the wind.

Sea-Level Rise
in this report, relative sea-level rise. In other contexts, the term may refer to global sea-level rise.

Seawall
a structure separating land and water areas, primarily designed to prevent erosion and other damage from wave action.

Sediments
fine particles of soil, sand, rock, and similar materials.

Sediment Broadcasting
a technique in which sediment from an external source would be spread onto salt marshes to supply the mineral material needed to enhance their ability to survive.

Sediment Supply
refers to the abundance or lack of sediment in a coastal system that is available to be reworked and contribute to the maintenance or evolution of coastal landforms including both exposed features such as beach and barrier islands as well as the seabed in a coastal region.

Setback
requirement that construction be located a minimum distance inland from tidal wetlands, tidal water, the primary dune line, or some other definition of the shore.

Shore
the narrow strip of land in immediate contact with the sea, including the zone between high and low water lines. A shore of unconsolidated material is usually called a beach.

Shore Retreat
managed or planned retreat allows the shoreline to advance inward unimpeded. As the shore erodes, buildings and other infrastructure are either demolished or relocated inland.

Shoreface
the narrow relatively steep surface that extends seaward from the beach, often to a depth of 30-to-60 ft, at which point the slope flattens and merges with the continental shelf.

Shoreline
the intersection of a specified plane of water with the shore or beach. The line delineating the shoreline on national ocean service nautical chars and surveys approximates the Mean High Water line.

Shoreline Armoring
a method of shore protection that prevents shore erosion through the use of hardened structures such as seawalls, bulkheads, and revetments.

Shore Protection
an activity that protects land from inundation, erosion, or storm-induced flooding.

Significant Wave Height
the average height of the highest one-third of waves in a given area.

Soft Shore Protection
a method of shore protection that prevents shore erosion through the use of materials similar to those already found in a given location, e.g., adding sand to an eroding beach, planting vegetation whose roots will retain soils along the shore.

Spit
a fingerlike extension of the beach that was formed by longshore sediment transport; typically, it is a curved or hook-like sandbar extending to an inlet.

Spring High Water
the average height of the high waters during the semi-monthly times of spring tides (full and new Moons).

Storm Surge
a rise above normal water level on the open coast due to the action of wind stress on the water surface. Storm surge resulting from a hurricane also includes that rise in level due to atmospheric pressure reduction as well as that due to wind stress.

Subsidence
the downward settling of material with little horizontal movement; the downwarping of the Earth’s crust relative to the surroundings.

Submergence
a rise of the water level relative to the land, so that areas that were formerly dry land become inundated; it is the result either of the sinking of the land or a net rise in sea level.

Surf Zone
the zone landward of the breaker zone where breaking waves create a turbulent form of water toward the beach.

Tidal Inlet
an opening in the shoreline through which water penetrates the land, thereby providing a connection between the ocean and bays, lagoons, and marsh and tidal creek systems. The main channel of a tidal inlet is maintained by tidal currents.

Tidal Range
the vertical difference between normal high and low tides often computed as the elevation difference between mean High Water and Mean Low Water. Spring tide range is the elevation difference between spring high water and spring low water.

Tidal Wetlands
wetlands that are flooded by high tides and exposed at low tides. In some context, this term refers to vegetated wetlands (e.g., marshes and swamps) but not non-vegetated wetlands such as tidal mudflats and beaches. In other contexts it may refer to both vegetated and non-vegetated wetlands.

Tide-Dominated Coast
coast where the morphology is primarily a product of tidal processes.

Tidelands
lands that are flooded during ordinary high water, and hence available to the public under the public trust doctrine.

Transgression
the landward and upward repositioning of the water line as a result of sea-level rise. It can occur by erosion, by simple immersion without a profile change, or by a combination of erosion and immersion. Ecosystems can also transgress as the environment adjusts to the new hydrologic conditions caused by the transgression of the water line.

Updrift
the direction opposite that of the predominant movement of littoral materials.

Wave-Dominated Coast
coast where the morphology is primarily a product of wave processes.

Wave Refraction
the bending of waves as they come ashore, begin to feel bottom, and slow down.

Wave Run-Up

the upper levels reached by a wave on a beach or coastal structure, relative to still-water level.

Wetland Accretion

a process by which the surface of wetlands increases in elevation. See Accretion, Vertical.

Wetland Migration

a process by which tidal wetlands adjust to rising sea level by advancing inland into areas previously above the ebb and flow of the tides.

Scientific Names - Chapter 4 Species	
American black duck	*Anas rubripes*
American oystercatcher	*Haematopus palliatus*
Atlantic menhaden	*Brevoortia tyrannus*
Atlantic silverside	*Menidia spp.*
bald eagle	*Haliaeetus leucocephalus*
bay anchovy	*Anchoa mitchilli*
belted kingfisher	*Ceryle alcyon*
black rail	*Laterallus jamaicensis*
black skimmer	*Rynchops niger*
bladderwort	*Utricularia spp.*
blue crab	*Callinectes sapidus*
bluefish	*Pomatomus saltatrix*
brant	*Branta bernicla*
canvasback duck	*Aythya valisineria*
carp	*Family Cyprinidae*
catfish	*Order Siluriformes*
clapper rail	*Rallus longirostris*
common tern	*Sterna hirundo*
crappie	*Pomoxis spp.*
diamondback terrapin	*Malaclemys terrapin*
eastern mud turtle	*Kinosternum subrubrum*
elfin skimmer (dragonfly)	*Nannothemis bella*
fiddler crab	*Uca spp.*
Forster’s tern	*Sterna forsteri*
fourspine stickleback	*Apeltes quadracus*
grass shrimp	*Hippolyte pleuracanthus*
great blue heron	*Ardea herodias*
gull-billed tern	*Sterna nilotica*
herring	*Clupea harengus*
horseshoe crab	*Limulus polyphemus*
Kemp’s Ridley sea turtle	*Lepidochelys kempii*

laughing gull	*Larus atricilla*
least bittern	*Ixobrychus exilis*
meadow vole	*Microtus pennsylvanicus*
minnows	*Family Cyprinidae*
mummichog	*Fundulus herteroclitus*
naked goby	*Gobiosoma bosci*
northern pipefish	*Syngnathus fuscus*
piping plover	*Charadrius melodus*
red drum	*Sciaenops ocellatus*
red knot	*Calidris canutus*
red-winged blackbird	*Agelaius phoeniceus*
ribbed mussel	*Geukensia demissa*
sand digger	*Neohaustorius schmitzi*
sand flea	*Talorchestia spp.*
sandpiper	*Family Scolopacidae*
sea lettuce	*Ulva lactuca*
sea trout	*Salvelinus fontinalis*
shad	*Alosa sapidissima*
sheepshead minnow	*Cyprinodon variegatus*
shiners	*Family Cyprinidae*
spot	*Leiostomus xanthurus*
striped anchovy	*Anchoa hepsetus*
striped bass	*Morone saxatilis*
striped killifish	*Fundulus majalis*
sundew	*Drosera spp.*
sunfish	*Family Centrarchidae*
threespine stickleback	*Gasterosteus aculeatus*
tiger beetle	*Cicindela spp.*
weakfish	*Cynoscion regalis*
white croaker	*Genyonemus lineatus*
white perch	*Morone americana*
widgeon grass	*Ruppia maritima*
willet	*Catoptrophorus semipalmatus*