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Background Documents Supporting Climate Change Science Program Synthesis and Assessment Product 4.1: Coastal Elevations and Sensitivity to Sea Level Rise

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Preface

Sea level has risen approximately 30 cm (1 foot) along most of the U.S. Atlantic and Gulf coasts in the last century.[1] In the next century, however, rising atmospheric and ocean temperatures are likely to expand ocean water and melt glaciers, and thereby accelerate the rise in sea level. By the end of the 21st century, global average sea level is likely to be rising 1.5–9.7 mm/yr even if polar ice sheets do not begin to disintegrate, according to the Intergovernmental Panel on Climate Change.[2] Additional contributions from the Greenland and Antarctic ice sheets could be negligible or add as much as 4 mm/yr.[3] Because of regional subsidence, sea level has risen, and almost certainly will continue to rise, 1–2 mm/yr more rapidly than the global average along the mid-Atlantic Coast.[4] Thus, by 2100, sea level could be rising 3–16 mm/yr.[5] Over the next century sea level is expected to rise 30 to 90 cm (1 to 3 feet) along the mid-Atlantic coast.[6]

Rising sea level inundates low-lying lands, erodes shorelines, exacerbates flooding, and increases the salinity of estuaries and aquifers. The ramifications can be broadly divided into two categories: the human impact and the environmental impact. The human impacts include flood damages, land and structures lost to the sea, costs of protecting land and structures from the sea, the indirect economic and human toll from the migration necessitated by the entire loss of a community, and the costs of shifting to alternative water supplies when the original supply becomes saline.

This collection of papers focuses on some of the environmental impacts of sea level rise on the mid-Atlantic Coast of the United States. All but two of these papers were prepared to support a forthcoming report by the United States Climate Change Science Program entitled *Coastal Elevations and Sensitivity to Sea Level Rise.*

Figures a–d provide an overview of the primary environmental impact examined by this report. Tidal wetlands are found where the elevation of the land is between high and low tides, with tidal marshes generally above mean sea level and tidal flats below mean sea level. (a) When sea level was rising rapidly, tidal wetlands would tend to be a narrow fringe along the shore, determined by the slope of the land. But wetlands have been able to keep pace with the relatively slow rate of sea level rise during the last several thousand years. As sea level rose, new wetlands would form inland; but the seaward boundary of tidal wetlands did not retreat to the same extent, and the area of tidal

[1]See, e.g., Zervas, C.E., 2001, Sea Level Variations of the United States 1854–1999, NOAA Technical Report NOS CO-OPS 36, Silver Spring, MD: National Oceanic and Atmospheric Administration.

[2]IPCC at Table 10.7; Meehl, G.A., T.F. Stocker, W.D. Collins, P. Friedlingstein, A.T. Gaye, J.M. Gregory, A. Kitoh, R. Knutti, J.M. Murphy, A. Noda, S.C.B. Raper, I.G. Watterson, A.J. Weaver and Z.-C. Zhao, 2007, Global Climate Projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.), United Kingdom and New York: Cambridge University Press, Cambridge,

[3]*Ibid*.

[4]See, e.g., Titus, J.G. and V. Narayanan, 1996, *The Probability of Sea Level Rise*, Washington, DC: U.S. Environmental Protection Agency, at chapter 9 (discussing methods for projecting relative sea level rise when given projections of global sea level rise).

[5]The global rate would be 1.5–13.6 mm/yr; IPCC at Table 10.7 (adding “sea level rise” to “scaled up ice charge”). *Ibid*.

[6]The global rise would be 19–77 cm. *Ibid*.

wetlands increased. (b) Today, the area of tidal wetlands—i.e., the land between the high and low tide shorelines—is much greater than the amount of dry land within a similar elevation range above the high tide shoreline. But there is a limit to the rate of sea level rise with which tidal wetlands can keep pace. (c) And if the sea rises more rapidly, most of the existing tidal wetlands will be lost, and the total area of tidal wetlands will decline to the narrow fringe determined by the slope. (d) Finally, in places where developed lands along the shore are protected from tidal inundation, new wetlands may not form inland and almost all tidal wetlands may be lost. Because the tidal wetlands support fish and wildlife, a loss of tidal wetlands could cause populations of birds and fish to decline or relocate.

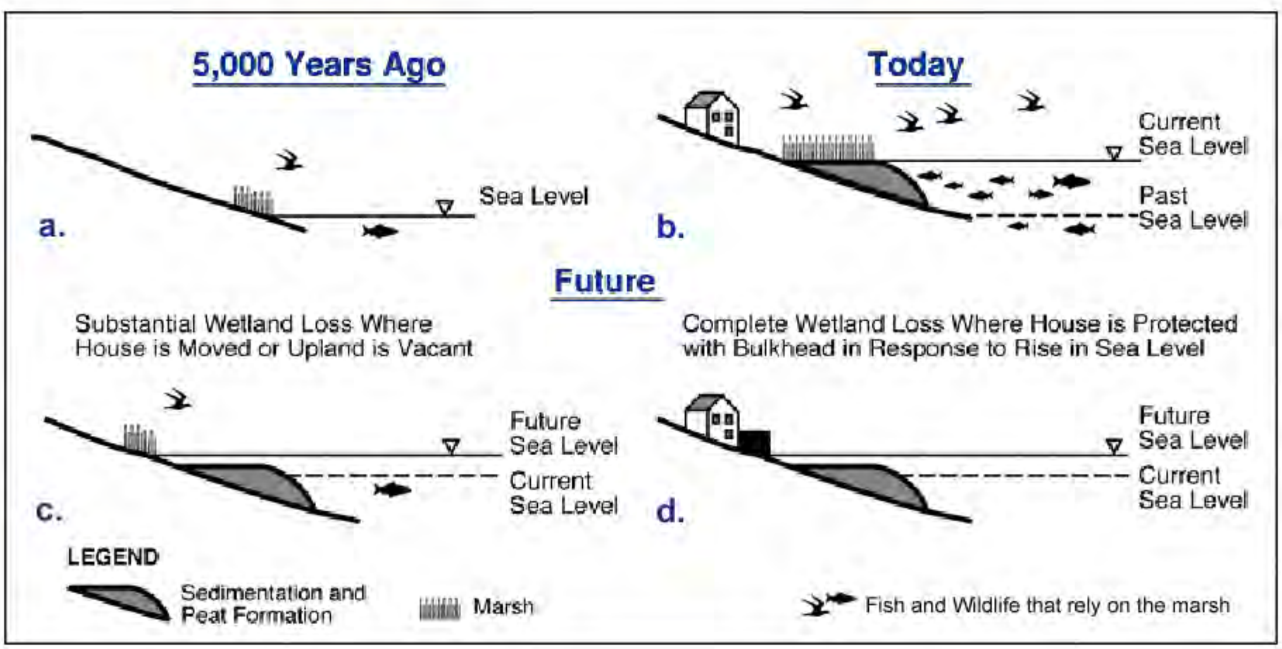
Examining the magnitude of this environmental impact requires us to address several questions, which are enumerated in the prospectus for *Coastal Elevations and Sensitivity to Sea Level Rise*[7]:

- How much dry land is immediately above the tides and hence potentially available for the creation of new wetlands (wetland migration) as sea level rises?

- To what extent can existing tidal wetlands—especially the vegetated wetlands—keep pace with rising sea level?

- Which species depend on the tidal wetlands that are potentially at risk if sea level rises?

In Section 1.1, Titus and Wang evaluate the first question. They collected the best available topographic information as well as data on tides and wetlands. Based on standard interpolation methods, they create maps of lands depicting elevations relative to spring high water, that is, the average elevation of the high tides during full and new moons. Because tidal wetlands generally extend up to approximately spring high water, those maps provide elevations relative to the upper boundary of tidal wetlands. Finally, they quantify the area of lands close to sea level. In Section 1.2, Jones and Wang provide additional details on the Titus and Wang approach to quantifying the area of land close to sea level by interpolation. This paper also explains the authors' approach



[7] Available at http://www.climatescience.gov/Library/sap/sap4-1/sap4-1prospectus-final.htm

to extending that type of analysis to include forthcoming data sets on shore protection and the vertical accretion of wetlands. Finally, Titus (in Section 1.3.1) and Cacela (in Section 1.3.2) estimate uncertainty ranges for the results developed in the previous two sections.

Chapter 2 has two papers that examine the ability of wetlands to keep pace with rising sea level through mechanisms collectively known as "wetland accretion." Section 2.1, by Reed et al., is the heart of the analysis: a panel assessment of the potential for wetland accretion in the mid-Atlantic from the south shore of Long Island to Virginia Beach. (They excluded North Carolina because the wetland accretionary processes are very different there.) This paper describes wetland accretionary processes and how they vary across different geomorphic settings. It also contains the panel's assessment of the potential for future wetland accretion. In Section 2.2, Titus, Jones, and Streeter generate GIS data and a set of maps to succinctly summarize the results of the Reed et al. analysis—and document a data set available for other researchers interested in modeling changes in mid-Atlantic wetlands. (The complete set of maps appears in Section 2.1 instead of 2.2 to facilitate the discussion of the various mid-Atlantic subregions.)

This report does not quantitatively integrate the results from the separate studies. However, an informal examination of the maps produced in these studies shows that accelerated sea level rise is likely to cause a loss of intertidal habitat, with higher rates of sea level rise causing a correspondingly greater loss of habitat. What are the consequences?

Ideally, we would develop an ecological model of the impacts of habitat loss throughout the mid-Atlantic as sea level rises. Given time and resource constraints, we had to limit our modeling to a single county and provide more qualitative descriptions for the rest of the region. Chapter 3 presents 20 papers that examine the species that depend on the vulnerable habitats. In Section 3.1, Jones and Bosch present an overview of the habitats that could be altered or lost as a result of sea level rise and the animal species found in these habitats, with emphasis on tidal marshes, estuarine beaches, tidal flats, and submerged aquatic vegetation. Eighteen brief literature reviews follow, each discussing the coastal ecosystems of a multicounty coastal region. These papers focus on the animals that depend on the vulnerable habitats for food, shelter, spawning, or nursery areas. Although it was not possible to discuss every bay, river, or tidal creek, we examine a representative sample. Five locator maps[8] show the specific areas that these papers discuss. Finally, Section 3.20 is a modeling study, which quantifies the impact of sea level rise and six scenarios of shore protection on the fish and bird species that inhabit Barnegat Bay and the smaller estuaries adjacent to Long Beach Island, New Jersey. This pilot study quantitatively integrates the three questions addressed by this report.

Chapters 1 and 2 are mapping assessments that rely mostly on published data and peer-reviewed scientific literature. Chapter 3, however, relies on a more diverse group of sources—including web sites, and emails and oral statements from experts. These types of sources are necessary because, in most cases, there is no peer-reviewed journal article that addresses the presence of a particular species at a particular location. Nevertheless, as long as an author reviews the reliability of a source, these more informal sources can be just as useful as a published scientific article. For example, an individual making a general statement about environmental vulnerability may not be as reliable as a peer-reviewed article doing the same thing; but a refuge manager stating species of birds that she has personally seen on her refuge would generally be at least as reliable as a journal article that mentioned that particular refuge in passing. In every case where these papers rely on a source that is not a peer-reviewed report, the footnote documenting the source includes enough information for a reader to understand the

[8]Maps 3-1, 3-2, 3-3, 3-7, and 3-8.

author's basis for assuming that the source is reliable *for the fact cited*.

Throughout Chesapeake Bay, tidal and intertidal lands are threatened by sea level rise. Although coastal wetlands may migrate inland in some locations, Chesapeake Bay is likely to experience a significant loss of tidal wetland habitat with even a small increase in the rate at which sea level rises—and if sea level rises more than 10 mm/yr—most saline and brackish wetlands are vulnerable. One would expect adverse effects on the species that use these habitats for critical life functions such as reproduction and feeding, but we know too little to determine cause and effect relationships or to quantify the impacts. In intertidal areas, deeper water will reduce light penetration, which can inhibit the growth and survival of submerged aquatic vegetation; whether these areas can transgress inland onto current marsh areas that become inundated is highly uncertain and depends on a variety of physical factors. Although beds of submerged aquatic vegetation play a critical role as nursery and food source for many fish and other aquatic species, we do not know the extent of consequences of the loss of submerged vegetation for these species—similarly, the impacts of substantial marsh loss on the species that feed on the fish that directly rely on the marsh are not quantified. The impact on birds is also unclear: Some species may be able to move inland to nest and find food—but perhaps only if nearshore farms, forests, and nontidal wetlands are not consumed by coastal development. Changing migration patterns with a warmer climate and shifts in estuarine species composition with warmer water temperatures are further confounding factors. Nevertheless, some species are clearly vulnerable, such as the horseshoe crab, which relies on estuarine beaches to reproduce—and the many migratory bird species that depend on horseshoe crab eggs to refuel during their long-distance migrations.

Our inability to forecast how complex animal communities respond to habitat loss as sea level rises need not obscure the importance of the few things that we do know. For several decades, the importance of tidal habitats has prompted governments and private conservancies to preserve coastal wetlands and shallow water habitats. Rising sea level threatens these habitats, and an accelerated rise is likely to eliminate much of it. This report identifies many animal species that will be forced to adapt to the impacts of rising sea level. How they might adapt and what managers might do to increase the likelihood of successful adaptations are outside the scope of this report. We hope that this collection of papers helps motivate the research needed to answer those questions.

Summary of the Review Process

In 2006, EPA initiated the review of a series of papers that were written as background for the U.S. Climate Change Science Program (CCSP) Synthesis and Assessment Product 4.1 Coastal Elevations and Sensitivity to Sea-Level Rise. These documents were linked to questions in the SAP4.1 Prospectus. The reviews were intended to serve as "Level One" peer reviews—short, brief reviews to help the authors ensure that each background paper contained reasonable assumptions, estimates, and conclusions given the available data.

Potential reviewers were identified on the basis of their areas of expertise, including knowledge of the specific coastal areas studied. To accommodate the range of topics explored in the papers (e.g., wetland accretion, GIS mapping, and coastal zone biology), reviewers were sought from a variety of backgrounds. Candidate reviewers included scientists, engineers, and others involved with mid-Atlantic coastal research, management, and policy in federal, state, and local agencies, nonprofit organizations, and the private sector.

For each document, reviewers were given the paper itself, a review charge, and other background documents as needed to support their review. Many of the papers were relatively brief, and reviewers were often asked to review more than one paper. Comments sent by reviewers were compiled in a comment spreadsheet for use by EPA, and each author was sent verbatim comments on the paper(s) that they wrote. The comments of all reviewers were carefully considered and incorporated, wherever possible, throughout the revised technical documents.

Contents

CHAPTER 3. MID-ATLANTIC COASTAL HABITATS AND ENVIRONMENTAL IMPLICATIONS OF SEA LEVEL RISE

CHAPTER 1. COASTAL ELEVATIONS IN THE MID-ATLANTIC

1.1. Maps of Lands Close to Sea Level along the Middle Atlantic Coast of the United States: An Elevation Data Set to Use While Waiting for LIDAR

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Abstract

This report provides a coastal elevation data set for the mid-Atlantic for purposes of assessing the potential for coastal lands to be inundated by rising sea level. Depending on what we were able to obtain, our elevation estimates are based on LIDAR, federal or state spot elevation data, local government topographic information, and USGS 1:24,000 scale topographic maps. We use wetlands and tide data to define a supplemental elevation contour at the upper boundary of tidal wetlands. Unlike most coastal mapping studies, we express elevations relative to spring high water rather than a fixed reference plane, so that the data set measures the magnitude of sea level rise required to tidally flood lands that are currently above the tides. Our study area includes the seven coastal states from New York to North Carolina, plus the District of Columbia.

We assess the accuracy of our approach by comparing our elevation estimates with LIDAR from Maryland and North Carolina. The root mean square error at individual locations appears to be approximately one-half the contour interval of the input data. We also compared the cumulative amount of land below particular elevations according to our estimates and the LIDAR; in that context, our error was generally less than one-quarter the contour interval of the input data.

We estimate that the dry land in the region has a relatively uniform elevation distribution within the first 5 meters above the tides, with about 1,200–1,500 km^2 for each 50 cm of elevation. With the exception of North Carolina, the area of nontidal wetlands declines gradually from about 250 km^2 within 50 cm above the tides to about 150 km^2 between 450 and 500 cm above the tides. North Carolina has approximately 3,000 km^2 of nontidal wetlands within 1 meter above spring high water; above that elevation, the amount of nontidal wetlands declines gradually as with the other states. North Carolina accounts for more than two-thirds of the dry land and nontidal wetlands within 1 meter above the tides.

We also compare our results to previous studies estimating the region's vulnerability to sea level rise. Our results are broadly consistent with an EPA mapping study published in 2001, which estimated the total amount of land below the 1.5- and 3.5-m contours (relative to the National Geodetic Vertical Datum of 1929). This study appears to be a significant downward revision, however, of EPA's 1989 Report to Congress. Our estimates of the dry land vulnerable to a 50- or 100-cm global rise in sea level are less than one-half the estimates of the Report to Congress. The regional estimates of that nationwide study, however, were based on a small sample. Therefore, one should not extrapolate our mid-Atlantic result to conclude that EPA's previously reported nationwide estimate overstates reality by a similar magnitude.

1.1.1 Introduction

During the last two decades, the issue of rising sea level has spread from being primarily a concern of coastal geologists (e.g., PILKEY et al., 1982) and those who measure the tides (e.g. HICKS et al., 1983; ZERVAS, 2001) to an issue that concerns planners, policymakers, and the public at large (e.g., KRISTOFF, 2005; DEAN 2006). One reason is that the sea is rising 3 mm/yr or more along many low-lying areas (Figure 1.1.1), enough for some areas that were developed 50–100 years ago to be flooded by high tides during new or full moons (Figure 1.1.2). Another reason is that increasing concentrations of carbon dioxide and other greenhouse gases appear to be contributing to a global warming responsible for at least part of the current rate of sea level rise (e.g., U.S. EPA, 1996; IPCC, 2007). Most scientists expect greenhouse gases to accelerate the rise in sea level (IPCC, 2001a), and some have suggested that it may already be doing so (CHURCH and WHITE, 2006).

Rising sea level inundates low-lying lands, erodes wetlands and beaches, exacerbates flooding, and increases the salinity of estuaries and aquifers (e.g., IPCC, 2001b). Studies over the last two decades have identified numerous decisions that may be sensitive to sea level rise (e.g., NRC, 1987; WILLIAMS et al., 1995; TITUS and NARAYANAN[1], 1996). During the Administration of President George W. Bush, the U.S. Climate Change Research Program (2003) has actively promoted decision support research to assist with adaptation to consequences of climate changes such as rising sea level. Studies sponsored by the U.S. EPA have suggested that local governments may be making the most important decisions regarding the eventual impact of rising sea level on the United States. Local governments create the land use plans and issue the construction permits that determine whether the areas at risk will be developed enough to require shore protection as the sea rises or will remain vacant enough for wetlands to migrate inland (TITUS, 1990, 1998).

Over the last several years, EPA staff and contractors have met with local governments concerning possible responses to sea level rise (TITUS, 2005). When we have asked what information might help them to better prepare, the most common answer has been better elevation maps. When senior government officials or newspaper reporters have asked us about vulnerability to sea level rise, the most common request has been for a map showing the lands that might be flooded. Yet maps depicting lands close to sea level using the best available data are unavailable for most areas.[2]

[1]Section 3.1 of that paper is an overview of decisions that depend on the probability of the sea rising a particular magnitude.

[2]But see WEISS AND OVERPECK (2006), which provides a map server using the USGS national elevation data series.

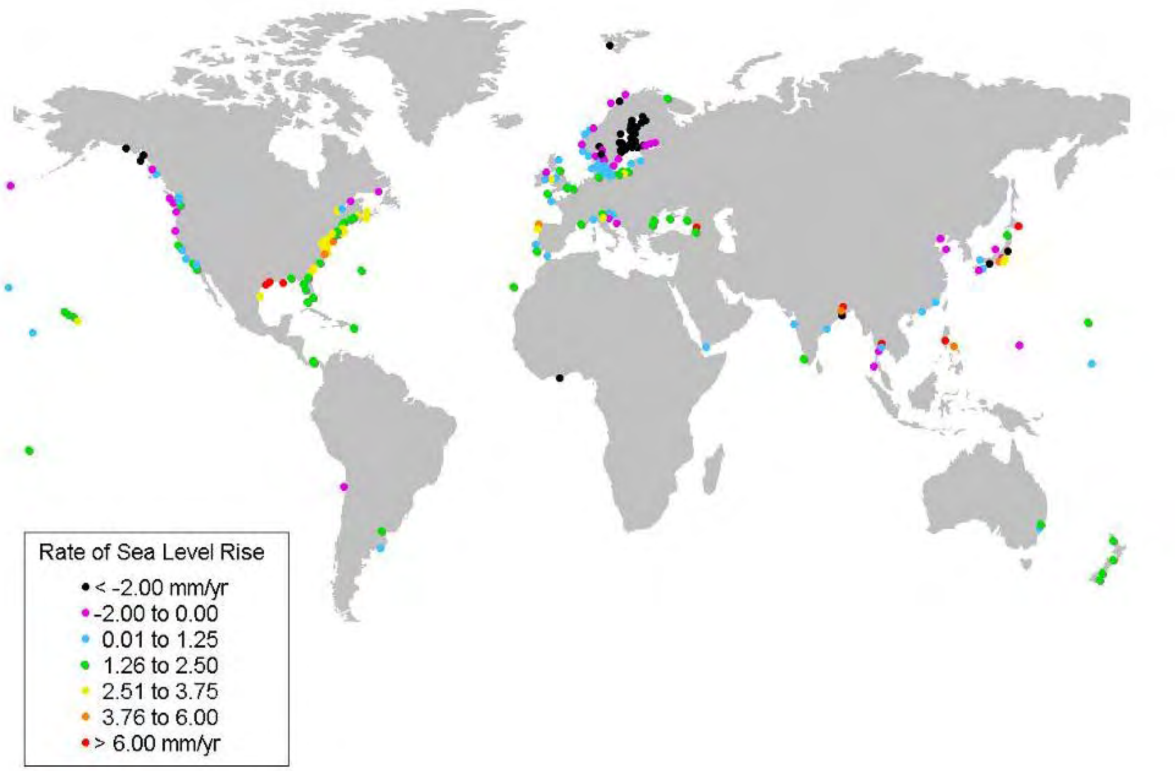

Figure 1.1.1. Relative sea level rise at locations with at least 50 years of tide station data. (Data Source: PERMANENT SERVICE FOR MEAN SEA LEVEL, 2003).

For many years, the EPA sea level rise project avoided this obvious endeavor because we expected LIDAR[3] data (hereafter LIDAR) to be available soon, which would make moot the entire exercise. But the LIDAR was slow in coming. Finally, we decided that a better way to manage the risk of creating unnecessary information would be to create an elevation data set anyway; if the LIDAR does not arrive, then we will have provided a useful elevation data set; if LIDAR does become available, then the public will have even better maps.

This report presents the methods we used to create maps and a dataset for analyzing the impacts of sea level rise. We provide elevation data for the coastal zone from New York to North Carolina. The purpose of this data set is to identify and quantify the land that could potentially be inundated as sea level rises, so that EPA and other researchers can (1) evaluate the land potentially available for wetland migration, (2) identify the areas that might require shore protection and quantify shore protection costs, and (3) estimate the population and assets within the area potentially at risk to sea level rise. Although this report has only a few example maps, map templates accompany the data set that we are distributing so that those with GIS software can easily create elevation maps to suit their needs.

Although our focus is on coastal elevations rather than scenarios of inundation, the elevation of our study area was broadly guided by the available literature estimating future sea level rise. IPCC (2007) estimated that global sea level is likely to rise 18–59 cm over the next century, but also indicated that the sea could rise 9–17 cm more if polar ice sheets begin to disintegrate.[4] Along the mid-Atlantic coast, sea level rise is generally expected to be 10–20 cm more than the global average rise.[5] Thus, as you examine our maps, you

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[3]Light Detection And Ranging (LIDAR) is similar to RADAR, except it relies on light instead of radio waves. The LIDAR instrument transmits light out to a target; the time it takes for the light to return is used to determine distance. Land elevations are estimated with low-flying aircrafts with LIDAR instruments.

[4]IPCC (2007) at table 10.7.

[5]See, e.g., Titus and Narayanan (1996) at Chapter 9.

Photo 1.1.1. Tidal flooding at Ship Bottom, New Jersey (Labor Day 2002).

might reasonably assume that sea level is likely to rise 30–100 cm in the next century. But IPCC also estimates that by the 21st century, global sea level could be rising 4–14 mm/yr,[6] which would imply a rise of 5–16 mm/yr along the mid-Atlantic coast. Thus a rise of several meters over the next few centuries is possible. Our maps all provide elevations up to either 3 or 6 meters above the ebb and flow of the tides. Our primary motivation for extending the maps this far inland was to convey at least a rough sense of the topography of the coastal zone, and doing so requires one to look above the elevation that is most immediately at risk. Nevertheless, sea level could rise 3–6 meters over the next few centuries.

The next section (1.1.2) discusses our general approach, which was to obtain the best available elevation data from the U.S. Geological Survey (USGS) and other federal, state, and local government agencies; create an extra contour at the inland boundary of tidal wetlands; and express elevations relative to the ebb and flow of the tides. After that, we describe (1.1.3) how we applied that approach to the data we were able to obtain, and explain (1.1.4) our accuracy assessment. The final section (1.1.5) presents the maps, estimates the area of land close to sea level, and compares our results to previous assessments.

Before proceeding with the analysis, a word of caution on the use of units in this report. We generally use metric units, with English units in parentheses where we cite a report whose results originally used English units. However, when discussing contour intervals of specific maps used in the analysis, we refer to the units that the maps actually used, which are often English units. We believe that it is more accurate to say (for example) that the USGS maps of Maryland include 1-m and 5-ft contour intervals, than to say that they include 1-m and 1.524-m contours. Although most writers would normally prefer to avoid mixing units of measurement, the underlying reality is that there is currently a relatively confusing patchwork of available elevation data sets, and different units of measurement is part of that reality.

[6]See IPCC (2007) at Table 10.7 (high estimate includes lines called “sea level rise” and “scaled-up ice sheet discharge”).

1.1.2 General Approach

This study is based on the relationship between the tidal elevations, tidal wetlands, and the reference elevations used by available elevation data. Figure 1.1.2 illustrates the relationship between these three factors along a typical shore profile, using the tidal elevations for Hampton Roads (VA). In this particular case, mean sea level is 17.2 cm above NGVD29,[7] which is the reference elevation used by the USGS topographic maps. Spring high water [8] is 43 cm above mean sea level, and thus 60 cm above NGVD29. Thus, the 5-ft contour is only 90 cm (3 feet) above spring high water. Because tidal marshes are found between mean sea level and spring high water, the 5-ft contour is also 90 cm (3 feet) above the tidal wetlands.

Our general approach has five main 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.
2. Use wetlands data to determine the location of the upper boundary of tidal wetlands, which we treat as the land flooded by spring high tide and, hence, the horizontal position of our wetland supplemental contour.
3. Use tidal data to estimate the elevation (relative to NGVD29), of spring high water, which we use as the vertical position of our wetland supplemental contour.
4. Interpolate elevations relative to the vertical datum for all land above spring high water using elevations obtained from the previous three steps.
5. Use the information from step 3 to calculate elevations relative to spring high water.

Figures 1.1.3 and 1.1.4 illustrate the results of these steps for a portion of Long Beach Island (New Jersey) and the adjacent mainland, including the portion of Ship Bottom (Figure 1.1.2) that is often flooded by spring tides. The USGS maps have a 10-ft contour interval (Figure 1.1.3a), but the U.S.
Army Corps of Engineers provided spot elevation data for the islands and some of the mainland (Figure 1.1.3b). For the mainland areas without spot elevation data, we created a supplemental contour representing spring high water and the upper edge of tidal wetlands. The wetlands data define the horizontal position of this contour (Figure 1.1.3a). We used tidal data to define the vertical position of the contour relative to NGVD29 (Figure 1.1.4). With that supplemental contour defined, we interpolated elevations in between the contours (Figure 1.1.3c), which yields elevations relative to NGVD29. Finally we subtract the tidal elevations from Figure 1.1.4 to express land elevations relative to spring high water (Figure 1.1.3d).

Difference from Other Elevation Mapping Assessments

Our approach differs from other elevation mapping studies in two fundamental ways. First, our final product represents elevations above the tides rather

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[7] Older maps generally measure elevations relative to the National Geodetic Vertical Datum of 1929, which was originally meant to be a fixed reference plane. NGVD was set equal to the sea level of 1929 at specific reference stations along the U.S. coast. The reference "plane" (actually a spheroid) in all other locations was based on leveling techniques. As a result, even in 1929, NGVD was not sea level in areas where average water levels diverge from the ideal "plane" because of winds, freshwater inflow, and other factors. Since 1929, rising sea level and subsidence have caused sea level and the NGVD to diverge 10–20 cm in most areas. Recognizing the problems with the deteriorating benchmarks, the USGS and the National Geodetic Survey converted to the North American Vertical Datum (NAVD) of 1988. The reference plane associated with this benchmark is based on a single fixed site. New data generally are relative to NAVD-1988. See, e.g., NATIONAL GEODETIC SURVEY et al. (1998).

[8] Spring tides refer to the extreme tides that occur during new and full moons, when the tidal forces of the moon and sun are aligned. Spring high water is the average height of high water during spring tides. See, e.g., NOS (2000).

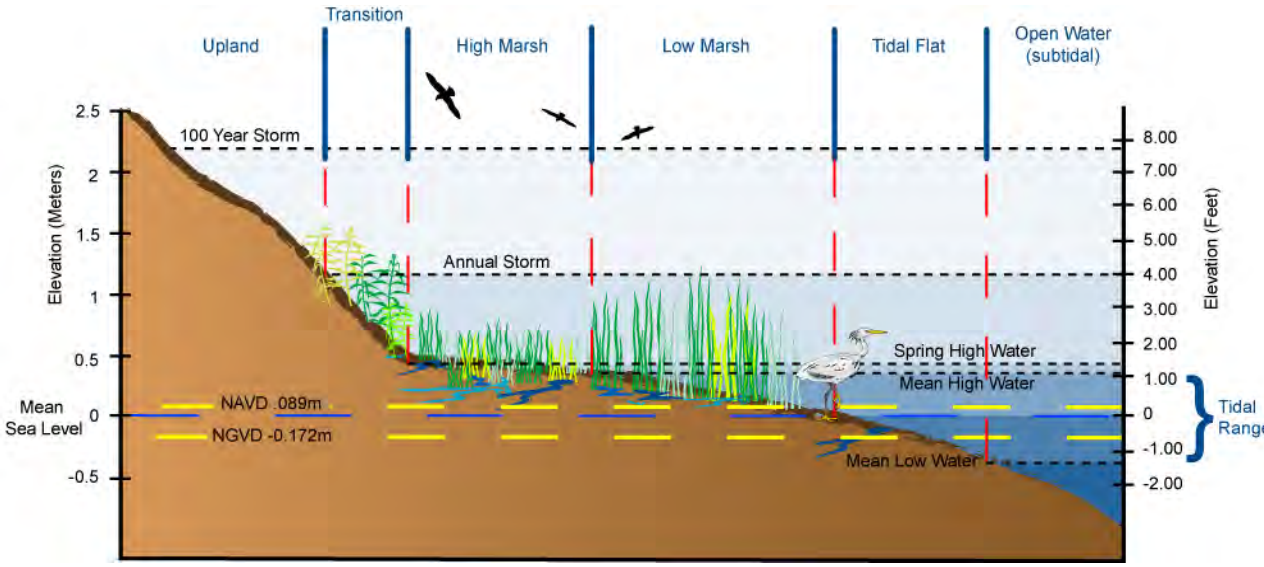

Figure 1.1.2. Relationship between tides, wetlands, and reference elevations for an example estuarine shore profile. The example elevations are based on the Hampton Roads (Virginia) Tide Station. See Gill and Schultz 2001. The wetland characterizations are based on Kana et al. 1988.[11]

than above a fixed reference elevation such as NGVD29. Second, we use tidal wetlands data to produce a single (but important) supplemental elevation contour, in addition to the conventional topographic information.

We estimate elevations relative to the sea because the intended use of these maps is to analyze the implications of sea level rise. Early assessments often ignored the difference between the NGVD29 and mean sea level. Because (local) mean sea level tends to be 10–20 cm above NGVD29, equating these two reference elevations was harmless when analyzing the impact of a 4.5–7.5-m (15–25-ft) sea level rise by 2030 (SCHNEIDER and CHEN, 1980), or even a 50–300-cm rise by 2100 (BARTH and TITUS, 1984). A more recent analysis provided maps relative to NGVD29 for the U.S. Atlantic and Gulf coasts, with an explicit warning about the difference between that benchmark and sea level (TITUS and RICHMAN, 2001). The print media generally ignored the caveat and rewrote the map key from "1.5 meters above NGVD" to "future shoreline resulting from 1.5 meter rise in sea level," not only confusing NGVD29 with sea level but also equating elevation with shoreline change.[9]

Unfortunately, the lack of interest in tidal datums is not limited to sea level rise assessments: In New Orleans, flood control engineers used NGVD29 and mean sea level interchangeably for decades, even though mean sea level was 50–60 cm higher than NGVD29. As a result, the levee along the Inner Harbor Navigation Canal (which failed during Hurricane Katrina) was about 60 cm lower than intended (INTERAGENCY PERFORMANCE EVALUATION TASKFORCE, 2006).

It is axiomatic that maps ought to depict the information they seek to convey rather than leave it up to the reader's imagination or ability to obtain additional data. Unfortunately, the absence of a data layer relating sea level to the fixed vertical benchmarks has made it impractical for coarse-scale national mapping studies to provide elevations relative to the sea.[10] As a byproduct of

[9]See, e.g., "Coasts in Peril: Exhibit E" in "Life in the Greenhouse", *Time*, 157:14:24,29 (April 9, 2001) "These maps show how much of the shoreline we know today will vanish if sea levels rise by the indicated amount." But see the *New York Times*, January 1, 2000 (closely paraphrasing the caveat that the journal article had recommended).

[10]Consider for example, the state-scale maps showing land below the 1.5- and 3.5-m (NGVD) contours in TITUS and RICHMAN (2001). Expressing elevations relative to the tides would have more than doubled the $75,000 cost of that study.

[11]Gill, S.K. and J.R. Schultz. 2001. Tidal Datums and Their Applications, NOAA Special Publication NOS CO-OPS 1, February 2001.

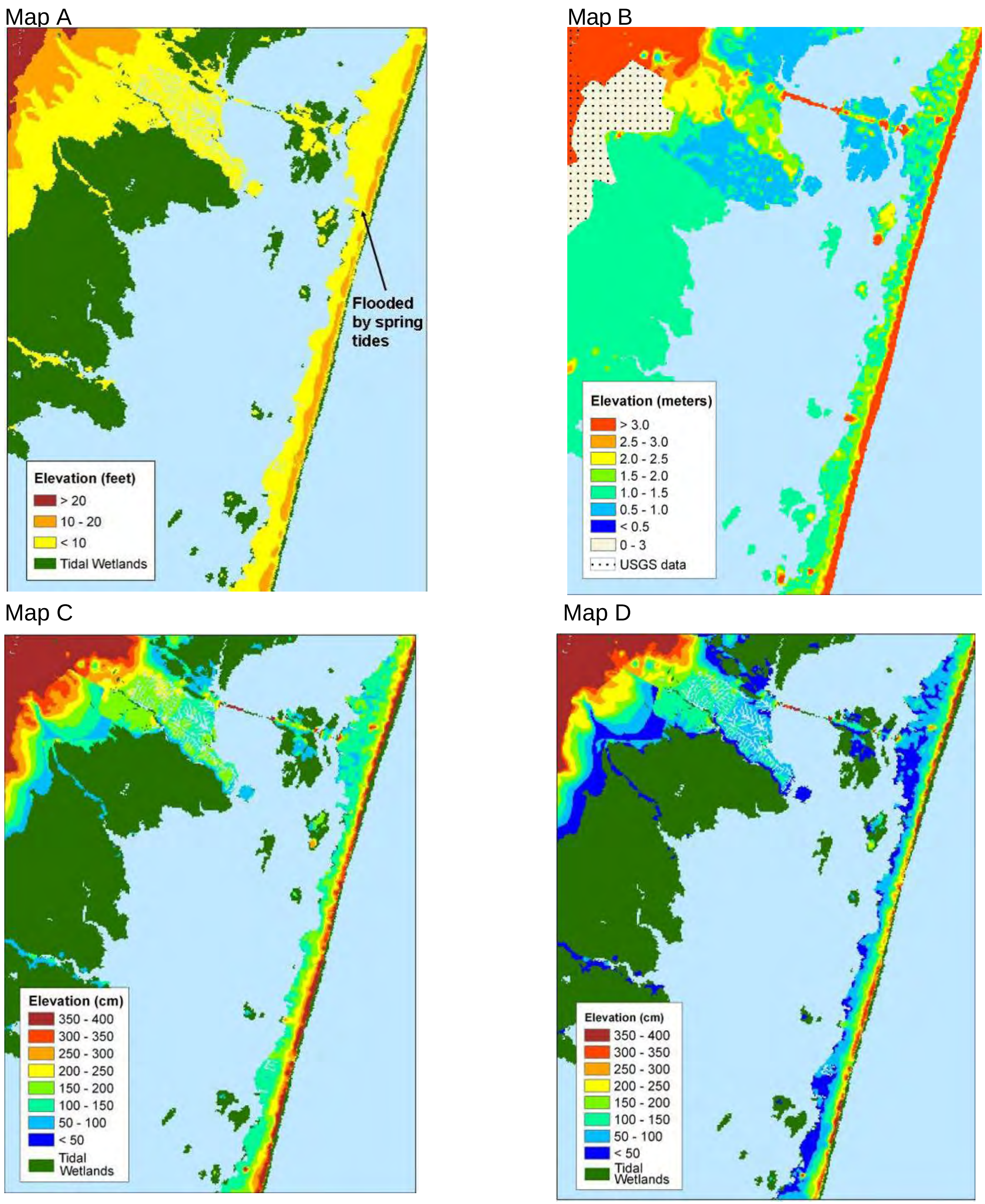

Figure 1.1.3. Estimated elevations around Long Beach Island, New Jersey. The first three maps show elevations relative to NGVD29 according to (a) the USGS 1:24,000 scale map, (b) spot elevations provided by the Corps of Engineers where available and USGS data elsewhere, and (c) our interpolations using wetlands data as a supplemental contour. The final map (d) shows the same elevations as (c), relative to spring high water. The first map also shows the location of spring tide flooding depicted in Photo 1.1.1.

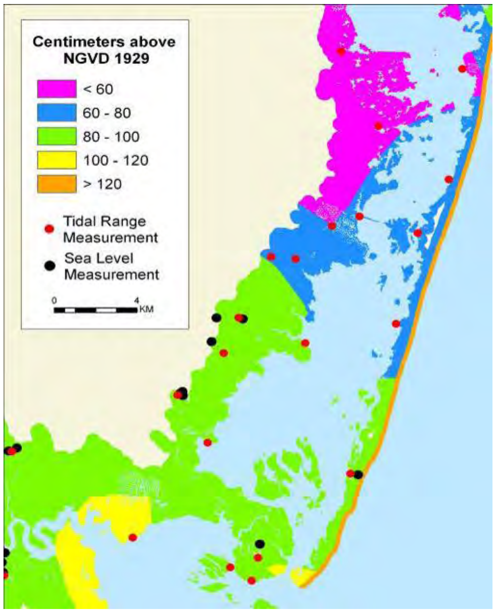

Figure 1.1.4. Elevation of spring high water relative to NGVD29. The red and black dots depict the locations of reported observations for mean tide level and spring tide range, respectively. The various colors of the land represent the interpolated values of spring high water. For the actual values of mean tide level and tide range observations, see Figures 1.1.6 and 1.1.7, respectively.

this effort, we create such a layer that others may find useful even as LIDAR becomes available.[12]

In ordinary conversations, people refer to elevations "above sea level." This report provides elevations relative to spring high water instead, for two reasons: First, one can map the existing high water mark more accurately than mean sea level. Wetland maps generally show the upper boundary of tidal wetlands, but maps illustrating the location of the shore at mean tide level are rarely available.

Second, showing elevations relative to high water is more useful than mean sea level, because the character of land changes fundamentally once it is subject to the ebb and flow of the tides: Marsh grasses replace trees, lawns, or crops that cannot tolerate the saltwater and frequent flooding[13] (see generally TEAL and TEAL, 1969). Moreover, the land becomes subject to tidal wetlands regulations,[14] and ownership shifts from the upland owner to the public in most states (SLADE et al. 1990). By contrast, elevation above mean sea level implies little about the impact of sea level rise. Because tide ranges vary, knowing that a parcel is 50 cm above mean sea level does not tell one whether it is even wet or dry land, let alone the rise in sea level necessary to convert the area to open water.

Difference from Other Sea Level Rise Impact Mapping Studies

This effort also differs from most sea level rise impact mapping studies because we report elevations rather than projected future shorelines. Maps of future shorelines are important, but elevations alone say something about vulnerability to sea level rise.

Converting our results into maps of future shorelines would represent, in effect, a separate study—and the final results would be more speculative. Elevation is a necessary precursor for estimating shoreline change due to sea level rise. But projecting future shorelines requires more questionable assumptions than one must make when estimating elevations. The Bruun (1962) Rule produces an approximation of sandy beach erosion that is useful for some purposes, but many geologists decline to project erosion of beaches without applying a more site-specific model

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[12]NOAA is developing a software tool that converts data between fixed benchmarks and elevations relative to the tides, making this aspect of our analysis obsolete as well in a few years. See, e.g., PARKER et al. (2003) and MYERS (2005). Results are available for Pamlico Sound, which we used.

[13]This generalization does not always apply in areas with low salinity. In nanotidal areas (i.e., areas where the astronomic tide range is only a few centimeters) the "tidal wetland" vegetation may be irregularly flooded because of winds rather than regularly flooded from astronomic tides. There may be a gradual transition between the irregularly flooded wetlands and adjacent nontidal wetlands, and even if the line is well-defined, the elevation is not a function of the tides. The Pamlico and Albemarle sounds are the most important example in our study area. Other exceptions include tidal freshwater forests and areas where extensive tidal freshwater wetlands are adjacent to nontidal wetlands with similar vegetation types.

[14]Clean Water Act § 404, 33 U.S.C. § 1344(a) (1994) and Rivers and Harbors Act of 1899, 33 U.S.C. §§ 403, 409 (1994).

requiring data collected over several years (e.g., DEAN and MAURMEYER, 1983; COWELL and THOM, 1994; COWELL et al., 1995; YOUNG and PILKEY, 1995). And sandy beaches are the best known shores! Wetland accretion is too poorly understood for coastal scientists to quantify how rapidly the sea could rise before it began to drown the wetlands (KANA et al., 1988; PARK et al., 1989; CAHOON et al., 1995).[15] The ability to predict erosion of muddy shores is so poor that for many geologists, the term "coastal erosion" refers only to sandy beaches.

Even in areas where we have a good model of shore erosion, projecting future shoreline can require a rather cumbersome set of analytical steps. Future sea level rise is uncertain; so one must evaluate the implications of several scenarios, taking care to ensure that one has encompassed the range of uncertainty. Different readers have different time horizons, so one typically must prepare maps for a few different projection years. Finally, actual shoreline migration will also depend on the type and extent of human activities to hold back the sea, so one must consider alternative shore-protection scenarios. Handling all these issues well on a regional scale requires too much effort to be undertaken as a final step of this study.

Fortunately, coastal elevations do tell us something about the impacts and responses to sea level rise. Coastal wildlife managers who want to ensure that new wetlands are created as sea level rises must identify the dry land that might be tidally flooded in the future. The importance of reserving a given parcel depends on how much the sea has to rise before the tides inundate the land. The need to elevate streets and back yards depends on the land's elevation. Moreover, an elevation map makes a suitable graphic for those attempting to convey the broad ramifications of sea level rise to the general public because it shows both existing wetlands and the dry land that will be inundated as the sea rises.

[15]Elsewhere in this report, however, a panel of wetland accretion specialists provide a consensus subjective assessment about whether mid-Atlantic wetlands could keep pace with three sea level rise scenarios. (See Reed et al., Section 2.1 of this report.)

1.1.3 Application of Our Approach

Step 1: Obtain Best Elevation Data

Table 1.1.1 summarizes the elevation data we used. For a given state, the order in which the table lists the data represents the quality of the data and, hence, the order in which we selected data layers. For example, in Maryland, we used the 10-ft contour from the Department of Natural Resources spot elevation data set in areas where the USGS maps had a contour interval of 20 feet.[16] If USGS 7.5-minute maps had a contour interval of 10 feet (or better), however, we preferred the USGS data. For four counties, we had county data with 2- or 5-ft contours, which was even better.

Our approach was more systematic than one might initially assume, given the variation in data quality indicated by Table 1.1.1. Our goal was to estimate the land potentially inundated by a 1-m rise in sea level where possible and, where we could not, at least map the area vulnerable to a 2- or 3-m rise. Although we would have preferred to rely solely on a nationwide data set, the USGS 7.5-minute maps do not have a consistent contour interval—and for much of the coast their contour intervals are too great, especially in New Jersey and Maryland (see Figure 1.1.5). Therefore, we attempted to supplement the USGS data where feasible.

Outside North Carolina, the USGS 5-ft contour is generally within 1 meter above the ebb and flow of the tides. Therefore, outside North Carolina, wherever the USGS maps had a contour interval of 5 feet or better, we did not actively seek better data.

[16]We obtained LIDAR for the lower Eastern Shore of Maryland after the analysis was complete. We use that data to assess the accuracy of our DEM in the section on Quality Control and Review. The primary data set we make available to the public will include these LIDAR data; we will also make the original data set available.

A 20-ft contour interval, by contrast, provides no information about lands vulnerable to sea level rise in any meaningful time horizon (although it does identify areas that are not vulnerable). Therefore, we made a relatively exhaustive effort to obtain alternative data in the portions of New Jersey and Maryland where the USGS maps had a 20-ft contour interval. Fortunately, Maryland had spot elevations on a 90-m grid with a vertical precision (90 percent interval) of 5 feet. Thus, according to national map accuracy standards (BUREAU OF THE BUDGET, 1947; Federal Geodetic Control Subcommittee, 1998), the Maryland data provide a 10-ft contour interval at a 1:180,000 scale. The horizontal scale is considerably poorer than the USGS 1:24,000 maps; but unlike a map with a 10-ft contour interval, the spot elevations provide estimates for points with intermediate elevations, allowing us to derive, for example, a 5-ft contour (albeit with twice the vertical error of national mapping standards). Unfortunately, New Jersey had no similar statewide data set.

Many counties have elevation data for coastal floodplain management, pollution runoff modeling, and identification of areas where slopes make land undevelopable. Unlike the federal government, however, the counties usually charge for the data—sometimes tens of thousands of dollars per quad. In some cases, the bonds used to raise the money to collect the data contain restrictions against giving the data away.[17] The restrictive county policies generally allow the GIS department to provide the data to a genuine partner doing work primarily to benefit the county. This study probably would not—by itself—qualify because we are analyzing the vulnerability of a multistate region to rising sea level and creating a product for researchers who will not, in general, collaborate with county staff to attain county objectives. Nevertheless, our collaboration with

[17]The planning director of Monmouth County, New Jersey, expressed this concern.

four counties led four county GIS departments to see this effort within the context of a joint federal–local partnership to understand the implications of rising sea level:

- Monmouth County (New Jersey): The only county along New Jersey's Atlantic Coast where USGS maps have a 20-ft contour interval.
- Anne Arundel County (Maryland): This county includes both Annapolis and the largest low-lying area on Maryland's Western Shore of Chesapeake Bay.
- Harford County (Maryland): This county includes the second largest area of very low-lying lands along the Western Shore.
- Baltimore County (Maryland). Unlike the other counties, Baltimore insisted that we provide elevation maps using their superior (2-ft contour) elevation data before they would even consider responses to sea level rise.

We also examined some maps that had been stored in the warehouse where FEMA keeps the documentation for the flood insurance rate maps. In general, whenever the USGS maps had contour intervals greater than 5 feet, FEMA obtained topographic maps. As a test, FEMA searched their archives for specific communities in Monmouth County, New Jersey, and found that for about half the townships and boroughs, the archives contained numerous maps with 2-ft contours at a scale better than 1:10,000. We were tempted to have those maps all digitized. FEMA, however, was reluctant to allow the entire collection to leave their premises—and we were not sure that the effort was worthwhile for areas with only partial coverage. We did persuade FEMA to lend us their map of Kent Island, Maryland, the eastern landing of the Chesapeake Bay Bridge, where our own eyes told us that the land is very low but the USGS maps have a 20-ft contour interval.

The supplemental data sources left us with only 24 quads where we have nothing better than a 20-ft contour interval.[18] All of those quads are along tidal rivers well inland or upstream from a major estuary, except for six quads along the north shore of Long Island, which is dominated by substantial bluffs, and three quads in northern New Jersey (see Figure 1.1.5).

Maps with 10-ft contour intervals give some insight on vulnerability to sea level rise, but not enough to justify their use if one can find a practical alternative. Unfortunately for us, most USGS maps have 10-ft contours in coastal New Jersey, New York, Pennsylvania, Virginia, the District of Columbia, and Virginia west of Chesapeake Bay. For most low land along the Atlantic Ocean and back barrier bays in New Jersey (except for Monmouth County, where we had 2-ft contours), the Corps of Engineers provided spot elevations with sufficient precision and density to identify 4-ft contour intervals at a 1:100,000 scale. The District of Columbia provided 1-m contour data. The City of Philadelphia provided 2-ft contours. Most of Pennsylvania's remaining low land is in Delaware County; because of the high tide range, the 10-ft contours in that region are only about 150 cm (5 feet) above spring high water.

North Carolina is a special case. Currituck, Pamlico, and Albemarle sounds have almost no tides because the areas of these bodies of water are large compared to their inlets to the ocean. With the high water mark barely above sea level, the sea would have to rise more than 1 meter to inundate the 5-ft contour during a high tide, unlike areas with larger tidal ranges. In the wake of Hurricane Floyd, however, the state collaborated with FEMA to substantially improve the already-good elevation data with LIDAR. Early on in the study,

[18]Those 24 quads also included all or part of the upper tidal portions of the Delaware River (Bucks County, Pennsylvania, and Burlington County, New Jersey), Choptank River (Caroline County, Maryland) Wicomico River (Worcester County, Maryland), and several small rivers or creeks in New Jersey.

we obtained LIDAR for most of the low-lying counties in the state[19]; and by the end of the study we had data for the entire state. As we discuss below, however, the absence of tides and tide data for this area diminishes the usefulness of our analysis for evaluating the possible impacts of sea level rise in North Carolina.

Step 2: Use Wetlands Data to Obtain the Location of the Upper Boundary of Tidal Wetlands

We used tidal wetlands to define a supplemental topographic contour, approximately equal to spring high water. The precise elevation of that contour varies, but it is almost always between zero and the lowest contour above zero. This supplemental contour is useful and important for two reasons: First, for many purposes we are interested in knowing elevations above the tides; so a contour that defines the upper boundary of the tides is essential. Second, where elevation information is poor, a supplemental contour is likely to be more accurate than elevations estimated by interpolating with a model.

Table 1.1.2 lists our wetlands data sources. Just as the USGS provides 7.5-minute quadrangles at a 1:24,000 scale for topography, so too the US Fish and Wildlife Service's National Wetlands Inventory (NWI) provides 1:24,000 maps with broad wetland categories. Several states, however, have developed their own wetlands maps; representatives from New Jersey, Maryland, and North Carolina asked us to use their data instead of the NWI maps.[20]

The key limitation of the NWI data is its age: the aerial photographs for New Jersey were from the 1970s, and the Maryland and North Carolina photographs were from the 1980s.[21] Since then wetland shores have eroded, low dry land areas have converted to wetlands, human activities have converted wetlands to dry land,[22] and some previously drained areas have converted back to wetlands.[23] A second limitation of NWI is scale. Small fringing wetlands along tidal creeks sometimes do not show up in the NWI data set, even though they are large enough to be seen on a 1:24,000 scale map. Given these limitations, and the availability of data that state agencies trust more for their uses, we took the three states' advice and used their data.

We use wetlands only to define the inland limit of tidal wetlands. Kana et al. (1988) originally proposed the approach that we apply here. While surveying marsh transects around Charleston (South Carolina) and Long Beach Island (New Jersey), they recalled that low marsh is generally flooded twice daily and high marsh is flooded at spring tides but not every day. With an estimate of mean high water and spring high water, they reasoned, the wetland zonation can give supplemental elevation contours at both mean high water[24] and spring high water. PARK et al. (1989) first applied that approach. Although their LANDSAT imagery did not distinguish between low and high marsh vegetation, PARK et al. attempted to do so by obtaining imagery at high tide during "half moons" (i.e., at mean high water) and delineating the flooded areas. The NWI and state wetlands data we used, however, made no such distinctions.

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[19]As we discuss, we obtained LIDAR for the rest of the state after we developed our elevation data. As with the Eastern Shore of Maryland, we use these data to assess the accuracy of our procedure and will make the better LIDAR data available to the public.

[20]New York also provided wetland data for a portion of its coastal zone. Delaware also has its own wetland data, but state officials did not specifically ask us to use their data, and given the cost of interpreting each new data set, we did not.

[21]See NWI Status Photo Page, accessed April 1, 2005, at http://www.nwi.fws.gov/statusphotoage.htm.

[22]Tidal wetlands are rarely converted to dry land for development, but occasionally some loss will be permitted for water-dependent uses such as marinas and ports. See generally U.S. EPA and U.S. Army Corps of Engineers (1990) (explaining the federal policy on wetland mitigation under section 404(b)(1) of the Clean Water Act).

[23]Along Delaware Bay, for example, diked wetlands had been converted to agriculture for more than a century. As part of an environmental mitigation program for a PSE&G nuclear power plant, most of the coastal zones of Cumberland County, New Jersey, and areas across the Bay in Delaware are being returned to nature.

[24]Mean high water is the average water level at high tide.

Table 1.1.1. Elevation data sources used in original analysis.

Area Included	Data Source	Scale	Contour Interval or Equivalent Precision	Benchmark
		New York		
Entire state	USGS[a]	1:24,000	5 or 10 ft	NGVD29
		New Jersey		
Monmouth County	County data[b]	1:1,200	2 ft	NAVD88
Atlantic coast east of US-9	Corps of Engineers, spot elevations[c]		2 ft	NGVD29
Atlantic, Delaware Estuary	USGS	1:24,000	5 or 10 ft	NGVD29
North Jersey	USGS	1:24,000	10 or 20 ft	NGVD29
		Pennsylvania		
Philadelphia	City data[d]	1:2,400	2 ft	PVD[d]
Delaware and Bucks counties	USGS	1:24,000	10 and 20 ft	NGVD29
		Delaware		
Entire state	USGS	1:24,000	Mostly 5 ft	NGVD29
		Maryland		
Baltimore County	County data[e]	1:100	2 ft	NAVD88
Anne Arundel County	County data[f]	1:2,400	5 ft	NAVD88
Harford County	County data[g], excludes Aberdeen Proving Grounds	1:2,400	5 ft	NGVD29
Kent Island	Hard-copy map FEMA used for flood insurance rate map[h]	1:7,200	2 ft	NGVD29
Dorchester County and nearby	USGS	1:24,000	1 m	NGVD29
Southern part of state, both E and W shores	USGS	1:24,000	5 ft	
Potomac and Western Shore	USGS	1:24,000	Mostly 10 ft, some 20 ft	NGVD29
Statewide except for a few small areas	Maryland DNR spot elevations[i]	90-m grid	*10 ft*	NGVD29
Northern Eastern Shore	USGS 1:24,000	1:24,000	Mostly 20 ft	NGVD29
		District of Columbia		
Entire district	City data[j]	1:1,000	1 m	NAVD88
		Virginia		
Entire state	USGS	1:24,000	5 and 10 ft	NGVD29
		North Carolina		
Most of Pamlico and Albermarle sounds to ocean	State LIDAR project with FEMA[k]		*40 cm*	NAVD88
Elsewhere	USGS	1:24,000	Mostly 5 ft, some 2 m	NAVD88

[a] USGS. Large Scale Digital Line Graphs. http://edc.usgs.gov/products/map.html accessed May 1, 2006.

[b] U.S. Army Corps of Engineers, St. Louis District. 1999. Intercoastal Waterway, NJ: Spot Elevations (LFHYPELS). Prepared by ADR, Inc., Pensauken, NJ. Vertical position accuracy: 1 ft. Horizontal position accuracy: 5.0 ft.

[c] Monmouth County Office of Geographic Information Systems. 1997. Contours. Contour interval: 2 ft. Scale: 1:1200. Complies with National Map Accuracy Standards.

[d] City of Philadelphia Water Department, Information Systems and Technology. 1996. Philadelphia Vertical Datum. "The Philadelphia datum was first established in 1682 by William Penn with a metal spike in the Delaware River pier at the foot of Chestnut St based on the mean height." Metadata file accompanying Philadelphia 2-ft contours. NAVD (1988) is 4.63 ft lower than the PVD.

[e] Baltimore County, Maryland. 1997. Baltimore County Topo Data. Towson, Maryland: Baltimore County OIT/GIS Services Unit. Complies with standards of the American Society Photogrammetry and Remote Sensing as well as with National Map Accuracy Standards.

[f] Anne Arundel County, Maryland. 1995. Anne Arundel County 1995 Topographic Mapping. Prepared by Photo Science, Inc. (now EarthData International, Inc.) for Anne Arundel County, Department of Public Works. Scale: Annapolis: Anne Arundel County Office of Information Technology. Complies with National Map Accuracy Standards.

[g] Harford County, Maryland, undated. Harford County 5-ft contour elevation maps. Contour Aberdeen: Harford County GIS Department.

[h] GEOD Surveying and Aerial Mapping Corporation. Kent Island, Maryland. Map prepared for the Flood Insurance Rate Maps of Kent Island, Project No. 1381-107. Archived by Dewberry and Davis, Annapolis, Maryland. Provided by the FEMA Flood Insurance Administration. Scale: Contour. Complies with National Map Accuracy Standards.

[i] Maryland Department of Natural Resources. 1992. *Digital Elevation Models.* Vertical position accuracy: 5 ft. Horizontal Accuracy, 33 ft.

[j] National Capital Planning Commission and District of Columbia Department of Public Works. 2001. Rooftop Elevation and Ground Elevation. Washington, D.C.: Office of Chief Technology Officer. Complies with the National Map Accuracy Standards.

[k] Floodplain Mapping Program, North Carolina Division of Emergency Management. May 2002. NC Floodplain Mapping: 50 ft Hydrologically Corrected Digital Elevation Modelv.1. White Oak, Tar-Pamlico, Neuse, and Pasquotank basins. Vertical accuracy: 20 cm for coastal counties.

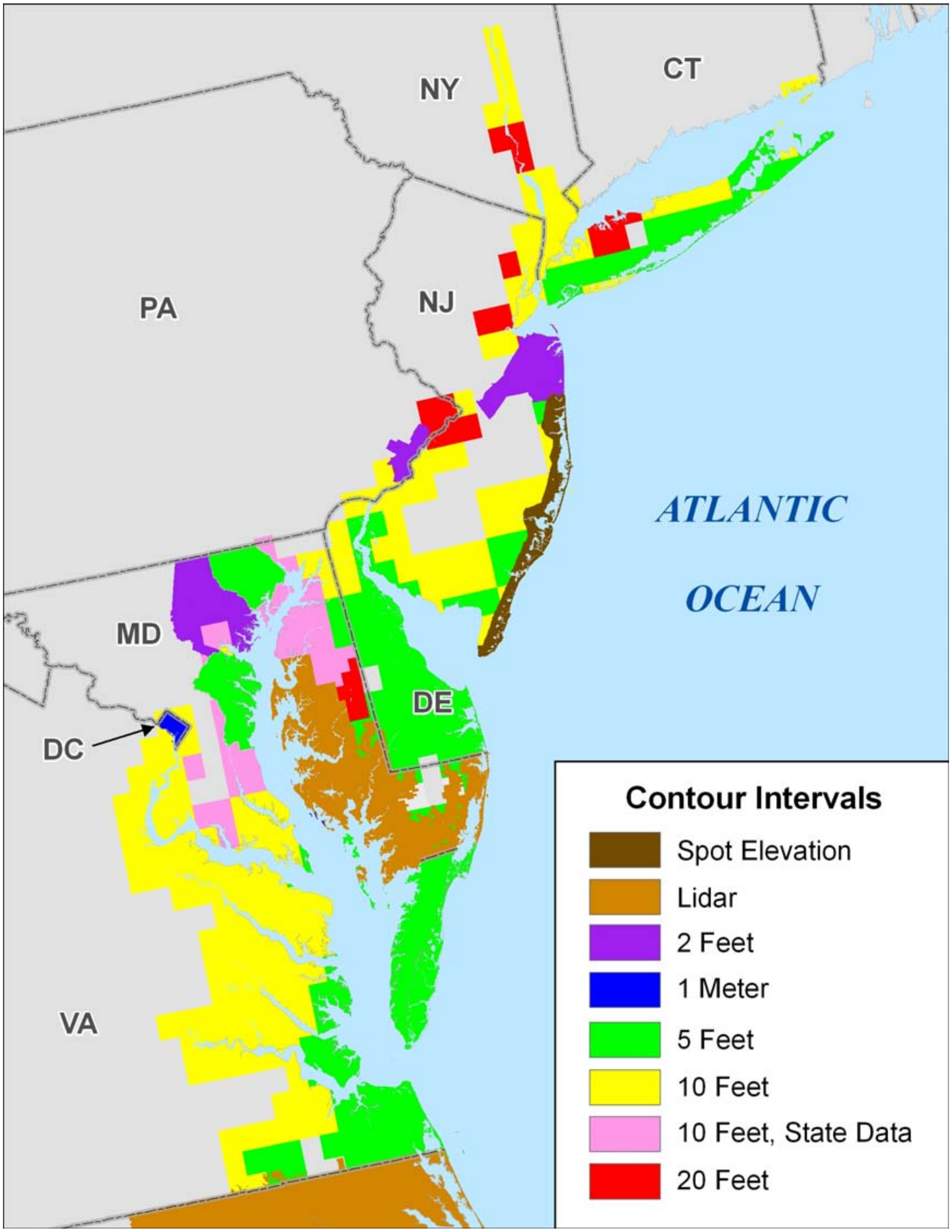

Figure 1.1.5. The elevation data used in this study. Rectangles generally signify USGS 1:24,000 data. The USGS maps had a 20-ft contour interval for the (pink) quads in Maryland where we used state data, and most or all of the four counties where we obtained 2- or 5-ft contour data (but 10-ft contours in the City of Philadelphia). We obtained the Maryland LIDAR and some of the North Carolina LIDAR after interpolating the elevations, and hence use that data to assess the accuracy of our approach. The final data set we provide has LIDAR for all of North Carolina.

Table 1.1.2. Wetlands data used in this study

State	County	Data Source	Year for Imagery	Scale
New York	Suffolk, Nassau, Rockland, Hudson above Tappan Zee	NWI[a]	1980, 1990	1:24,000
	New York City, Westchester: Long Island Sound and Hudson below Tappan Zee	New York[b]	1974	1:12,000
New Jersey	All but part of Delaware River	Rutgers Land Cover[c]	1995	30-m grid
	Delaware River upstream of Commodore Barry Bridge	NJ Upper Wetland Boundary[d]	1970	1:12,000
Pennsylvania	Entire state	NWI[a]	1980	1:24,000
Delaware	Entire state	NWI[a]	1982	1:24,000
Maryland	All but three areas where data lagged[f]	MD-DNR[e]	1988-1995	1:12,000
	Three areas where DNR data lagged[f]	NWI[a]	1980s	1:24,000
District of Columbia	Entire district	NWI[a]	1983	1:24,000
Virginia	Entire state	NWI[a]	1990, 2000	1:24,000
North Carolina	Entire state	NC DENR[g]	1981-1983 and 1994	1:24,000

[a] U.S. Fish and Wildlife Service. National Wetlands Inventory. http://www.nwi.fws.gov/ [accessed January 2006.] Scale: 1:24,000. The following types of polygons were treated as tidal wetlands: M2RS (Rocky Shore), M2US (Unconsolidated Shore), E2RS (Rocky Shore) E2US (Unconsolidated Shore), E2EM (Characterized by erect, rooted, herbaceous hydrophytes), E2SS (Scrub-shrub), E2FO (Forested). In addition, for areas with a water-regime characterized as N (Regularly Flooded--exposed daily), P (Irregularly Flooded, less than daily), S (Temporary-Tidal), or R (Seasonal-Tidal), we also used L2EM and PEM (both characterized by erect, rooted, herbaceous hydrophytes) , L2RS (Rocky Shore), L2US and PUS (Unconsolidated Shore), PML (Moss-lichen), PSS (Scrub-shrub), and PFO (Forested). In cases where the water regime was unknown, we included a polygon-specific inspection.

[b] New York State Department of Environmental Conservation. 2000. Tidal Wetlands Map: 1974.

[c] Rutgers Land Cover. Richard Lathrop. 2000. New Jersey 1995 Level III Land Cover Classification. Grant F. Walton Center for Remote Sensing and Spatial Analysis, Rutgers University. Reported in: Richard G. Lathrop. 2001. Final Report. Land Use/Land Cover Update To Year 2000/2001. NJ DEP. http://www.nj.gov/dep/dsr/landuse/landuse00-01.pdf accessed January 2006.]

[d] New Jersey Department of Environmental Protection. NJDEP Upper Wetlands Boundary/Upper Wetlands Limit for New Jersey.

[e] Maryland Department of Natural Resources Wetlands Data. 2001. Chesapeake and Coastal Watershed Services, Geographic Information Services Division. Minimum mapping unit: ½ acre. Scale: 1:12,000. Codes same as for NWI.

[f] The three areas where DNR data lagged: (a) Caroline, Talbot counties south of Easton-St Michaels, and parts of Dorchester along the Choptank River; (b) Cecil and Kent except for Chester River and Chesapeake Bay south of Rock Point; (c) Baltimore County west of Glenn L. Martin airport and Baltimore City north side of Baltimore Harbor.

[g] North Carolina Department of Environment and Natural Resources. 1999. DCM Wetland Mapping in Coastal North Carolina. Scale: 1:24,000 for portions relying on NWI and soils data. (Note: Scale is 1:58,000 for nontidal wetland boundaries areas relying on 30-m grid data [1994 update]. Those boundaries do not inform our elevation data, but do affect calculations of the area of nontidal wetlands vulnerable to sea level rise.) Polygons with a code of 1, 3, or 15 were treated as tidal wetlands, as well as any polygons identified with the code “e” (estuarine wetland).

New Jersey and North Carolina were special cases. For most of New Jersey, we used the 30-m grid data developed by Richard Lathrop for the State of New Jersey. These data provide a more detailed vegetation classification system, and it would have been possible to differentiate low from high marsh.[25]

For much of North Carolina, by contrast, we lacked the wetlands data necessary to completely apply our approach. Pamlico and Albemarle sounds, as well as their tributaries, are nanotidal estuaries: their astronomic tide ranges are so small that for most practical purposes there are no tides. As a result, wetlands data sets misleadingly classify the wetlands along the shore as "nontidal wetlands." Unlike true nontidal wetlands, these wetlands are at sea level and experience the full force of the tides in the bodies of water to which they are attached. Thus, unlike nontidal wetlands, which would eventually be inundated by a rising sea level, the nanotidal wetlands are already inundated. But the wetlands data do not distinguish the nanotidal wetlands from the nontidal wetlands (other than areas where salinities are high enough in the estuary to support brackish marsh). Thus, the wetlands data do not provide the location for the supplemental contour we would have hoped to create. North Carolina's LIDAR provided us with better elevation data than we would have been able to derive using the wetlands data; but the failure of the data to distinguish nontidal wetlands from nanotidal wetlands changes the meaning of any estimates of the area of tidal wetlands in North Carolina.

Step 3: Use Information on Tide Ranges and Benchmark Elevations to Estimate the Absolute Elevation of the Upper Boundary of Tidal Wetlands

Creating a supplemental contour using wetlands data requires us to have an estimate of the elevation of the upper tidal wetland boundary. That elevation depends on the elevation of mean tide level[26] (MTL) (relative to the benchmark) and the tidal range.

Relate benchmark elevations to mean tide level. NOAA's Published Benchmark Sheets (NOS, 2005) and the corresponding National Geodetic Survey (NGS) Data Sheets[27] provide estimates of the difference between mean tide level and the benchmark elevations at 125 locations throughout the study area. As Figure 1.1.6 shows, the majority of those locations are in or adjacent to New Jersey. Observations are especially sparse, by contrast, in the sounds of Long Island and North Carolina. Typically, mean tide level in the ocean is approximately 20–30 cm above NGVD29 in the mid-Atlantic, reflecting the rise in relative sea level since the benchmark was established. The average water level in a back bay, however, is often several centimeters higher than the mean tide level on the ocean side of the barrier island:[28] The cross sections of inlets and channels are greater at high tide than low tide. As a result, a flood tide brings more water into the bay when the inlet is 1 meter above the bay than the ebb tide carries away when the inlet is 1 meter lower. Therefore, ignoring rainfall, the flows during the ebb and flood tides are in balance only if the average bay level is somewhat higher than the ocean.

Rainfall and runoff are additional sources of water in estuaries, further increasing water levels relative to the nearby ocean. During wet periods, water levels in back bays behind barrier islands may be 10–30 cm higher than normal. This effect may be greatest in freshwater tidal rivers, given their distance from the ocean and prevailing seaward flow of water. Hence, as Figure 1.1.6 shows, mean tide level is higher at Philadelphia and Washington, D.C., than along the shores of

[25]This study did not make such a differentiation. However, we provided the data for Ocean County for the study by Jones and Strange (Section 3.20 in Section 3 of this report), which did make such a distinction.

[26]Mean tide level is the average of mean high water and mean low water. It is generally very close to mean sea level (the average water level) but requires fewer data points to calculate.

[27]The Published Benchmark Sheets include links to the NGS information relating mean tide level to the vertical benchmark elevations.

[28]For example, the stations inside Little Egg Harbor Bay near Long Beach Island (New Jersey) show MTL to be about 1.25 feet above NGVD29.

Delaware and Chesapeake bays, respectively. Along major bodies of water, the coverage is sufficient to estimate the elevation of mean tide level through interpolation.[29] For back bays lacking such data, we assumed that the elevation of mean tide level was similar to that of a nearby bay where data are available. The complete lack of data for Albemarle and Pamlico sounds was the most problematic. Fortunately, we had the best land elevation data—LIDAR—for that area; thus our need for a supplemental contour based on wetlands and tidal data was least. NOAA has developed a hydraulic model to estimate water levels in Pamlico Sound, but not Albemarle Sound; we used the NOAA results wherever they were available (PARKER et al., 2003; MYERS, 2005).

Use tidal range data to estimate the elevation of spring high water. Estimates of tide ranges are more prevalent than the absolute elevation of mean sea level. NOAA's tide tables[30] provide estimates[31] of the mean and spring-tide range at 768 discrete locations in the study area (see Figure 1.1.7).[32] As with the elevation of mean tide level, coverage is poor in Albemarle and Pamlico sounds, where astronomic tides are small compared to wind-generated tides; and again we used NOAA's model for Pamlico Sound. The NOAA estimates consider only astronomic tides, whereas tidal wetlands are also found in areas that are flooded irregularly by the winds. The distinction is minor in areas with a large tidal range, but where astronomic tide ranges are small, the wind-generated tides tend to enable wetland vegetation to form tens of centimeters above mean tide level, even if the spring tide range is negligible.

As with mean tide level, we used the available data to estimate the spring tide range through interpolation. We then calculated the elevation of spring high water relative to NGVD29 for the tidal epoch 1983–2001[33] as one-half the spring tide range plus the elevation of mean tide level calculated in the previous subsection. Based on various wetland transect studies relating wetland elevations to the tides (e.g., KANA et al., 1988), we assume that this elevation also represents the elevation of the upper boundary of tidal wetlands.

This assumption is only an approximation: wetlands may extend above spring high water, for example, in areas with small tide ranges where winds frequently cause areas above spring high water to flood. This discrepancy will not affect our estimate of the amount of dry land within (for example) 50 cm above spring high water; but it does lead us to overlook that some of the land (for example) 50–75 cm above spring high water would be flooded enough to support tidal wetlands if sea level rises 50 cm. This error is small compared to the accuracy of most USGS topographic maps—but it would be very significant in areas where LIDAR is available.[34]

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[29]We interpolated elevations using the TopoGrid function in ESRI's ArcInfo Grid module (ESRI, 1998). See the section on Step 3 for additional details on interpolation algorithms. The algorithm allowed us to treat intervening land as a "barrier" in the interpolation. In a back bay, for example, we use measurements from the bay—but not nearby ocean locations, because the impoundment effect of an inlet can elevate mean tide level within the bay.

[30]See, e.g., NOS (2004). The hard-copy report "Tide Tables" is now provided online. In 2004 it was still called "Tide Tables" but more recent versions of the web site have dropped the traditional title.

[31]The estimates in the NOAA tide tables are long-term averages.

[32]Each USGS 1:24,000 scale map includes an estimate of the mean tide range, which PARK et al. (1989) used in their assessment.

[33]NOAA's Published Benchmark Sheets adjust estimates of mean tide level so that they refer to the mean tide level averaged over a 18.6-yr lunar cycle. See, e.g., GILL and SCHULTZ (2001).

[34]Commenting on this report, Christopher Spaur of the Corps of Engineers provided the following: Regularly flooded tidal marshes have a predictable—and easily ascertainable—flooding regime controlled by astronomical tides, and along the Atlantic Coast possess broad areas dominated by tall-form *Spartina alterniflora*. Irregularly flooded marshes are found in areas where the pattern of flooding is at most partly related to astronomical tidal regime instead of wind and seasonal tides (e.g., wet and dry periods causing water levels to vary). These marshes lack the pronounced break between tall-form *Spartina alterniflora* and other marsh plants that occurs in regularly flooded marshes (Frey and Basan, 1985). Surfaces are subject to long periods of exposure and inundation (Stout, 1988). Because duration of inundation determines the lower limits of marshes, the longer duration of inundation causes the lower limit of marshes to be higher than in an area where tides dominate. The surface of irregularly

How accurate is our surface estimating spring high water? The NOAA data on spring tide range and mean tide level are based on substantial data and thus are precise for our purposes. Interpolation model error, however, can be significant. In large estuaries with substantial data, the variations of spring tide range from location to location are on the order of 5 cm; hence our interpolation error is likely to be small. In back barrier bays, however, tide ranges can vary by tens of centimeters. In many cases, the tide range simply dampens away from the inlets, and interpolation between stations can largely account for this dampening. In some cases, however, there are tidal creeks with no tide stations. In these locations, our error in calculating spring tide range—and hence spring high water—is likely to be on the order of tens of centimeters.

Adjusting tidal elevations to account for sea level rise. Only by sheer coincidence would the wetland maps be based on imagery taken during the midpoint of the 19.6-year tidal epoch that NOAA used to define local mean sea level. Given our assumptions, the wetlands maps provide the location for spring high water the year the photos were taken. In parts of New Jersey, sea level has risen 10 cm since the photos were taken (e.g., PERMANENT SERVICE FOR MEAN SEA LEVEL, 2003). Even though this discrepancy is less than 5 cm in most areas, we corrected for it because it is a systematic error that can be corrected, unlike the substantial random error resulting from large contour intervals of most elevation data.

We used the regression coefficients published by the Permanent Service for Mean Sea Level[35] for all locations with more than 40 years of data (see Figure 1.1.1). We then estimated the current rate of sea level rise at intermediate locations through interpolation. Multiplying that rate by the number of years between the map date and the NOAA base year provided us with site-specific adjustments to our surface estimating the elevation of spring high water.

Step 4: Interpolate Elevations Relative to the Vertical Datum for All Land above the Tidal Wetlands Using Elevations Obtained from the Previous Three Steps

From the aforementioned steps, we had the standard elevation contours, plus a supplemental contour along the upper boundary of tidal wetlands. We now examine how we used those contours to characterize elevations of locations between the contours. Doing so required us to decide on a rule for addressing data conflicts and pick an interpolation algorithm.

The primary potential for data conflicts concerned discrepancies between topographic contours and the tidal wetland boundary.[36] Along the Delaware River and parts of Delaware Bay, the upper edge of the tidal wetlands is about 4 to 5 feet (NGVD29), so we expected the wetland boundary to occasionally be landward of the 5-ft contour. In areas with 2-ft and 1-m contours, we expected to see a similar overlap even in areas with low tidal ranges. We limited ourselves to two possible solutions: Either the wetlands data or the contour always takes precedence over the other.

We decided that the wetlands data should take precedence over the contour information, for three reasons. First, accepting both data sets at face value, the elevation and wetlands data typically had a scale of 1:24,000 and hence an allowable horizontal error of 12 m. But the topographic maps also have a vertical error of one-half contour interval. Therefore, by its very terms, the typical topographic map allows for the possibility that the 5-ft contour may be as low as 75 cm (2.5 ft) (NGVD29), which would be tidal wetlands in most areas. Second, the wetlands data are newer.[37]

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flooded marsh occurs at about mean high water (Reimold, 1977). In the coastal bays, where tidal range is generally 30–50 cm, the elevation range across the marsh surface is much less and the marshes tend to lack much habitat below MHW or so. The short form of *Spartina alterniflora* is dominant on the seaward edge, and the tall form is either lacking or very local in occurrence along tidal creeks.

[35]The Service obtains the data for the United States from NOAA's National Ocean Service.

[36]With the exception of Maryland, we used only one source of standard topographic data in a given location. For Maryland, where we used USGS and MD-DNR information, the USGS contours took precedence.

[37]USGS has made planimetric updates to most of the maps since 1970. However, the contour dates are generally from

Because of shore erosion, wetlands may now exist in areas that had previously been above the 10- or 20-ft contour. Finally, this approach leaves us with a reasonable landscape. If we gave precedence to the 5-ft contour, we would be left with a bluff over the wetlands along the 5-ft contour; removal of the 5-ft contour, by contrast, means that we interpolate between the wetlands and the 10-ft contour.

In selecting an interpolation algorithm, we had to consider our three objectives:

- Estimate the amount of land that could be inundated by rising sea level to the level of precision allowable by existing data.
- Produce maps depicting the elevations of land close to sea level.
- Provide an elevation data set for other researchers.

Estimate the amount of land that could be inundated. The contours provide polygons of various elevation classifications. In a location with a 5-ft contour interval, for example, we have polygons that represent the land between spring high water and the 5-ft (152-cm) (NGVD29) contour, as well as 152 to 304 cm, etc. If spring high water happens to be 60 cm above NGVD29 in a given area, then we have polygons that tell us how much land is 0 to 92 cm above spring high water, as well as 92 to 244 cm, etc. However, contour intervals and the elevation of the tides vary, so the polygons in different locations represent different elevation ranges relative to the tides. This situation prevents us from simply adding the calculated area across all localities.[38] Estimating the amount of land at particular elevations requires an assumption about how elevations are distributed in the land between the contours.

We considered two approaches for estimating elevations between contours: using linear interpolation and using a digital elevation model (DEM) to fit an estimated land surface through the contour data we had. We tried the DEM approach first, because it was going to be necessary for creating the maps. We quickly concluded, however, that readily available algorithms would unreasonably skew our results. When the shore and the contours are all fairly straight or well-behaved, results seem reasonable; but when the contours have sharp turns, the algorithms assume that a disproportionate amount of land has an elevation close to that of the contour. In effect, the algorithms tend to create plateaus on either side of the contours.[39]

Therefore, our estimates are based on linear interpolations; i.e., we assume that elevation is uniformly distributed between contours. To keep the calculations manageable, we interpolated elevations at the quad level.[40]

Produce maps and elevation datasets. We interpolated between the contours and spot elevations using the TopoGrid algorithm provided by ESRI (1998) software. This procedure was developed based on Hutchinson’s (1988, 1989) approach to estimating DEMs. The fundamental insight embodied in that algorithm is that ground surfaces have many local peaks, but few local minimums, because water generally flows toward the sea rather than being impounded. For our purposes, that aspect was not important because we are not concerned about slopes; instead we are concerned with improving the accuracy of

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the 1945–1970 period. See, e.g., the order forms provided by the New York State Center for Geographic Information (showing the planimetric and contour dates for every USGS 7.5-minute quad). Accessed on August 12, 2006, at http://www.nysgis.state.ny.us/mapssales/orderfrm/brantlk.htm.

[38] In areas where we have accurate spot elevations (e.g., LIDAR), we do not face this problem.

[39] In Figure 1.1.8, TopoGrid correctly creates a stream valley in an area with a fairly simple topography. But when we applied that algorithm over our entire study area, we found numerous plateaus along the contours. Someone more skilled with the algorithm may have been able to set parameters to better replicate normal topography; but this algorithm was designed for correct drainage, not for correctly duplicating the distribution of elevations.

[40] For each quad, we estimated the average elevation of spring high water (SHW). We then calculated the amount of land between SHW and the 5-ft contour, and allocated it proportionally between 0 and 5-SHW. We then calculated the land between 5 and 10 feet and allocated it between 5-SHW and 10-SHW. We stored the results in bins of 0.1 feet. We followed this approach twice for each quad, so that we could distinguish nontidal wetlands from dry land (using nontidal wetlands polygons from the data sources displayed in Table 1.1.2).

elevations at particular locations and correctly describing the overall distribution of elevations. Nevertheless, the algorithm's use of stream data to characterize slopes should tend to ensure that stream valleys are captured below the lowest topographic contour, even in areas where the stream is above the tides (and hence would not provide a contour).[41] We used a cell size of 30 meters because when we began the study, a 10-m cell size slowed processing time too much.

Before settling on TopoGrid, we tested three other readily available algorithms: inverse distance weighting[42] (IDW), spline,[43] and triangulated irregular networks (TIN),[44] using the (5-ft interval) contours in the general vicinity of Ocean City, Maryland. All four algorithms created plateaus near contours with sharp curves, with approximately the same amount of land having an elevation within 15 cm (0.5 feet) above or below the contour as the amount of land with an elevation 15 to 75 cm above or below the nearest contour.

Figure 1.1.8 compares the four algorithms. Each started with the same set of set of contours, with a circular hill to the right, a U-shaped bluff to the left, a stream valley in between, and a shore that is otherwise fairly straight. The various colors represent the elevations that the four algorithms estimated. Between the 20- and 40- ft contours, the yellow-brown and pink-red shades in the TopoGrid and TIN maps suggest that these algorithms create intermediate elevation contours that are evenly spaced between the input contours. IDW, by contrast, assigns virtually all of this land to elevations of 20, 30, or 40 feet, as if the land were a series of steps. Spline creates 50-ft and 200-ft hills between the 20- and 30-ft contours for no obvious reasons. This example generally confirmed the literature: IDW is more appropriate when one has many points that already outline the shape of the surface (e.g., CHILDS, 2004). Spline tends to produce spurious hills, especially with unevenly spaced input data (e.g., ROGERS and SATTERFIELD, 1980; OLSEN and BLISS, 1997). Given the relatively large study area, we needed an algorithm that required less supervision than spline.

Our choice between TIN and TopoGrid was a close call. In areas where the contours are one or two cells apart, TIN faithfully interpolates between the contours, whereas TopoGrid seems prone to horizontal errors of one or two cells. TIN completely misses the stream valley, however, treating both the valley and the U-shaped hill as a single flat area. TopoGrid, by contrast, creates a stream valley with a reasonably constant slope between the 10- and 20-ft contours. Similarly, TIN assumes that all the land within the 40-ft contour is at precisely 40 feet, whereas TopoGrid creates a peak in the center just above 45 feet. We decided to use TopoGrid because we were more willing to tolerate its one- or two-cell errors than maps that missed hills and streams.

Step 5: Use the Information from Step 3 to Calculate Elevations Relative to Spring High Water

We conducted both sets of interpolation relative to the fixed benchmark elevation. We created maps and a data set of elevations relative to spring high water by subtracting our estimate of the elevation of spring high water from every data point. We derived our estimates of the area of land within a given elevation above spring high water by subtracting the average elevation of spring high water within a given USGS quad from the elevation of the contours between which we were interpolating. The effect of this conversion is that our maps show the land below a given contour (e.g., USGS 5-ft contour) to be lower in areas with large tide ranges than in areas with small tide ranges.

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[41] If there is a 10-ft contour on either side of a creek, without additional information, an interpolation algorithm is likely to assume that the land between the contours (the stream valley) is also at 10 feet.

[42] IDW interpolates by defining the elevation of a point X as the weighted average of points A within a given neighborhood, with the weights being the inverse of the distance between X and the various points X, possibly raised to a power. See, e.g., SHEPARD (1968), FISHER et al. (1987), and CHILDS (2004).

[43] See, e.g., CHILDS (2004).

[44] A TIN is a digital data structure that represents terrain with a series of triangles. We used the ESRI command "CreateTin". See, e.g., PRICE (1999).

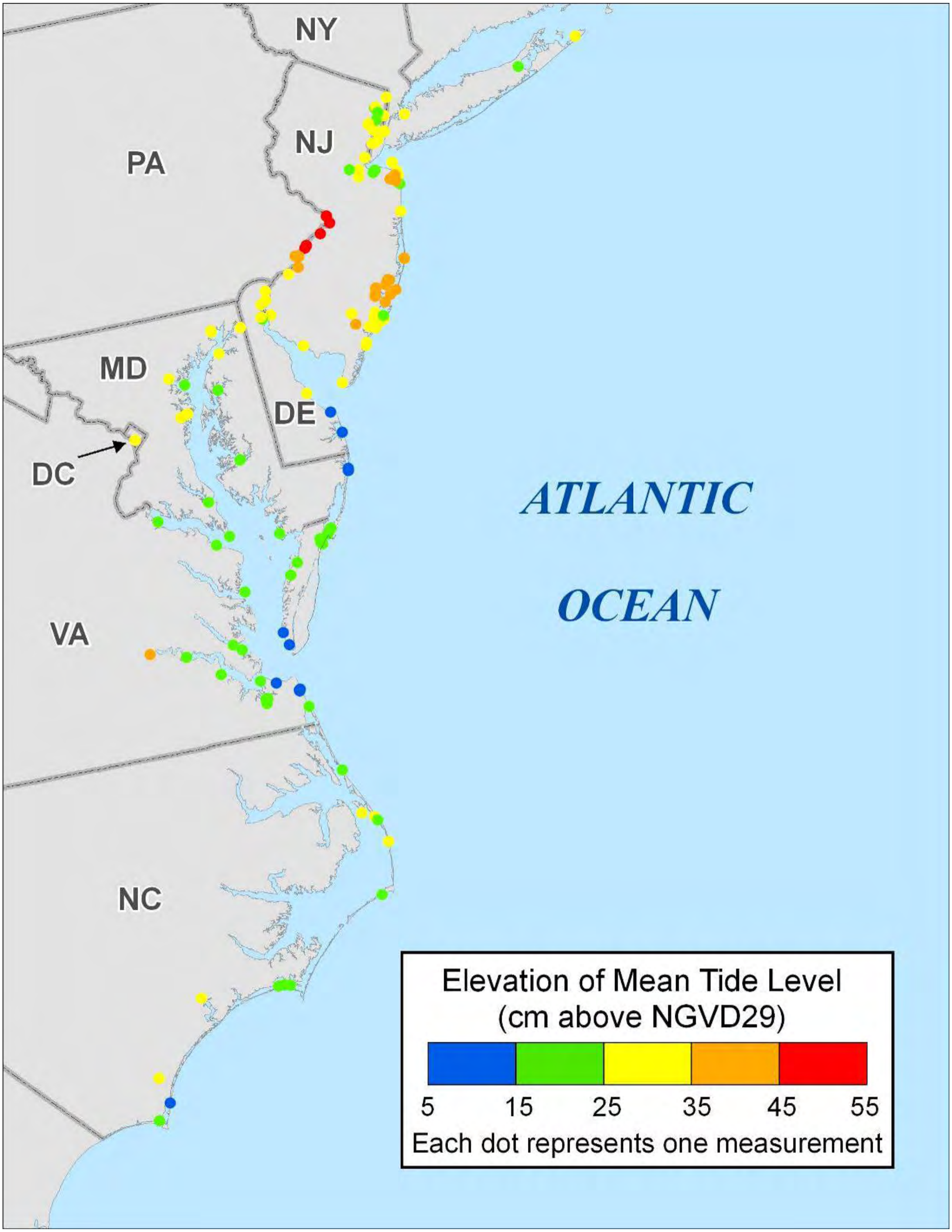

Figure 1.1.6. Observations of mean tide level used in this study. This map depicts the 125 observations from NOAA's Published Benchmark Sheets and the National Geodetic Survey's data sheets used in this study to create a surface depicting mean tide level relative to NGVD29.

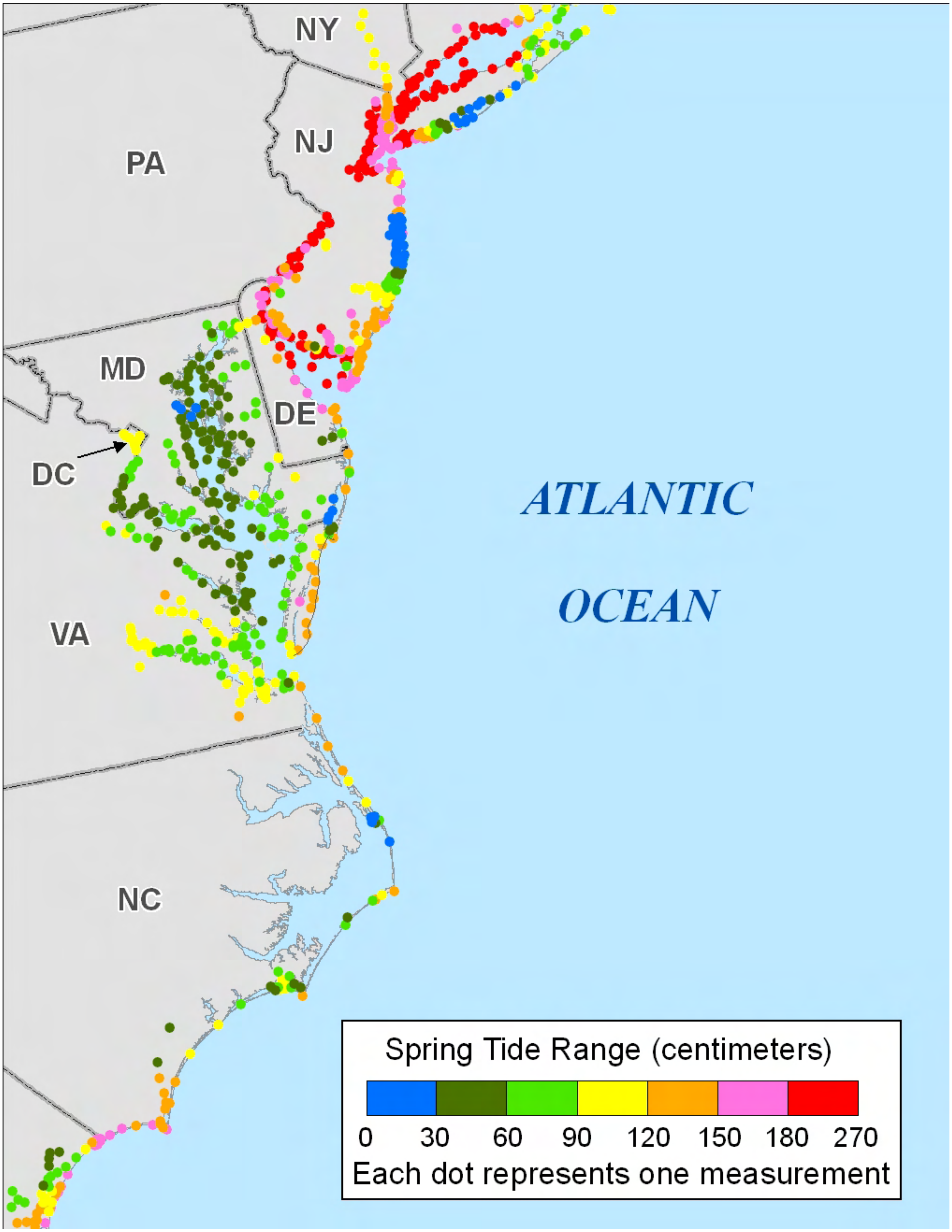

Figure 1.1.7. Observations of tide ranges used in this study. This figure depicts the 768 observations from NOAA's tide tables used in this study to create a surface depicting spring tide range.

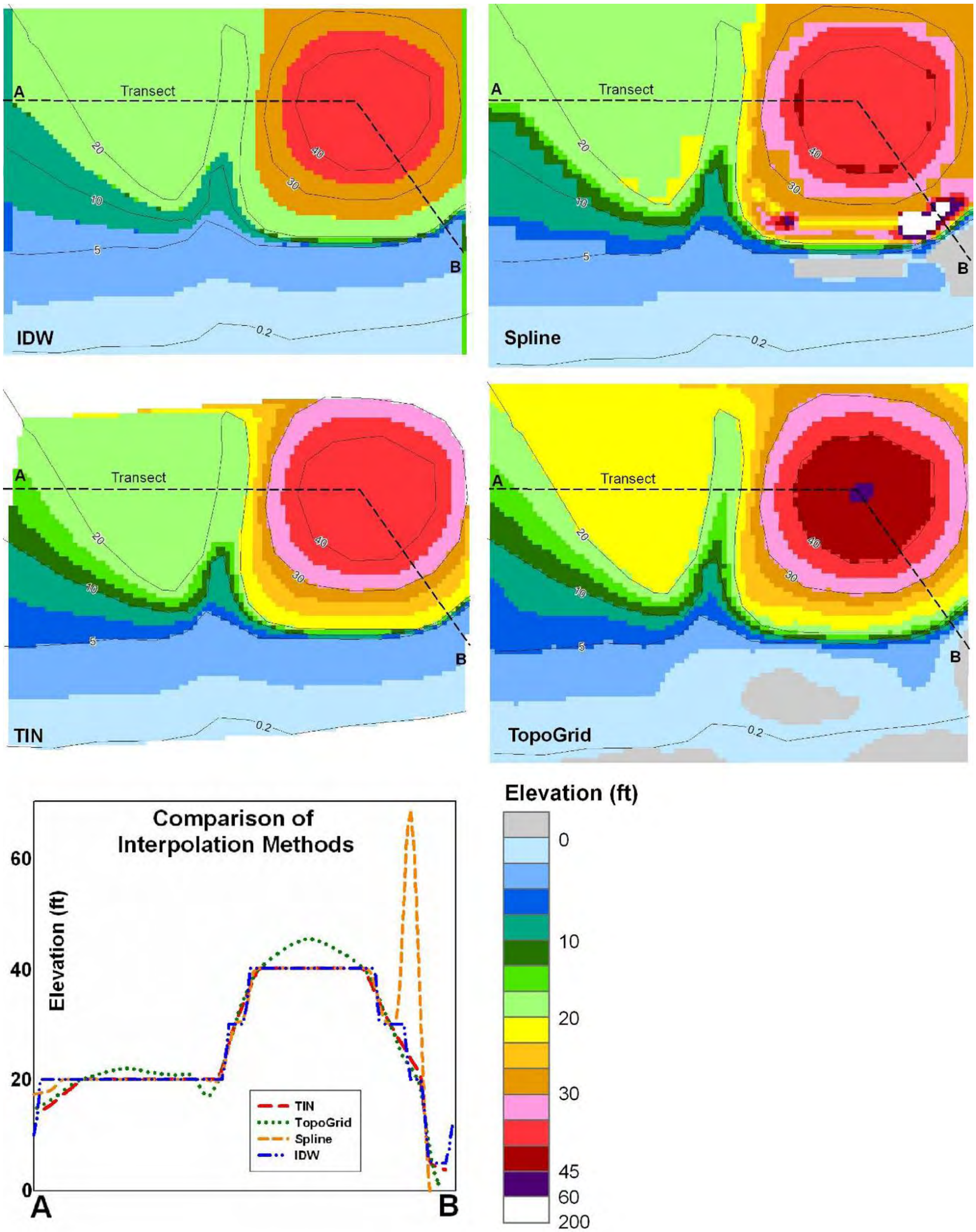

Figure 1.1.8. Test of four interpolation models. The colors represent the elevations calculated by each of the four algorithms for the same set of contours. The box to the left shows a cross section of the elevations as one travels from point A to point B for the surfaces created by each algorithms.

1.1.4 Quality Control and Review: Error Estimation

We corrected all the errors and questionable aspects that we noticed—but a test of what we did not notice was also necessary. We enlisted Russ Jones of Stratus Consulting to test the algorithm and validate the results against an independent data set. Let us briefly examine the results of the tests we asked him to perform.

Testing the interpolation algorithm

The intent of the algorithm is to interpolate between contours. Values that are outside the contours represent a failure, regardless of whether the problem is caused by TopoGrid or some other error. We asked Jones to pick 12 representative quads, including at least 1 quad for each state, encompassing the different contour intervals and data sources. After he picked the quads, we sent him the DEM (grid) results and the input data (see Table 1.1.1) representing polygons of land between the wetlands and the first contour (e.g., 5 ft), the first and second contour (e.g., 5–10 ft), etc. For each quad, we asked him to compare the areas of the source contour polygons with those of the interpolated DEM for the same elevation range and to produce a histogram of the DEM elevations by contour polygon.

Table 1.1.3 shows the results of this comparison. Topogrid did not duplicate the area of dry land below the lowest contour as well as we had hoped, with percentage errors of 20 percent or more in 5 of the 12 quads. For the second and third contours, the percentage error was less than half as great, but hardly inspiring.

The errors do not seem as large, however, when viewed as vertical error. The fourth column in Table 1.1.3 provides the "effective" elevation of the polygon contour as estimated by the DEM.[45] For example, the polygon area below the 2-m contour of the Merry Hill quad is 241 ha. Although the DEM found only 152 ha below the 2-m (6.56-ft) contour, it also finds 241 below 6.67 ft.[46] In 8 of the 12 quads, this effective elevation is less than 0.11 feet above the corresponding USGS contour. The area error is large and the vertical error is small, because the algorithm created a plateau along the contour; more land was slightly above the contour than slightly below it.

Moreover, in most quads, most of the land below the first contour is tidal wetland. Hence, an error of 20 percent of the dry land is typically about 5 percent of the total land. Thus, if we included all low land in the denominator, our percentage error estimates for the lowest contour would have the same magnitude as for the other contours. This is particularly true for the Middle River quad in Baltimore County, Maryland, where the dry land below the 2-ft (NAVD88) contour is a very narrow strip adjacent to the tidal wetlands, whose inland boundary is often 1.5 feet above NAVD88. Thus, any such dry land in our data set may largely represent errors in the input data. We are unable to explain why our algorithm underestimated the low land below the first contour for the other 10 quads,[47] but it may be an artifact related to the relative complexity of wetland shores.

Comparing results with an independent dataset

As this study proceeded, LIDAR data became available for the entire state of North Carolina as well as Maryland's Eastern Shore south of Rock Hall (MD DNR, 2004). JONES (2007) converted

[45] That is, the elevation below which the DEM estimates an area equal to the polygon area below the first contour.

[46] For some of the quads, plateaus emerged at the contours in spite of our efforts to avoid them.

[47] We used Corps of Engineers spot elevation data for most of the Atlantic City quad, so the comparison with the USGS polygon area represents a comparison of Corps data to USGS maps more than a test of our algorithm.

the LIDAR from NAVD88 to NGVD, and then compared our results to the LIDAR. Table 1.1.4 shows (a) the mean error and (b) the root mean square error of the DEM, by LIDAR elevation increment and source of input data. Figure 1.1.9 depicts the difference in elevation estimates for Maryland, which has the wider variety of data quality.

Overall, wherever we relied on USGS maps, our RMS error was approximately one-half the contour interval. In those areas where the USGS maps had a contour interval of 2 meters or better, the mean error was usually less than 1 foot (30 cm). Note, however, the tendency for the DEM to overestimate the elevations of the lowest land while underestimating the elevations of higher ground. For example, in Maryland where we had USGS 5-ft contours, the DEM overestimated elevations by an average of 48 cm in the area below 50 cm while underestimating elevations an average of 10 cm in the area between 450 and 500 cm. This pattern occurs for two reasons. First, the LIDAR has a random error on the order of 20 cm, and the set of dry land locations where LIDAR suggests an elevation of 40 cm will include cases where the true elevation is 60 cm, but few if any cases where the true elevation is 20 cm because such land would be tidal wetland. Second, if land has an elevation between 0 and 50 cm, the error of our interpolation algorithm will assign some of this land as between 50 and 150 cm; but by design none of it will be assigned values below spring high water (typically about 30 cm NGVD for these areas).

It would be wrong to conclude, however, that our analysis is systematically understating vulnerability to sea level rise. We also created a similar table (not shown) with the 50-cm increments based on DEM elevation. That table shows that most of our lowest DEM elevations are less than the LIDAR elevation at that location, while higher DEM elevations overstate the LIDAR elevation. That pattern resulted largely from the plateau problem (see previous discussion of Step 4). If the DEM assigns an elevation barely above the contour, it is often underestimating an elevation; but if it assigns an elevation barely below the next contour, it is probably overstating the elevation. Thus, if the DEM finds a very low elevation, quite often the land is truly higher; but when the land is truly very low, often the DEM assigns a higher value. Does either tendency dominate?

Table 1.1.4c suggests that the DEM is about as likely to overstate as understate the amount of land below a particular elevation. For each data source, we calculated the cumulative elevation distribution.[48] We then took the area of land below a particular elevation (e.g., 1 meter) as estimated by our DEM interpolation, and then looked up the elevation below which the LIDAR estimated the same elevation. For example, our interpolated DEM estimates 24.75 km^2 (excluding tidal wetlands) below 1 meter SHW in the part of Maryland where USGS maps have a 1-m contour interval, and the LIDAR shows the same amount of land below 72 cm. Thus, the land vulnerable to a 1-m rise according to the DEM would be inundated by a 72-cm rise according to LIDAR. Hence the table shows a vertical error of 28 cm.

Our analysis of the cumulative error shows that errors offset to a large extent in Maryland, with the vertical error generally less than ¼ contour interval, and generally less than the mean error (except for the undocumented Kent Island map provided by FEMA). In North Carolina, however, the error appears to be more systematic: the cumulative error is not substantially less than the mean error (and in some cases is greater). Fortunately, we now have LIDAR for all of North Carolina, so our problems there may have no practical importance, provided they are confined to that state. Is Maryland alone a good test of our method, or must one give weight to North Carolina as well?

Considering the probable causes of the systematic error in North Carolina, the accuracy assessment of Maryland alone is probably more representative of the error in the rest of the study area. Our approach of defining a supplemental contour along the upper boundary of tidal wetlands breaks down in North Carolina, for three reasons. First, as we have mentioned, the failure of available wetlands

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[48]The cumulative vertical error in Table 1.1.4c is similar to the difference between the two contour elevations in Table 1.1.3 and discussed in the last section.

data sets to distinguish nanotidal wetlands from nontidal wetlands in Albemarle Sound and its tributaries led our interpolation to treat them as ranging in elevation from just above the tides to 50–100 cm above spring high water, even though some are at sea level. Second, several nontidal rivers have wide floodplains consisting of nontidal wetlands, with a bank at approximately the 2-m (or 5-ft) contour. Lacking a supplemental contour, TopoGrid has no basis for estimating how much below the 2-m contour those lands might be, and hence tends to assign elevations close to, albeit below, the 2-m contour. Finally, as Figures 1.1.4 and 1.1.6 show, the stations for estimating mean tide level and spring high water are sparse.

Table 1.1.3. How well the DEM duplicated the polygons in our input data.

USGS Quad Name	State	Lowest Contour (ft)	DEM Elevation of Contour (ft) [a]	First Contour DEM Area[b] (ha)	First Contour Polygon Area[c] (ha)	% Error of Area Estimate[d]	Second Contour DEM Area (ha)	% Error of Area Estimate	Third Contour DEM Area (ha)	% Error of Area Estimate
Central Park	New York	10	10.1	399.3	428.1	-6.7	1472.2	-1.5	1350.6	-1.3
Atlantic City[e]	New Jersey	5	4.6	164.2	132.2	24.2	1011.4	-5.6	146.7	11.0
Port Norris	New Jersey	5	5	202.0	209.9	-3.8	522.2	2.6	107.9	0.4
Marcus Hook	Pennsylvania	10	10.1	69.2	87.8	-21.2	308.3	0.3	257.9	-1.7
Bethany	Delaware	5	5.1	885.2	1002.6	-11.7	2211.8	7.9	1412.2	10.7
Middle River	Maryland	2	1.25	54.8	28.3	93.4	96.3	-11.0	117.5	-0.9
South River	Maryland	5	7.3	162.4	344.5	-52.9	444.4	-5.2	606.4	0.8
Ocean City	Maryland	5	5.1	416.3	426.6	-2.4	505.3	-20.9	391.9	16.7
Broomes	Maryland	5	5.8	84.2	108.2	-22.2	228.2	-38.2	607.6	17.4
Accomack	Virginia	5	5.1	123.7	151.6	-18.5	1193.9	0.5	1382.0	0.5
Irvington	Virginia	10	10	471.2	471.3	0.0	1309.9	2.1	1654.6	13.2
Merry Hill	North Carolina	6.56	6.666	151.7	240.8	-37.0	247.8	35.4	333.2	8.4
Total				**3184.2**	**3632.0**	**-12.3**	**9551.6**	**-1.2**	**8368.4**	**6.4**

[a] For example, the Central Park quad has 428.1 ha below the USGS 10-ft contour according to the input polygon data, and 428.1 ha below an elevation of 10.1 feet according to the DEM. Therefore, we say that the DEM's estimated elevation of the USGS 10-ft contour is 10.1 feet, and the vertical error of DEM's estimate of the contour elevation is thus +0.1 feet.

[b] For example, area of land (other than tidal wetlands) between 0 and 10 feet in the Central Park quadrangle, according to our DEM.

[c] For example, the area of land below the 10-ft contour in the Central Park quadrangle (other than tidal wetlands). Comparing the difference between the areas of the DEM and polygons is a measure of our procedure.

[d] The DEM's estimate of 399.3 ha is 6.7% less than the area of the input polygons. Therefore, the error of our area estimate is -6.7%.

[e] The Atlantic City Quad is not a test of the algorithm because we had Corps of Engineers spot elevation data for most of the quad. However, it does provide an indication of the difference between the Corps data and the USGS maps.

Table 1.1.4. Accuracy of DEM Results: Comparison with LIDAR

Source:	Maryland Eastern Shore					North Carolina	
	Kent Island	1-m	5-ft	MD-DNR	20-ft	5 ft	2m
Contour (cm)	60	100	152	305	610	152	200
Elevation[a]	A. *Mean Error (Difference between DEM and LIDAR)*[b]						
50	60	26	48	102	17	58	56
100	12	18	9	74	-25	54	67
150	0	56	27	71	-67	38	53
200	4	23	54	72	-109	23	27
250	-1	-7	43	59	-155	13	19
300	-7	-9	21	37	-193	2	15
350	-8	12	9	2	-240	-2	7
400	-9	2	3	-35	-276	-4	1
450	-13	-2	-3	-59	-304	-3	-5
500	-42	-9	-10	-80	-341	2	-11
	B. *RMS Error (Root Mean Square Difference between LIDAR and DEM)*[c]						
50	102	38	107	160	18	113	116
100	74	59	70	151	28	92	92
150	72	83	95	146	74	99	87
200	80	41	100	135	124	100	84
250	80	37	71	110	170	100	94
300	76	52	56	91	218	91	96
350	78	57	61	82	263	84	90
400	94	49	63	84	308	77	81
450	121	59	65	98	345	76	73
500	135	71	66	119	387	86	73
	C. *Vertical Error (Difference in Cumulative Elevation Distribution)*[d]						
50	-48	3	-21	-36	-54	36	52
100	-65	28	-1	-19	-75	38	80
150	-35	41	3	-18	-93	49	105
200	-30	35	9	-7	-106	52	109
250	-32	-3	23	-12	-110	46	130
300	-30	1	10	-11	-113	52	115
350	-29	-5	-2	-46	-111	73	67
400	-21	-5	-6	-101	-108	94	68
450	7	-14	-7	-104	-101	104	82
500	16	-16	-8	*	*	113	98

[a] In parts A and B, results are presented for 50-cm increments relative to NGVD29 as measured by LIDAR. For example, the second row in each case provides results averaged over all lands with elevations between 50 and 100 cm according to LIDAR. In part C, results are cumulative, and relative to spring high water as estimated by the DEM interpolations. For example, the second row is based on the area of land whose DEM interpolated elevation is less than 100 cm above SHW.

[b] The mean of LIDAR-DEM. For example, in parts of Maryland where USGS maps had a 5-ft contour and LIDAR showed elevations between 100 and 150 cm, the DEM estimate was 27 cm higher than the LIDAR value, on average. If LIDAR represents the true elevation, the mean difference represents mean error.

[c] Root mean square difference is calculated by taking the difference between the LIDAR and DEM elevations at each point, squaring that value, adding all the squares and dividing by the number of data points, then taking the square root. If the mean difference is zero, it is the same as the standard deviation. If LIDAR represents the true elevation, this value is the root mean square error.

[d] A measure of the sensitivity to sea level rise of an estimate of the amount of land vulnerable to inundation. For example, in parts of Maryland where USGS maps have a 1-m contour interval (excluding tidal wetlands), our interpolated DEM estimates 24.75 km^2 below 1 meter, while the LIDAR shows the same amount of land below 72 cm. Assuming LIDAR to be accurate, the land vulnerable to a 1-m rise according to the DEM would actually be inundated by a 72-cm rise. Hence the table shows a vertical error of 28 cm.

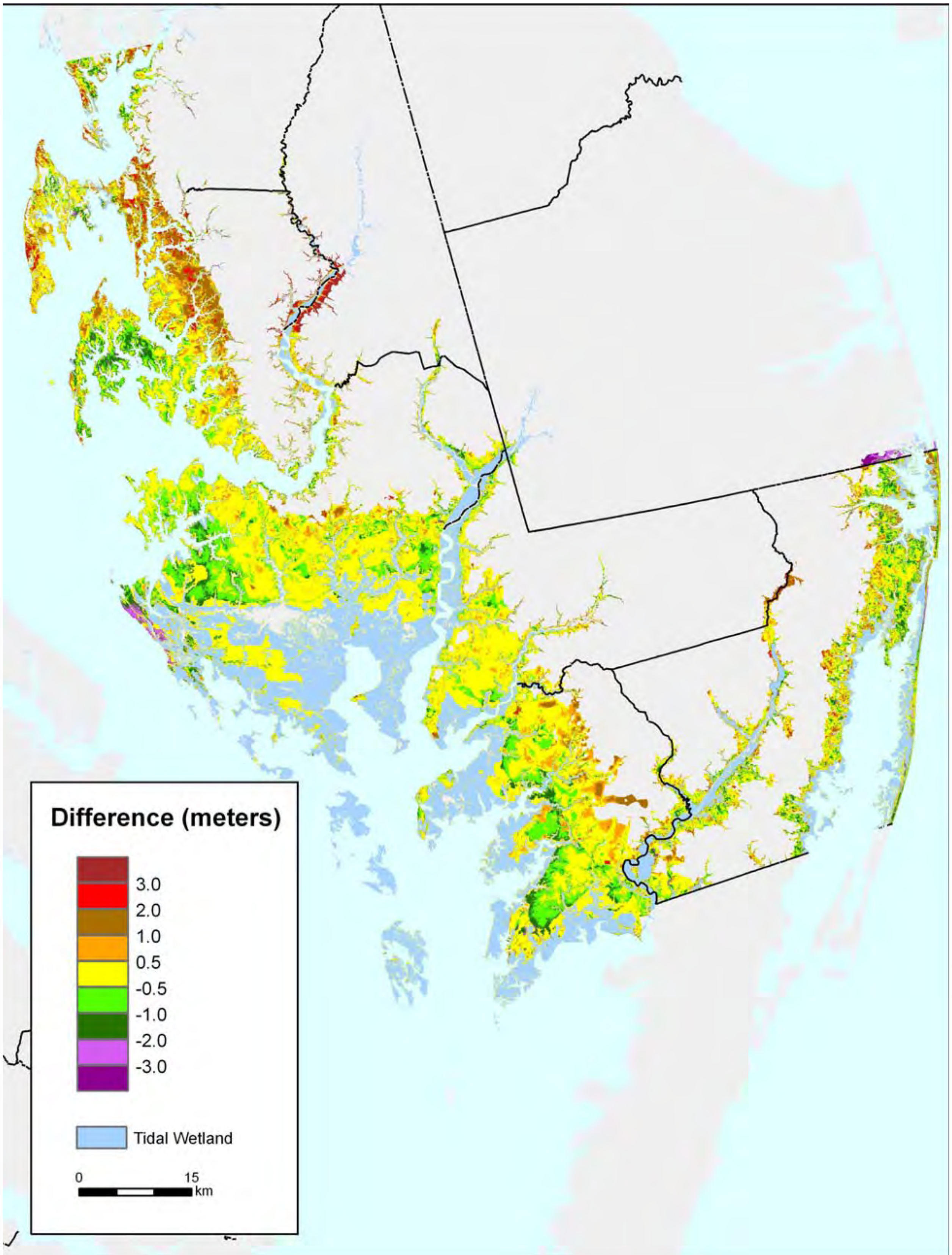


Figure 1.1.9. Elevation as estimated by LIDAR minus elevation estimated by our DEM: Eastern Shore of Maryland.

1.1.5 Maps and Results

Maps

Figures 1.1.10 to 1.1.14 show our maps using various scales and formats. Figure 1.1.10 compares our new maps of Maryland with the coarser-scale maps published by TITUS and RICHMAN (2001).[49] At that scale, our new maps do not appear to be a major improvement over the previous maps—except that that we have a smaller contour interval. Unlike the previous effort, however, the current study provides elevations relative to the tides. In Figure 1.1.10, the 1-m (spring high water) contour looks like the 1.5-m NGVD29 contour, but that varies from place to place. Perhaps more important, the current data provide maps at a much larger scale. Figure 1.1.11 shows the area around Washington, D.C.

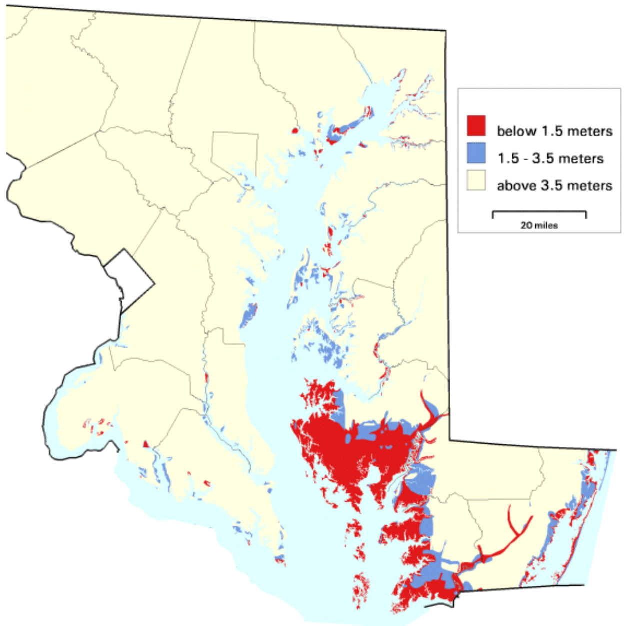
Depending on the needs of a particular audience, it may be useful to distinguish nontidal wetlands from dry land rather than simply presenting elevations. Figure 1.1.12 shows the lands along the Delaware River between the Delaware/Pennsylvania border and Northeast Philadelphia. The maps show open water and tidal wetlands as light and dark blue, respectively. For other lands, Figure 1.1.12a depicts elevations relative to the upper tidal wetland boundary using a 50-cm contour interval with colors following the spectrum from green to yellow to red. The contours look relatively smooth outside of Philadelphia, because we had to interpolate between the upper tidal wetland boundary and the USGS 10-ft contour, which is about 2 meters above the tides. For the city itself we had 2-ft contours. One limitation of our approach is that we do not make use of contours below the tidal wetlands. Both Philadelphia and Gloucester County, New Jersey, have land below sea level protected by dikes; it simply shows up as land less than 50 cm above the tides in our maps.

Figure 1.1.12b is similar, except that the green-to-red spectrum applies only to dry land; we show nontidal wetlands using two shades of purple. The rationale for this format is that elevation alone is not always the best guide to risk of inundation as sea level rises. From the perspective of many property owners and planners, the tidal inundation of previously dry land represents a significant loss of property, whereas inundation of nontidal wetlands may be viewed as less problematic. Nontidal wetlands tend to be found well inland from tidal waters. Because a dike runs along the Delaware River in Gloucester County, New Jersey, nontidal wetlands are found very close to the river, albeit on the other side of a dike.

Figures 1.1.13 and 1.1.14 show the entire study area using the same two formats. At this scale, one notices that the lowest lands are mostly dry land in Maryland and Delaware, but nontidal wetland in North Carolina, and split evenly between the two in New Jersey.

We are making both our maps and the underlying data available to the public. We will provide the maps with and without nontidal wetlands, at the 1:100,000 scale, county by county, state by state, and a few multicounty and multistate regions. The maps will generally show elevations above the tidal wetland boundary, with the 50-cm contour interval generally used in this report. However, the county- and 1:100,000-scale maps will use a 1-m contour interval wherever the underlying topographic data had a 10-ft contour interval[50]; where we relied on maps with a 20-ft contour interval, we will not include those maps in materials oriented for the general public. Both the digital elevations and the coastal wetland maps will be available from the authors as well.

[49] We added the tidal wetlands to the Titus and Richman map to make them more comparable.



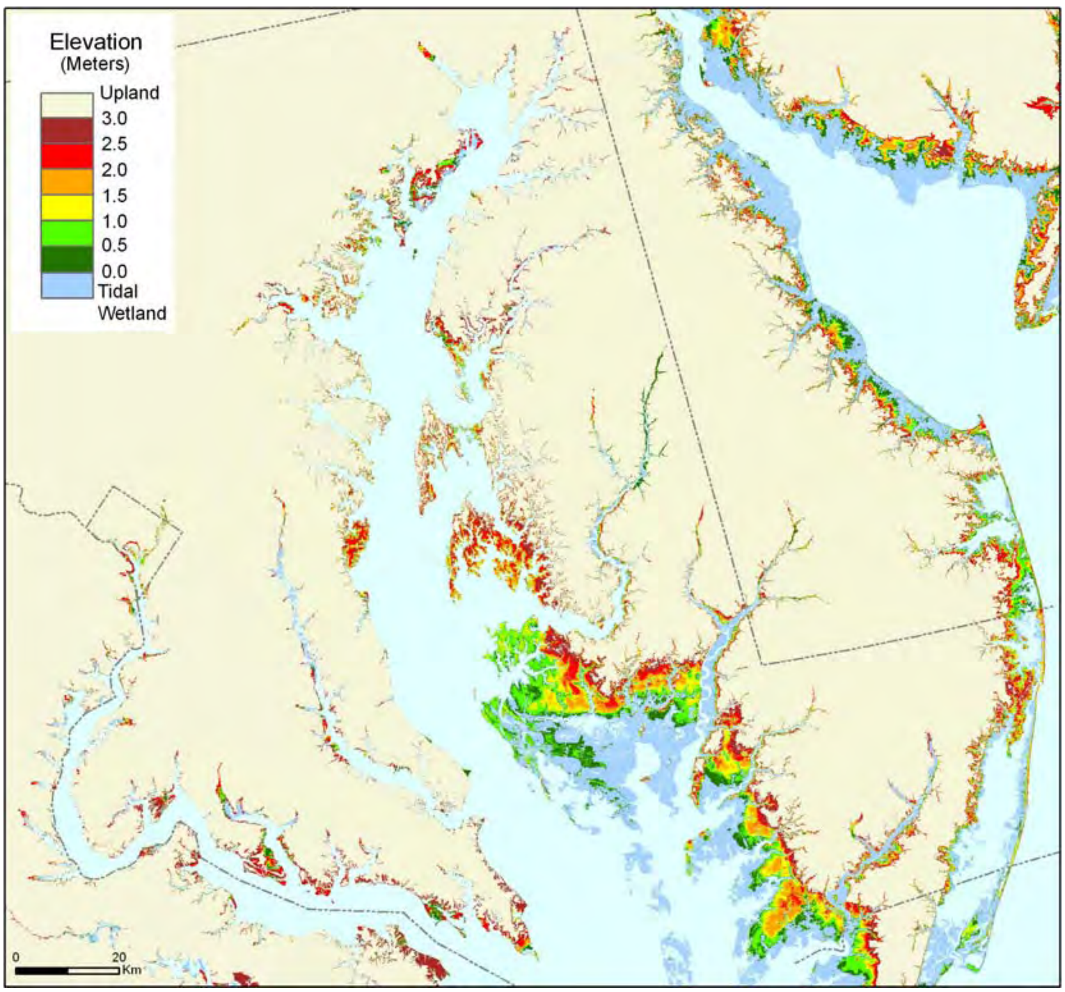


Figure 1.1.10. Maryland: Comparison of TITUS and RICHMAN (2001) with this study. Map (a) shows elevations relative to NGVD29 from TITUS and RICHMAN (2001). Map (b) shows elevations relative to spring high water according to this study.

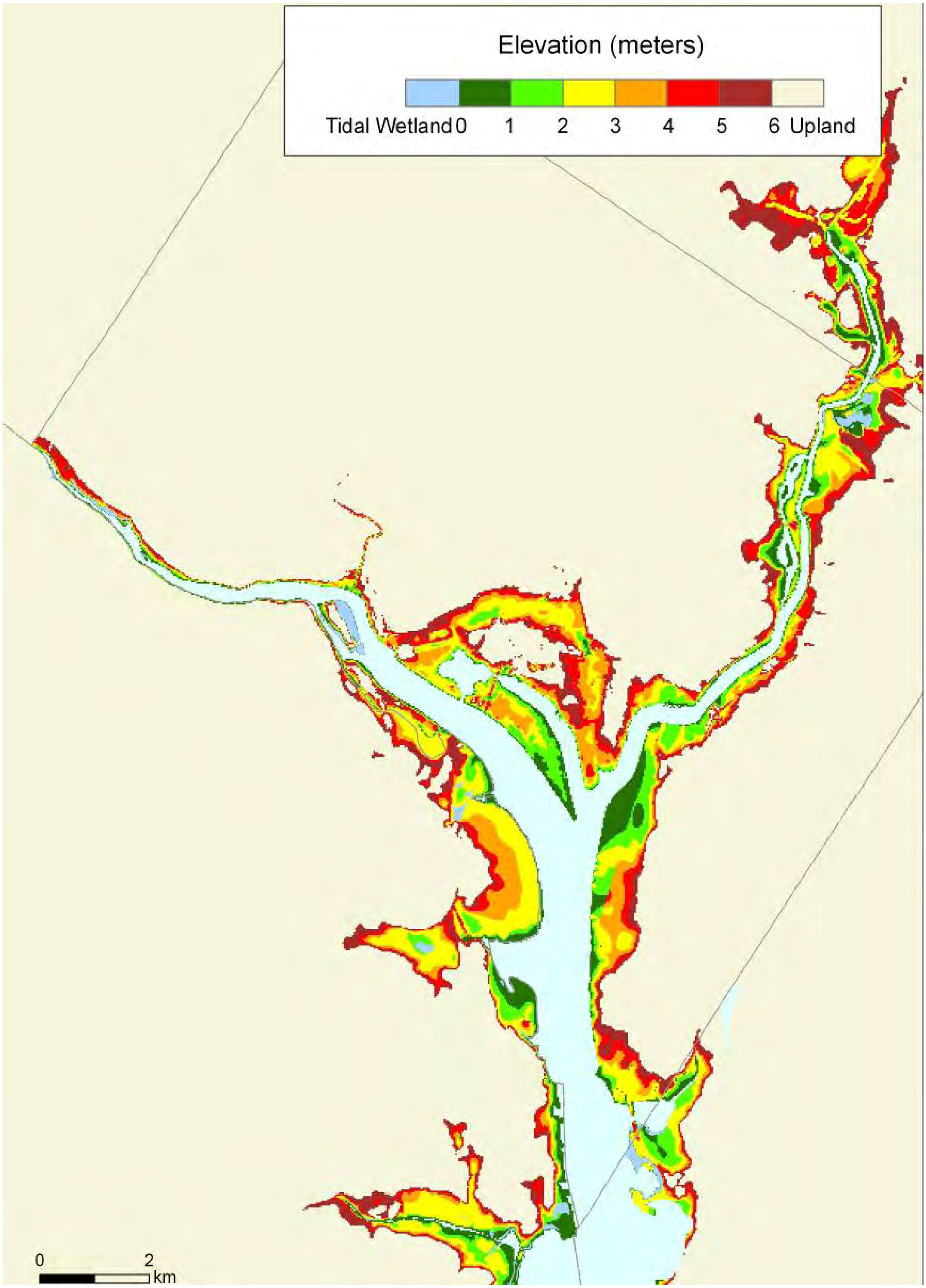


Figure 1.1.11. Elevations relative to spring high water: Washington, D.C., and vicinity

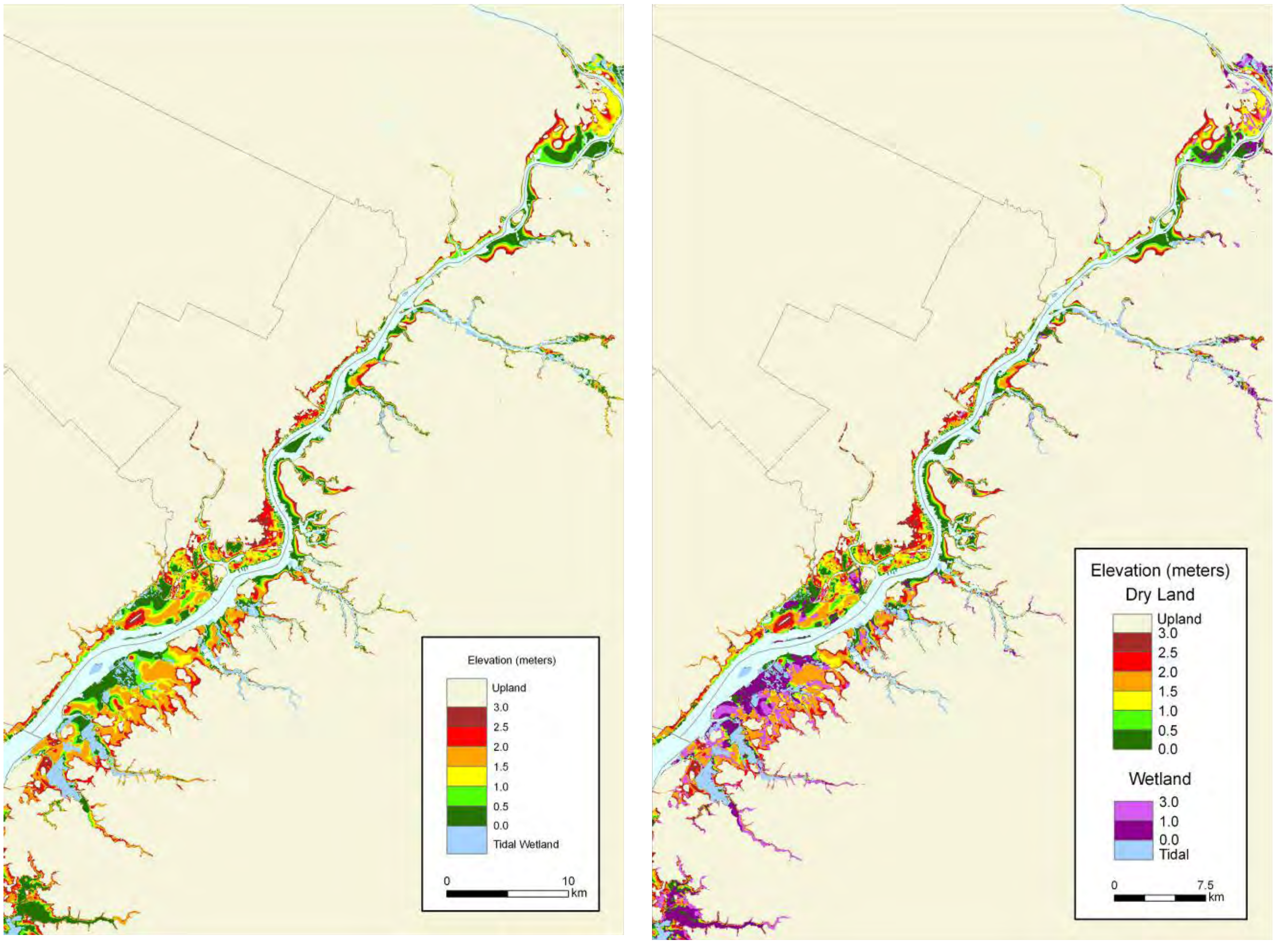


Figure 1.1.12. Lands close to sea level in Pennsylvania and nearby New Jersey. Map (a) shows elevations relative to spring high water. Map (b) distinguishes dry land from nontidal wetlands, depicted in purple.

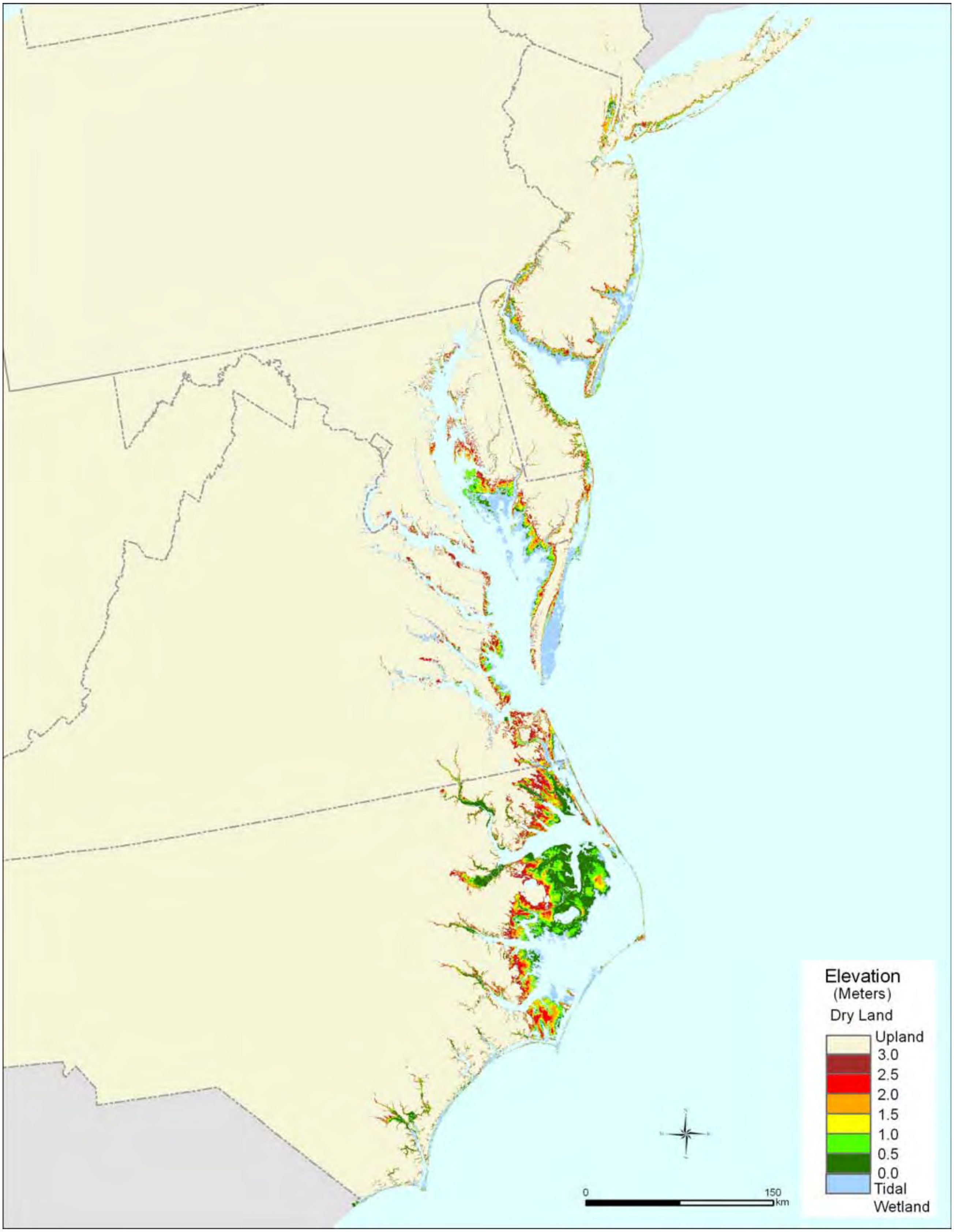


Figure 1.1.13. Elevations relative to spring high water: New York to North Carolina.

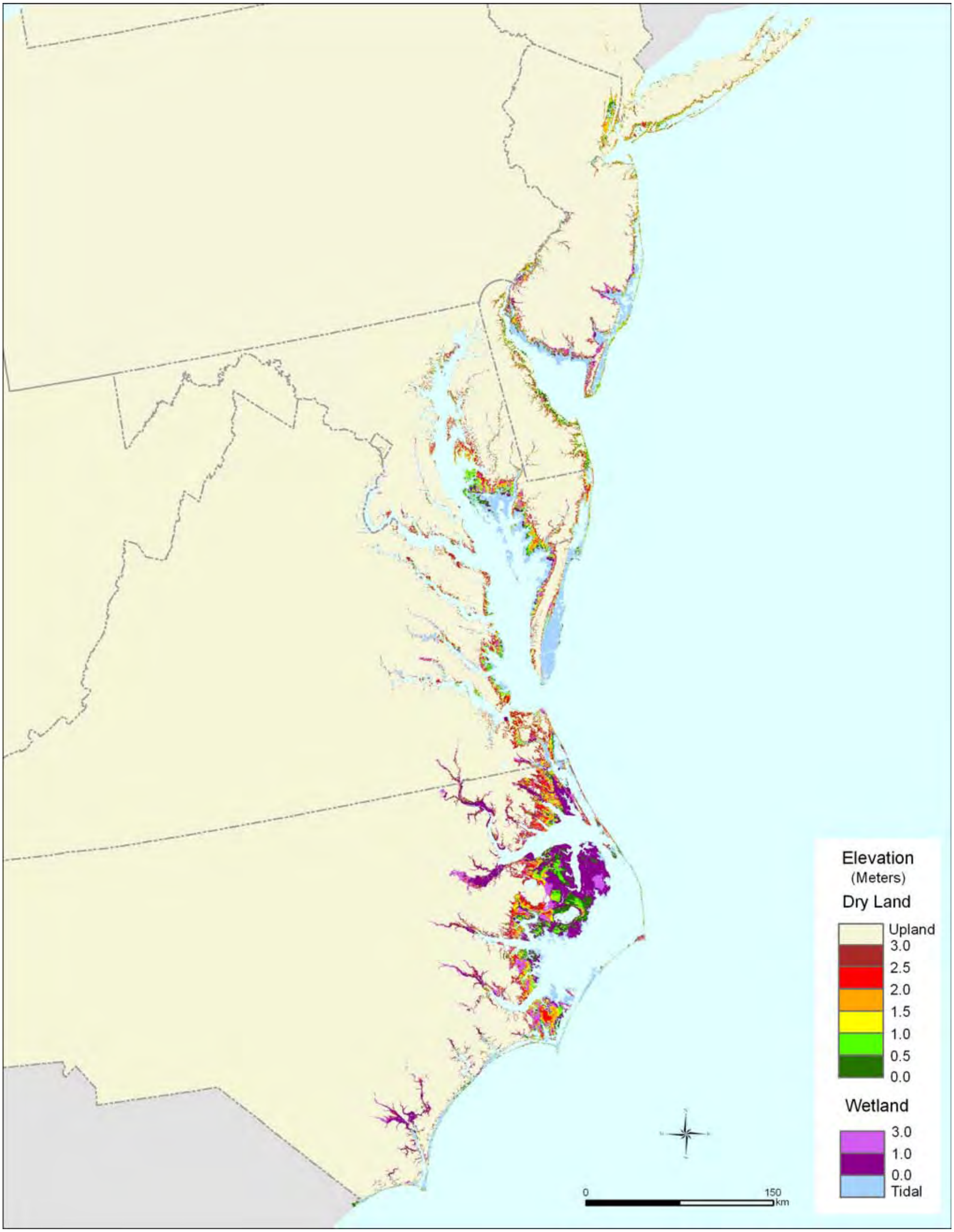


Figure 1.1.14. Elevations of dry land and nontidal wetlands relative to spring high water: New York to North Carolina.

Results

Tables 1.1.5 and 1.1.6 provide our estimates of the land within 6 meters above spring high water, in 50-cm elevation increments. Although the maps show that the distribution of elevations varies from place to place, Table 1.1.5 shows that at the statewide level, the amount of dry land at various elevations is fairly uniform. Previous studies that were forced to rely on 5-m contour intervals and assume that the dry land below 1 meter is one-fifth that amount, for example, appear to have made a reasonable assumption. For the most part, the amount of dry land within 1 meter of high water is within 25 percent of the amount of land between 4 and 5 meters. Given the various geological processes that cause land to form just above sea level, it is not surprising that that area of land within 1 meter would be slightly greater than the area between 4 and 5 meters.

At first glance, North Carolina appears to be an important exception to this tendency, with less land below 50 cm than at other elevation increments. At most of the elevations depicted, North Carolina has 500–700 km^2, almost as much as the 600–800 km^2 for the other seven states combined. Below 50 cm, however, North Carolina has only approximately 100 km^2 of dry land. Table 1.1.6 (and Figure 1.1.14) shows why: close to 2,000 km^2 of nontidal wetlands. Looking at all lands above the tides, North Carolina has about 2,000 km^2 between 0 and 50 cm, 1,400 km^2 between 50 and 100 cm, and 800–900 km^2 for each of the other 50-cm increments below 5 meters. Thus, considering Tables 1.1.5 and 1.1.6 together gives us the opposite picture as Table 1.1.5 alone: more land between 0 and 1 meters than between 1 and 2 meters and other elevation increments. That result, however, is probably an artifact of the definition of tidal wetlands. As we have discussed, the nanotidal wetlands of Albemarle and Pamlico sounds and their tributaries are generally classified as nontidal wetlands. These wetlands depend on sea level, however, as much as most tidal wetlands: their vertical accretion is in part a function of sea level rise. The nontidal wetlands may be vulnerable to sea level rise as well: their irregular flooding tends to occur either from high water levels in the sounds or because of a combination of rainfall and the very slow drainage that results from being barely above sea level. Agricultural and other dry lands just above these nontidal wetlands could become wet if the sea rose, just as lands above tidal wetlands can be inundated as sea level rises. Thus, it is somewhat misleading to classify those wetlands with other nontidal wetlands in an analysis of sea level rise. As Table 1.1.6 shows, North Carolina is unique in that its area of nontidal wetlands below 50 cm is greater than the area of tidal wetlands; the remaining states, by contrast, have about 20 times as much tidal wetlands as nontidal wetlands below 50 cm.

Tables 1.1.5 and 1.1.6 also support previous assessments suggesting a potential for a significant net loss of wetlands if sea level rise accelerates. This report focuses solely on the topographic vulnerability of wetlands, that is, the ratio of current tidal wetlands to the area of low land that could potentially become inundated. Companion studies are examining the potential for vertical accretion and the extent to which shore protection might thwart landward migration. 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 less than 50 cm above the tides, but only 700 km^2 of dry land within 1 meter above the tides. Figure 1.1.15 shows county-by-county variability of the ratio of tidal wetlands to dry land within 1 meter above the tides.[51] Because 1 meter is somewhat arbitrary, Figure 1.1.15b shows a similar ratio, but with the area of land within one-half the tide range (instead of 1 meter) above spring high water in the denominator. This ratio indicates the net loss of tidal wetlands that would occur if sea level were to rise one-half the tide range instantaneously. (We exclude North Carolina because the small tide range would give us a meaninglessly large ratio.) Equivalently, this figure shows 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, the average ratio is about eight. That is, if wetlands were able to migrate inland unfettered by

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

shore protection, but were not able to vertically accrete, sea level rise would eventually cause the area of tidal wetlands to decline by 7/8.

Thus, the fate of tidal wetlands in the mid-Atlantic is likely to depend more on their ability to accrete vertically than to migrate inland. The potential for wetlands to keep pace with an accelerated rise is sea level uncertain (see Reed et al., Section 2.1 of this report). A priority for additional research would thus be 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.

Comparison with Comparable Studies

Two previous mapping studies funded by the EPA assessed the amount of mid-Atlantic land vulnerable to sea level rise. TITUS and RICHMAN (2001) reported results only for the 1.5 and 3.5 contours, relative to NGVD29, without distinguishing wet from dry land, for each state in the Atlantic and Gulf coasts. Table 1.1.7 compares our results to their results for the eight Mid-Atlantic states. For both elevation increments, this analysis finds more low land than the previous effort for every state except North Carolina. In fact, for the seven states from New York to Virginia, our estimate of tidal wetlands alone is greater than the previous estimate of land below 1.5 m. Because the 2001 study was largely based on the USGS 1° (1:250,000 scale) maps, our results are almost certainly more accurate. Our primary reliance on 5- and 10-ft contour intervals—as well as the coarse (30-m) cell size—suggests that comparable (or greater) improvements are likely whenever this assessment can be revised using LIDAR.

Finally, Table 1.1.8 compares our results to that of EPA's 1989 Report to Congress, which remains the sole nationwide estimate of the land vulnerable to a 50- or 100-cm rise in sea level (PARK et al. 1989; TITUS and GREENE 1989). That study was primarily designed to estimate the vulnerability to a 2-m global rise in sea level, for which the available elevation maps seemed adequate. The need for an assessment of the more likely and near-term scenarios led the authors to interpolate elevations below the contours, primarily using triangular irregular networks. PARK et al. included a dynamic model of how wetlands respond to sea level and provided land loss in 5-year increments, based on 48 sites equally dispersed around the nation representing 10 percent of the coastal 7.5-minute quads. Like this effort, that study used wetlands data to distinguish dry land and defined elevations using the USGS 7.5 minute quads—but the cell size was 500 meters. The Report to Congress (TITUS and GREENE 1989) grouped the sites into seven regions, so that confidence intervals could (barely) be developed to capture uncertainty regarding the extent to which the sample sites were representative of the coastal zone; the mid-Atlantic region was defined as New York to Virginia. The authors of the Report to Congress no longer have the intermediate results, so our only available comparison is the aggregate land loss for New York to Virginia. As Table 1.1.8 shows, our estimate of the land vulnerable to a 2-m rise is about 30 percent less than the estimate[52] from the Report to Congress. 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 close to uniformly distributed by elevation below 5 meters,[53] although PARK et al. found the dry land to be disproportionately close to sea level. As the final column shows, the Report to Congress, in effect, estimated land to be 30–40 cm lower on average than this study.

Does our downward revision for the mid-Atlantic imply that the Report to Congress also overestimated the nationwide loss of land vulnerable to a 50-cm rise by a factor of three? Probably not: only three of the regions showed such a disproportionate amount of low land in the 1989 study. Moreover, the Report to Congress was based on a nationwide sample of 48 sites, only 8 of

[52] The Report to Congress did not report a confidence range for the regional estimates of dry land loss because the central estimates were less than two times the standard deviation.

[53] Of course, our results assume linearity between contours—but Tables 1.1.6 and 1.1.7 show elevations to be fairly uniform from contour interval to contour interval as well. Our areas with spot elevation data and LIDAR also show a fairly constant pattern.

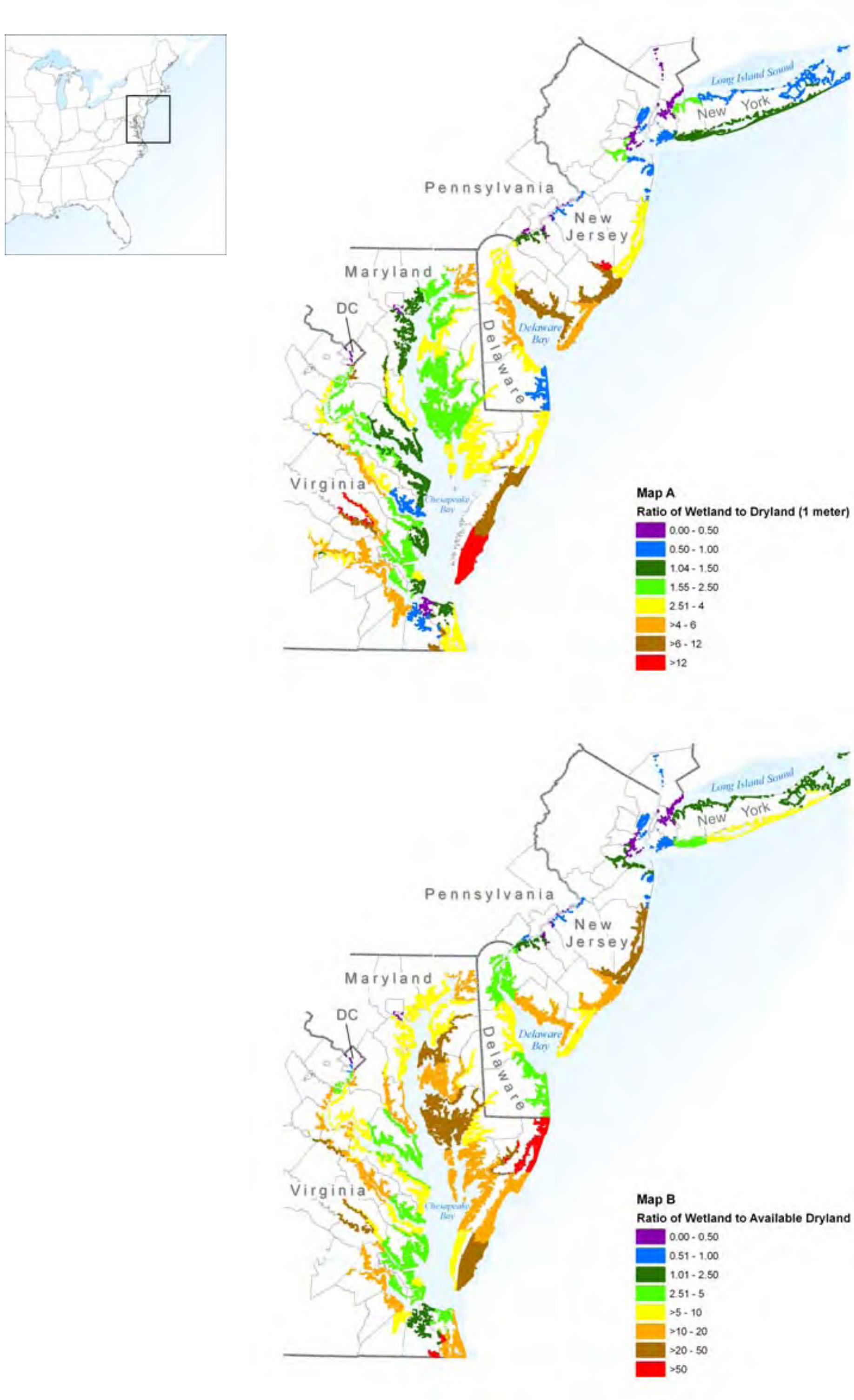
Table 1.1.5: Area of Dry Land Close to Sea Level (km^2, 50-cm elevation increments)

Elevation above Tidal Wetlands (m)	New York	New Jersey	Pennsylvania	Delaware	Maryland	District of Columbia	Virginia	New York to Virginia	North Carolina	New York to North Carolina
< 0			2.4							
0.5	82	127	10.2	72	184	2.4	172	651	741	1391
1.0	81	148	11.1	54	265	1.2	177	737	626	1364
1.5	86	150	15.0	52	240	1.4	223	768	582	1350
2.0	86	125	13.4	56	265	1.4	237	785	637	1422
2.5	78	111	11.3	66	226	1.8	253	748	633	1381
3.0	71	108	11.3	69	244	1.8	332	837	572	1409
3.5	67	104	9.8	71	246	1.8	346	846	618	1464
4.0	61	100	9.2	74	231	1.8	338	816	715	1531
4.5	58	99	9.3	75	203	1.7	275	721	567	1288
5.0	52	95	9.1	73	195	1.6	253	679	412	1090
5.5	35	80	8.3	70	164	1.4	254	613	294	907
6.0	20	80	8.2	71	108	1.3	230	519	156	676

Table 1.1.6: Area of Wetlands Close to Sea Level (km^2, in 50-cm increments).

Elevation above tidal Wetlands (m)	New York	New Jersey	Pennsylvania	Delaware	Maryland	District of Columbia	Virginia	New York to Virginia	North Carolina	New York to North Carolina
Tidal Wetlands	149	980	6	357	1116	0.8	1619	4228	1272	5500
< 0			0.4							
0.5	5.0	99	1.5	22.2	64	0.04	73	266	2372	2637
1.0	4.8	73	1.5	9.8	57	0.02	75	221	719	940
1.5	3.4	71	1.7	9.2	54	0.03	70	209	394	604
2.0	3.2	64	1.6	8.9	58	0.02	69	204	321	525
2.5	2.8	43	1.1	7.9	41	0.02	73	168	296	464
3.0	2.0	41	1.0	7.8	47	0.02	74	173	259	432
3.5	1.9	40	1.0	7.9	54	0.03	74	178	233	411
4.0	1.9	36	1.0	7.6	47	0.03	74	168	238	405
4.5	1.9	36	0.8	7.5	41	0.05	67	154	219	373
5.0	1.8	35	0.3	7.4	40	0.05	64	148	234	372
5.5	1.7	30	0.4	7.3	42	0.02	81	162	166	328
6.0	1.3	30	0.4	7.5	38	0.02	84	161	79	240

which were in the mid-Atlantic. Nevertheless, until a nationwide revision of the Report to Congress is undertaken, those needing a nationwide estimate of land loss for a 50-cm rise would probably be better advised to linearly interpolate the 2-m estimate from that study rather than rely on the reported results. Doing so yields an estimate at the lower end of the 8,500 to 19,000 km^2 range from the Report to Congress. Alternatively, viewing our newer results as a vertical revision, instead of saying that a 50-cm rise could inundate (or require shore protection for) 8,500–19,000 km^2 of land, it would seem more reasonable to suggest that this area of land is vulnerable to a 50–100 cm rise in sea level.



Figures 1.1.15 Topographic Vulnerability of Tidal Wetlands in the Mid-Atlantic. (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 our tidal wetlands data set. Small polygons are exaggerated to ensure visibility. (b) Ratio of tidal wetlands to the area of dry land within one-half the tide range above spring high water. Calculation of the denominator was undertaken quad by quad, using procedures similar to the approach for calculating land within 1 meter above spring high water. The map shows county-by-county ratios

Table 1.1.7: Comparison of this Study with Previous Studies (km^2).

Elevation (m)	New York	New Jersey	Pennsylvania	Delaware	Maryland	District of Columbia	Virginia	New York To Virginia	North Carolina	New York To North Carolina
This Study (7.5-minute maps)										
<1.5	277	1552	10	452	1737	3.2	2061	6092	5716	11808
1.5–3.5	341	798	53	262	1158	5.9	1322	3941	3559	7500
Titus and Richman (1-degree maps)										
<1.5	240	1083	2.5	388	1547	1.5	969	4230	5836	10066
1.5–3.5	266	638	2.5	172	806	4.0	1041	2930	3865	6794

Table 1.1.8. Mid-Atlantic Dry Land Potentially Inundated by Sea Level Rise: Comparison of this study with EPA's 1989 Report to Congress

Global Sea Level Rise (cm)	Relative Sea Level Rise[a] (cm)	EPA 1989[b] (km^2)	This Study (km^2)	This Study's Estimate of the relative rise required to inundate Corresponding estimate from EPA (1989) (cm)	Vertical Difference between the two studies (cm)
50	70	2341	948	112	42
100	120	3121	1697	162	42
200	220	4587	3242	253	33

[a] The EPA Report to Congress assumed that relative sea level rise in the mid-Atlantic would be 20 cm more than the global sea level rise over the period being analyzed.
[b] From Titus and Greene (1989) Table 5 (p. 5-26).

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1.2. Interpolating Elevations: Proposed Method for Conducting Overlay Analysis of GIS Data on Coastal Elevations, Shore Protection, and Wetland Accretion

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1.2.1 Introduction

Section 1.1 (by Titus and Wang) of this report and the metadata provided with the elevation Geographic Information System (GIS) data document the methods used to generate state-specific GIS data sets of elevation relative to spring high water (Jones, 2008, Jones et al., 2008).[1]. Titus and Hudgens (unpublished analysis) generated data on the likelihood of shoreline protection. In that analysis, the authors attempted to divide all dry land below the 20-ft (NGVD29) contour—as well as all land within 1,000 ft of the shore regardless of elevation—into one of four categories representing the likelihood of shore protection: shore protection almost certain (PC), shore protection likely (PL), shore protection unlikely (PU), and no protection (NP). Using these two data sets, this section shows the methods used to quantify the area of land close to sea level by shore by various elevation increments and protection category. However, because the results of the shore protection analysis are unpublished, we report only the elevation statistics.

Using the elevation data discussed in Section 1.1, and wetland data compiled from a combination of the U.S. Fish and Wildlife Service National Wetlands Inventory (NWI) data and state-specific wetlands data, we created summary tables, which we explain in Section 1.2.2. Those tables provide the area of land within 50 cm elevation increments at the state level of aggregation and are provided in the appendix to this section.[2] The versions with 0.1-ft increments were used by the uncertainty analysis described in Section 1.3.[3]

Our analysis (as well that of Section 2.1) had to confront the fact that the attempt to assign a shore protection category to all dry land close to sea level was not entirely successful. In some cases, the state-specific studies failed to assign land to one of these four categories because (for example) land use data were unavailable. This happened particularly at the seaward boundary of their study areas. They called these areas "not considered" (NC).

Section 1.2.3 discusses several supplemental analyses. Using a tide range GIS surface generated by Titus and Wang, along with the dry land elevation and tidal wetlands data, we generated additional sets of tables[4]. Some of these tables estimate the area of dry land within one-half tide range above spring high water. Assuming that tidal wetlands are within one-half tide range below spring high water (i.e., between mean sea level and spring high water), these tables give us the ratio of slopes above and below spring high water, that is, the ratio of existing wetlands to the potential for new wetland creation. Other tables estimate the area of potential tidal wetland loss by estimating the portion of existing tidal wetlands that would fall below mean sea level if sea level were to rise a particular magnitude, with and without wetland accretion.

1.2.2. Estimating Land Area by Elevation Increment and Protection Category

We estimated the land area by protection category using several steps. First, to summarize the protection data by elevation, it was necessary

[1] Titus and Wang in Section 1.1 generated the DEM data by interpolating elevations from a variety of source data sets for the eight states covered by this report. To make the elevations relative to SHW, they used the National Ocean Service's (NOS) estimated tide ranges, NOS estimated sea level trends, and the NOS published benchmark sheets along with National Geodetic Survey North American Vertical Datum Conversion Utility (VERTCON) program to convert the mean tide level (MTL) above NAVD88 to NGVD29. See "General Approach" of Section 1.1 for a brief overview. Jones (2007) created a revised dataset for North Carolina.

[2] Additionally, subregional and regional low and high estimates of land area are provided in Appendices B and C, respectively, to Section 1.3.

[3]. Horizontal and vertical accuracy issues are addressed in Section 1.3. An additional discussion on reporting data at 0.1 ft increments is provided here. The increments used imperial rather than metric units because the interpolation is facilitated when the contour interval (mostly in imperial units as well) are an integer multiple of the increment.

[4]These tables are not provided as the likelihood of shoreline protection data from which they were generated are based on an unpublished analysis.

to first convert the shore protection GIS data from a vector format (i.e., polygons) into a raster (or grid) format to match the digital elevation model (DEM) data. As part of this step, we developed a procedure to lessen the amount of land classified as “not considered” (which would otherwise be enhanced by the vector-to-raster conversion process). Once this was done, we were able to quantify the amount of land at specific elevations by protection category. To improve our elevation-specific area estimates, we tailored our approach to the accuracy of the source data—interpolating lower accuracy data and using the area estimates directly from the DEM for those with higher accuracies. We then provided summary results in tables “rolled up” by different elevations. The appendix to this section provides county-by-county results for the analysis we describe in this section. Section 1.3 provides additional information about variations in data quality and the associated appendices also provides results, by state, subregion, and region.

Converting shore protection polygons to grid

General approach

In converting vector data into grid format, several considerations need to be taken into account. Spatially, the size of the raster cell generated should be based on the estimated accuracy or minimum mapping unit, as well as whether the output raster data will be combined with other data sets. We generated our raster based on a 30-m cell size to match our DEM data. In addition, this cell size was not inappropriate given the source of the information. Similarly, because the cell boundaries will inevitably cross the vector polygons (cell boundaries rarely coincide exactly to vector polygon outlines of the input data), different approaches can be taken to transfer the attributes of a particular polygon to the output raster cells. The attribute assignment can be based on the centroid of the cell (i.e., the attribute of the polygon is assigned to the raster cell whose center it encapsulates), on the polygon covering the majority of the cell (or the combined area of multiple polygons with the same attribute), or through attribute priority (i.e., if any portion of the polygon has a certain attribute, the cell is assigned that attribute). We used a combination of approaches in our analysis. In our initial conversion, we used a centroid approach. In subsequent reclassification, we assigned attributes based on attribute values (i.e., priority approach), and attributed remaining cells based on proximity of neighboring cells. The specific methods used are described below.

Approach for avoiding the “not considered” designation

One of our main goals was to limit the amount of land classified as “not considered.” The original shapefile dataset had numerous narrow polygons along the shore classified as “not considered.” Usually, those polygons were not visible in the county-scale maps that county officials and the authors had closely examined, which the state-specific chapters of this report display. Usually, the polygons of “not considered” resulted because the planning data used in the state-specific analyses did not extend all the way out to the wetland/dryland boundary defined by the wetlands data set we were using. This occurred for at least two reasons: In some cases, the planning data were more precise than the old NWI wetlands data we used; in other cases, the planning study had used very coarse land use data. Whenever the land use data extended seaward of the wetland boundary, the use of wetlands data as a “mask” resolved the data conflict. But if the land use data did not extend all the way to the wetlands or open water, we were left with dry land with no protection category (i.e., not considered).

A related problem was that the shore protection polygons created by the state-specific studies sometimes labeled lands as “wetlands” even though that study ostensibly categorized dry land by likelihood of shore protection and relied on a wetlands data set to define wetlands. In several cases—particularly the Hampton Roads area of Virginia and some Maryland counties, local data defined wetlands in areas that the statewide data set classified as being dry. The study authors wanted the maps to show those areas as wetlands—a reasonable objective given that the local planning data that form the basis of the studies treated it as wetlands. But we wanted our results to be consistent with the Section 1.1 estimates of dry land and wetlands that relied on the wetlands data set rather than local planning data.

We converted the shapefile planning data according to the general process shown in Figure 1.2.1. Figure 1.2.2 shows an example of the process using GIS data. Specifically, we recoded any polygons designated as a wetland in the source protection data as protection unlikely. We then clipped the data to the extent of the study area boundary and excluded any polygons that overlapped with tidal wetland or tidal open water as determined by the state-specific wetlands layers. Additionally, we coded any cells without an attribute as NC. We then converted the protection data from a vector (i.e., polygon) format to raster (grid-based) format with a cell size of 30 meters to match the resolution of the elevation data.[5] Attributes were assigned to the cells based on whichever polygon from the source vector data covered the centroid of the output raster cell. This approach was preferable over dominant category, because in some cases there are narrow environmental buffers along the shore. The buffers are PL or PU along an area where the rest of the land is PC. The buffers are too narrow to be the dominant shore protection category in a cell. Thus, using dominant category would create a downward bias for that category, while picking the centroid would be expected to yield area estimates similar to the actual area estimate.

We then subset the raster layer to elevations less than 20 feet and converted the NC cells back into a vector format. The result was a vector polygon layer of NC cells. The resulting polygons were then overlaid with the original polygon vector shoreline protection data, and the NC polygons were assigned the same attribute as any overlapping polygons. Only individual 30-m

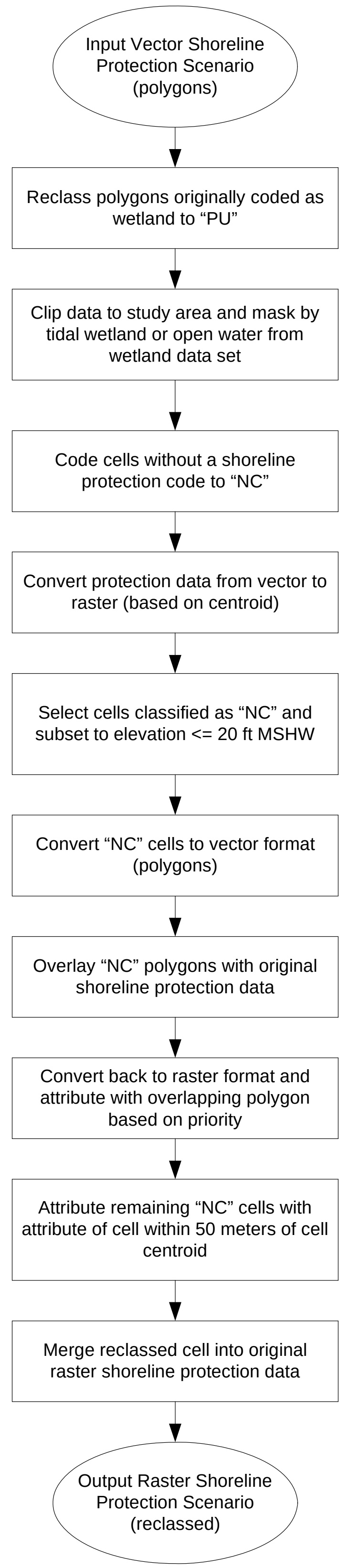


Figure 1.2.1. Approach used to reclassify not-considered shoreline protection scenario cells.

5. The conversion from vector to raster was conducted using ArcGIS Spatial Analyst extension (ESRI, 2006).

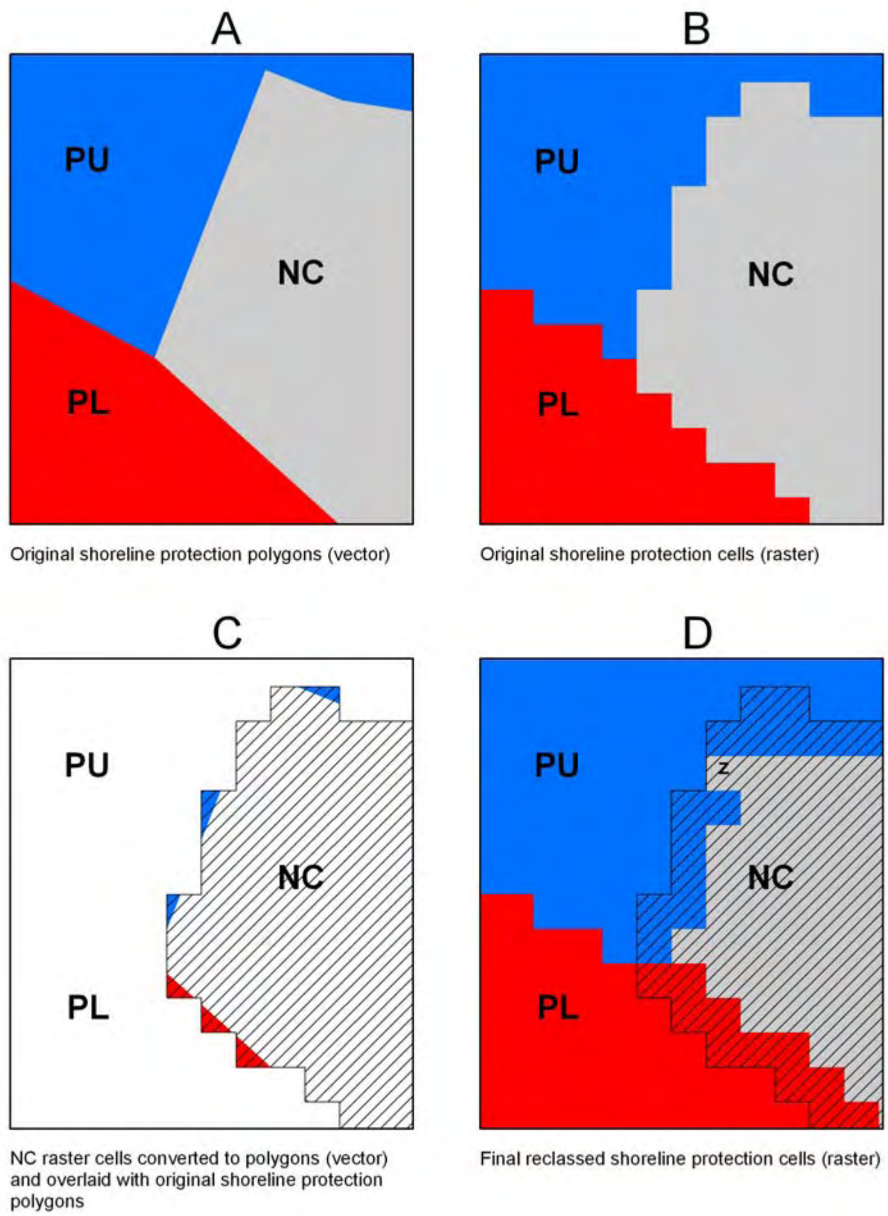


Figure 1.2.2. Graphical Representation Showing How Original Shoreline Protection Scenario Data in Vector Format was Reclassified to Reduce the Amount of "Not Considered" (NC) Lands.

cells of NC were recoded. Where multiple polygons overlapped with the NC cells, and none crossed the cell centroid, attribute assignment was based on the following priority: NP, PU, PL, and PC. We used this priority rule instead of picking the category that accounted for the greatest portion of the cell because such cells are generally along the water or wetlands (and assumed to be water or wetlands in the land use data set that gave rise to the shore protection classifications). If any of the overlapping cells did not contain any of these categories, the cell remained NC. Finally, any remaining NC cells were assigned the attribute of any other non-NC cells within a maximum distance of 50 meters (centroid to centroid).[6] All other NC cells remained NC. Finally, we merged the

6. Given the cell size of 30 meters, this effectively means that NC cells would be attributed the same as any adjacent (including cells diagonal to the NC cell) non-NC cell. Note also the cell shown by “z” (panel D) remained NC because it fell entirely within tidal wetlands.

reclassified NC layer with the original raster version of the protection data.

Estimating area of land at specific elevations by shore protection category

Combining elevation, protection, wetland, quadrangle, and county data

Our first step was to segment the final DEM data (see Section 1.1) by the source data from which they were derived.[7] We needed to do this for two reasons. First, the interpolations (discussed in the following section) depended on contour interval. Second, one of the expected uses of our output was the creation of high and low estimates; and the uncertainty would be a function of the data quality (see Section 1.3).

Using the same resolution and projection as the elevation data, we generated raster data sets from the following vector GIS layers: USGS 1:24K quadrangles, county boundaries, and source data extent polygons, as well as a nontidal open water (NO) and nontidal wetlands (NW) layer generated from wetlands data from each state data set. We then combined these raster layers with the elevation data and reclassified shore protection data to generate a composite raster layer with attributes from each source data set (e.g., quadrangle, county, wetland type, source data name, elevation, and shoreline protection scenario). We calculated a final protection scenario attribute field from the shore protection category and NO/NW wetlands data, with priority assigned to the wetlands data. The resulting protection scenario field contained one of the following categories: NO, NW, PC, PL, PU, NP, or NC.

7. USGS data varied by 24K quadrangle, whereas other data sets were provided by county or other boundary.

Areas with source elevations of 1-m contours or worse

As noted in Section 1.1, the ESRI GRID extension function TOPOGRID (ESRI, 2006) that was used to interpolate contours into a DEM was spatially biased toward each input contour. The resultant DEM data therefore contained "plateaus" on either side of the source contours. Given our objective of estimating the area of land within elevation increments of 50 cm, this was not a significant problem for our source data sets with contour intervals of 2 feet (60 cm) or better. But it presented a significant bias in the lower accuracy data sets. As in Section 1.1, we corrected for this distortion in the lower accuracy data sets by redistributing the land area evenly into 0.1-ft elevation bins between each source contour elevation interval (e.g., for each 5 feet for data with a 5-ft contour interval) for each combination of quadrangle, county, and protection scenario.[8] For the first contour, the area between SHW and the first contour (e.g., 5-ft NGVD) was used. We calculated the SHW value (relative to the NGVD29 vertical datum) by overlaying the SHW surface generated by Titus and Wang[9] with the quadrangle/county grid and taking the average for all cells over each quadrangle/county combination.

The process used for the lower accuracy source areas is summarized in the following steps with the tabular data shown in Figure 1.2.3 (for USGS 24K quadrangles in Sussex County, Delaware, under the PC scenario):

8. This approach effectively generates a linear interpolation of land area. Lacking site-specific topographic information, the exact profile of the landscape cannot be determined. Therefore, this linear interpolation represents a conservative approach and differences in coastal profiles at any specific locality could be thought to average out over the broad areas where this was applied. Certainly the reader may question any quantification of land at the 0.1-ft increment; however, to assess vulnerability of lands to inundation by small rates of SLR over different time periods, the increment chosen is necessary. Accuracy issues are discussed in Annex 3.

9. The SHW surface was derived by Titus and Wang through interpolation of local tide gage point data that was referenced to the NVGD29 vertical datum. See Section 1.1 for full processing details.

1. Sum the area of land between SHW and source contour interval or between successive contour intervals (SHW Table in Figure 1.2.3).

2. Determine the number of 0.1-ft elevation bins between the SHW/first contour or successive contours.

3. Divide the sum in #1 by the number of bins in #2.

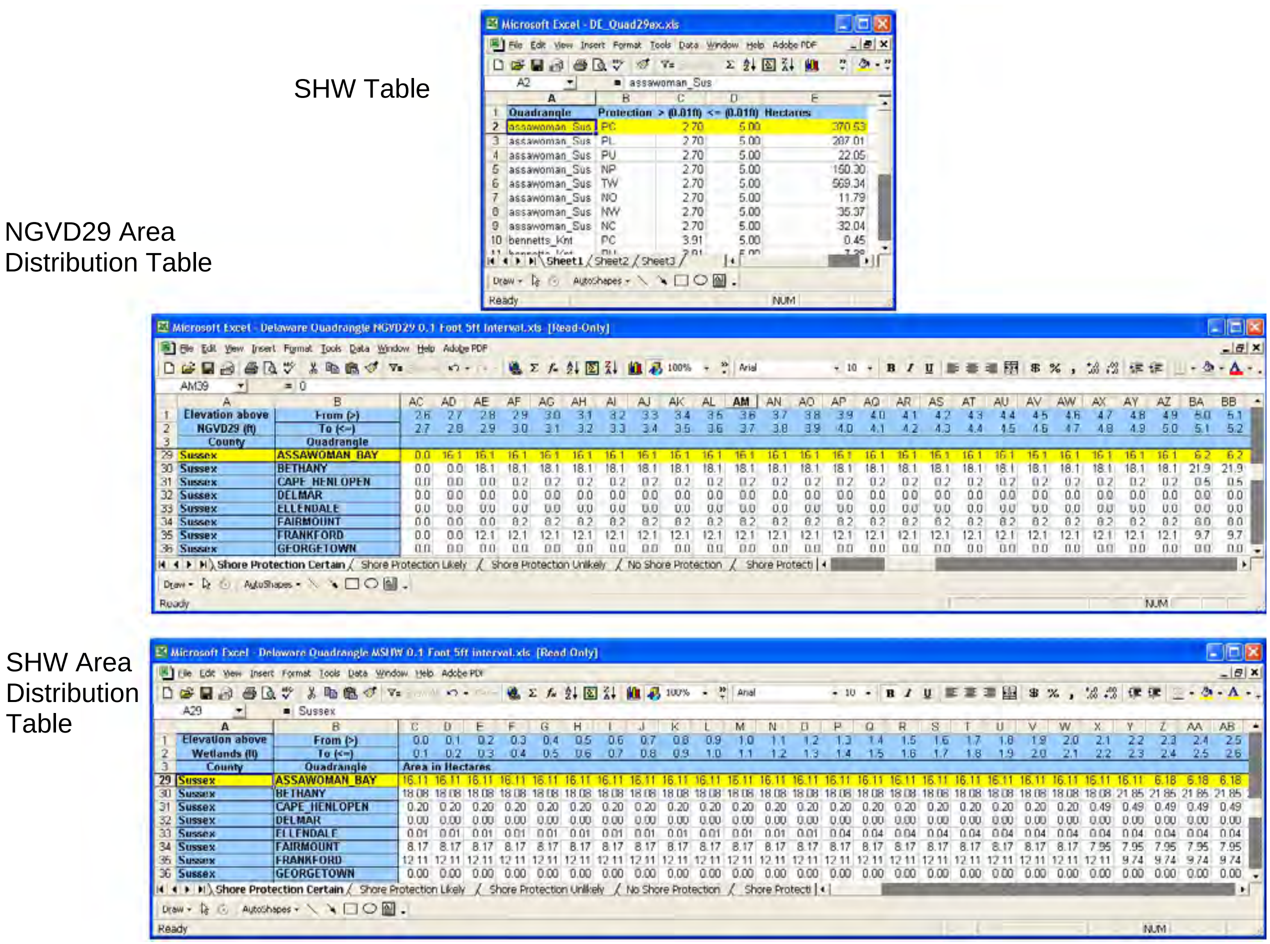
4. Assign each 0.1-ft bin the output value from #3 (NGVD29 Area Distribution Table in Figure 1.2.3).

For example, using the Assawoman Bay quadrangle in Sussex County, Delaware, as an example (highlighted in Figure 1.2.3), the source data is 5-ft USGS, the SHW value is 2.7-ft NGVD29, and the total area between SHW and the 5-ft contour under the PC scenario is 370.53 hectares (ha). The land area was redistributed as follows:

1. Sum of land between 2.7 and 5 feet (NGVD) = 370.53 ha

2. Number of 0.1 ft bins: round (5—2.7) / 0.1) = 23

3. Land area reported in each 0.1 ft bin: 370.53 / 23 = 16.1 ha



	A	B	C	D	E
1	Quadrangle	Protection	> (0.01ft)	<= (0.01ft)	Hectares
2	assawoman_Sus	PC	2.70	5.00	370.53
3	assawoman_Sus	PL	2.70	5.00	207.01
4	assawoman_Sus	PU	2.70	5.00	22.05
5	assawoman_Sus	NP	2.70	5.00	150.30
6	assawoman_Sus	TW	2.70	5.00	569.34
7	assawoman_Sus	NO	2.70	5.00	11.79
8	assawoman_Sus	NW	2.70	5.00	35.37
9	assawoman_Sus	NC	2.70	5.00	32.04
10	bennetts_Knt	PC	3.91	5.00	0.45

	A	B	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ	AR	AS	AT	AU	AV	AW	AX	AY	AZ	BA	BB
1	Elevation above	From (>)	2.6	2.7	2.8	2.9	3.0	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	4.0	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9	5.0	5.1
2	NGVD29 (ft)	To (<=)	2.7	2.8	2.9	3.0	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	4.0	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9	5.0	5.1	5.2
3	County	Quadrangle																										
29	Sussex	ASSAWOMAN_BAY	0.0	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1	6.2	6.2
30	Sussex	BETHANY	0.0	0.0	18.1	18.1	18.1	18.1	18.1	18.1	18.1	18.1	18.1	18.1	18.1	18.1	18.1	18.1	18.1	18.1	18.1	18.1	18.1	18.1	18.1	18.1	21.9	21.9
31	Sussex	CAPE_HENLOPEN	0.0	0.0	0.0	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.5	0.5
32	Sussex	DELMAR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
33	Sussex	ELLENDALE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
34	Sussex	FAIRMOUNT	0.0	0.0	0.0	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.0	8.0
35	Sussex	FRANKFORD	0.0	0.0	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	9.7	9.7
36	Sussex	GEORGETOWN	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB
1	Elevation above	From (>)	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5
2	Wetlands (ft)	To (<=)	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6
3	County	Quadrangle	Area in Hectares																									
29	Sussex	ASSAWOMAN_BAY	16.11	16.11	16.11	16.11	16.11	16.11	16.11	16.11	16.11	16.11	16.11	16.11	16.11	16.11	16.11	16.11	16.11	16.11	16.11	16.11	16.11	16.11	16.11	6.18	6.18	6.18
30	Sussex	BETHANY	18.08	18.08	18.08	18.08	18.08	18.08	18.08	18.08	18.08	18.08	18.08	18.08	18.08	18.08	18.08	18.08	18.08	18.08	18.08	18.08	18.08	18.08	21.85	21.85	21.85	21.85
31	Sussex	CAPE_HENLOPEN	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.49	0.49	0.49	0.49	0.49
32	Sussex	DELMAR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
33	Sussex	ELLENDALE	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
34	Sussex	FAIRMOUNT	8.17	8.17	8.17	8.17	8.17	8.17	8.17	8.17	8.17	8.17	8.17	8.17	8.17	8.17	8.17	8.17	8.17	8.17	8.17	8.17	8.17	7.95	7.95	7.95	7.95	7.95
35	Sussex	FRANKFORD	12.11	12.11	12.11	12.11	12.11	12.11	12.11	12.11	12.11	12.11	12.11	12.11	12.11	12.11	12.11	12.11	12.11	12.11	12.11	12.11	12.11	12.11	9.74	9.74	9.74	9.74
36	Sussex	GEORGETOWN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Figure 1.2.3. Example Tabular Summary Output of Land Elevation for Shore Protection Certain (PC) Scenario for USGS 24K Quadrangles in Sussex County, Delaware. SHW Table shows land area (in hectares) of PC between SHW relative to NGVD29 vertical datum and the 5-ft USGS contour. NGVD29 Area Distribution Table shows how land area in SHW Table was distributed evenly into 0.1-ft elevation bins. The SHW Area Distribution Table shows the re-distributed NGVD29 Table data adjusted relative to SHW elevations. The highlighted row pertains to an example in the text.

Figure 1.2.3 for the Assawoman Bay quadrangle shows that 16.1 ha was input into each 0.1-ft bin between 2.7 feet (SHW) and 5 feet. The same procedure was used for each successive 5-ft contour.

Areas with source elevations better than a 1-m contour

For the higher accuracy data sources, the land area was summarized by larger elevation increments (e.g., 50 cm and 1 foot) and output directly from the DEM without any reallocation.

Final output

We subsequently output the land areas by elevation bin into individual Excel workbooks for each elevation data source. Individual sheets within the workbooks were divided by protection scenario and contained the area of land (in hectares) within each elevation increment—50 cm and 1 foot for both low and higher resolution data sets and 0.1-ft increments where the source data was 1-m contour or worse.[10] Area estimates were reported from 0 to 20 feet for English unit tables and from 0 to 7 meters for metric tables. A second set of Excel workbooks was generated relative to SHW by subtracting the SHW-NGVD29 elevation bin reported from each quadrangle/county record within the spreadsheets. An example of the output is shown in the SHW Area Distribution Table in Figure 1.2.3. Therefore, relative to SHW, the 16.1-ha bins are distributed between 0 and 2.3 feet (after conversion from 2.7 to 5.0 feet relative to NGVD29).

Finally, we added two additional sheets to each Excel workbook: "All Land" and "Dry Land." The first worksheet summarized all the other shoreline protection scenario worksheets with the exception of the NO sheet, and the "Dry Land" worksheet represented the summary of all worksheets except NO and NW.

10. In subsequent elevation rollups, to make the data compatible with the lower accuracy data, we divide the area of 1-ft increments evenly into 0.1-ft elevation bins. This differs from the method used for the lower accuracy data in that the redistribution occurred at 1-ft increments instead of over the entire contour interval.

Once the individual source, quadrangle, county, and protection scenario tables were generated, we were able to summarize total areas for each scenario or groups of scenarios by various groupings, including state, county, or various region (e.g., Chesapeake Bay) where each quadrangle/county combination could be assigned to the appropriate region.

In addition to the tables just described, we also generated land area summaries for each shoreline protection scenario by elevation taking into account the uncertainty associated with different source data sets. This was accomplished by creating a lookup table of the root mean squared error (RMSE) associated with each source data set. By reporting the RMSE by individual quadrangle, county, and source combination, we were able to make low and high estimates of land area similar to the tables generated using the central estimate. The methods used to generate the uncertainty tables are in Section 1.3.

1.2.3. Other Products—Summarizing Land Area Vulnerable to Inundation

General approach

In addition to the summaries described, we generated another set of tables showing the area of tidal wetlands at risk of inundation from SLR and area of potentially new wetlands resulting from inundation of lands above SHW under alternative SLR and protection scenarios.[11] To derive this information we used the summary statistics tables described and combined them with lookup tables we developed. The lookup tables were created for dry land and tidal wetlands (TW) and provide the following information: the mean (arithmetic) of full tide range, the mean of the reciprocal of the tide range (harmonic mean), the mean SLR rate, the dominant accretion code, and the percentage of wetland area with a specific accretion code of the total wetlands for each quadrangle/county combination. The sections that follow describe

[11] These tables are not provided because the likelihood of shoreline protection data from which they were generated are based on an unpublished analysis.

the methods we used to calculate the values in the lookup tables.

Calculating average and average reciprocal spring tide range values

To derive the mean spring tide range (STR) for each quadrangle/county combination for the dry land, we overlaid a raster layer of the combination of quadrangle and county with a raster surface of spring tide range developed from interpolation of tide gauge data.[12] We then calculated the average STR using the ESRI GRID extension function "ZONALSTATS" (ESRI, 2006), which calculates the mean of the values of all raster cells in the STR surface that spatially coincide with the same quadrangle/county combination. Similarly, we calculated the reciprocal mean of STR by first generating the raster layer of the inverse of the STR surface (1/STR surface) and then calculating the mean using the inverse layer as an input into the ZONALSTATS function.

To calculate the average STR and average reciprocal STR for the tidal wetlands, we first overlaid the tidal wetland layer for each state[13] with a GIS raster layer of accretion data developed by Titus, Jones, and Streeter (in Section 2.2) (based on a science panel assessment and hand-annotated maps delineated by Reed et al. [in Section 2.1]). We then calculated the average STR values (mean and reciprocal mean) using the same procedure that was followed for the dry land data, but limiting our averages to only the wetland/accretion code combination within a quadrangle/county instead of using the entire quadrangle/county that was used in the dry land analysis.

Calculating the dominant accretion code for tidal wetlands

Because the minimum mapping unit of analysis (minimum unit of analysis) for dry land was the quadrangle/county combination, we needed to have a single accretion code for each quadrangle/county combination. In addition, because the accretion potential defined by Reed et al. (2008) was categorical rather than representing an average, we needed to use the dominant accretion code instead of taking an average. To determine the dominant accretion code for wetlands within a quadrangle/county, we first summed the area of tidal wetlands by accretion code within a quadrangle/county and divided it by the total area of tidal wetlands for all accretion codes within a quadrangle/county. The percentage of each tidal wetlands/accretion code of the total wetlands within the quadrangle/county was calculated as *% TW accretion = (Area specific TW accretion / total TW area) * 100*.

The accretion code that accounted for the most tidal wetlands was classified as the dominant code.

Calculating the accretion code for dry land

To determine the accretion code for each quadrangle/county combination for dry land, we overlaid the raster accretion layer with the quadrangle/county raster layer and assigned the accretion code based on whichever accretion code covered the majority of the quadrangle/county. Where the accretion layer did not extend far enough inland to cover all nontidal lands being evaluated, the accretion code nearest the quadrangle/county dry land being evaluated was used. Figure 1.2.4 shows an example of the output in the lookup tables (dry land and tidal wetland) for Delaware. This table was then used with the summary elevation statistics tables to roll up elevations at various increments to estimate the loss of tidal wetlands as well as the

12. Titus and Wang (Section 1.1) generated vertical elevations for the tide points using the National Ocean Service's (NOS) estimated tide ranges, NOS estimated sea level trends, and the NOS published benchmark sheets along with National Geodetic Survey North American Vertical Datum Conversion Utility (VERTCON) program to convert the mean tide level (MTL) above NAVD88 to NGVD29.

13. For all states except Pennsylvania, the wetland layer that was generated by Titus and Wang was used. Titus and Wang did not include mudflats in the tidal wetlands classification for Pennsylvania. Because mudflats represent a significant portion of tidal wetlands in Pennsylvania, we extracted mudflats from the NWI source data and added them to the final Pennsylvania wetlands layer.

generation of new wetlands from inundation of dry lands (these tables are not provided because the likelihood of shoreline protection data from which this was generated is based on an unpublished analysis).

Generating tabular summaries of potential wetland creation and loss

After we generated the lookup tables, we were able to summarize the elevation data into tables that provide information on the potential tidal wetland creation and loss. For example, using the elevation by protection scenario data along with the tide range data in the lookup table, we were able to calculate the area of tidal wetlands and the area of dry land within 1 meter or one-half tide range above spring high water by protection scenario (results are part of an ongoing analysis). Similarly, we calculated the amount of land available for wetland migration by shore protection likelihood by looking at the amount of land between mean sea level and spring high water if the sea level rises 1 meter (results are part of ongoing analysis). Additionally, other modifications included summarizing the area of wetlands below a particular elevation assuming uniform elevation distribution, and subdividing quadrangle-specific estimates by dominant accretion code that was assigned to both wetlands and drylands.

References

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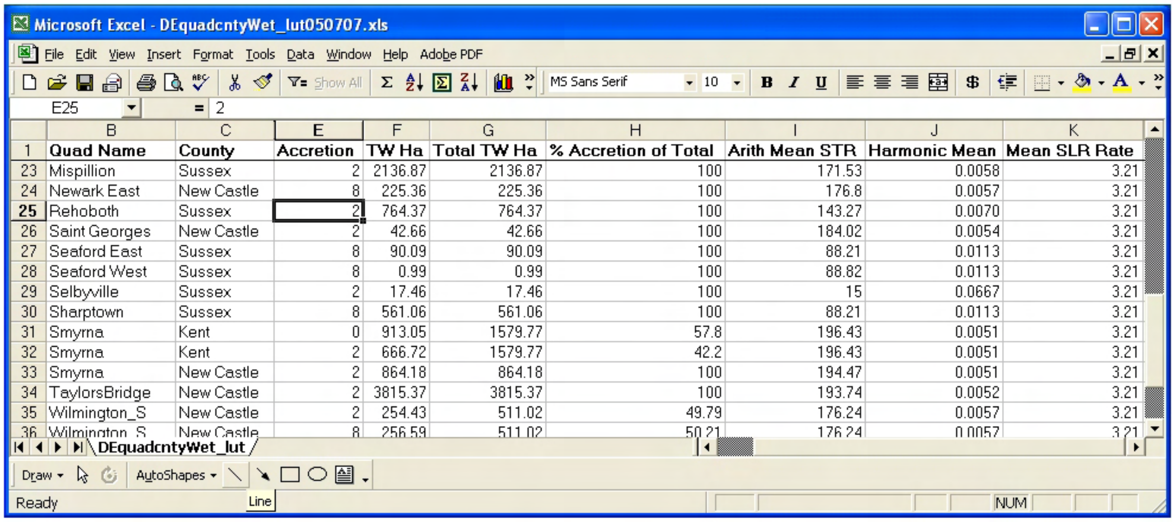
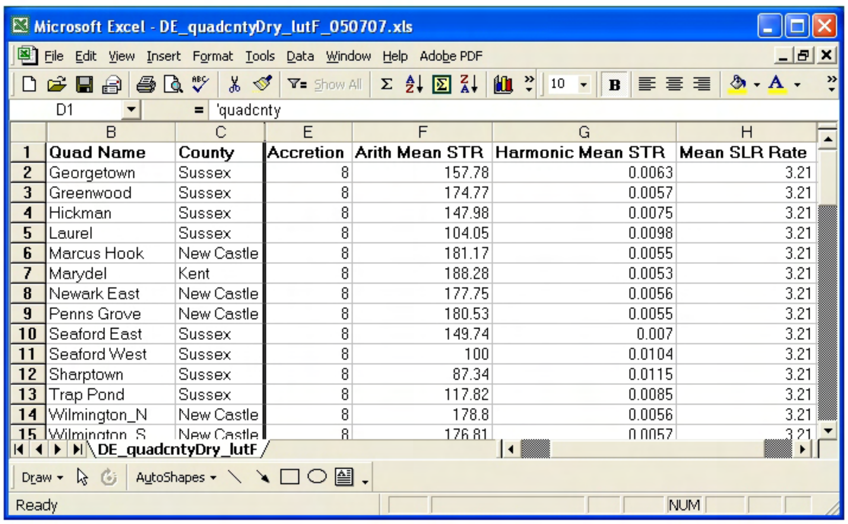
Jones, R. 2007. Accuracy Assessment of EPA Digital Elevation Model Results. Memorandum and attached spreadsheets prepared for the U.S. EPA under Work Assignment 409 of EPA Contract #68-W-02-027.

Jones, R., J. Titus, and J. Wang. 2008. *Metadata for Elevations of Lands Close to Sea Level in the Middle Atlantic Region of the United States.* Metadata accompanying Digital Elevation Model data set. Distributed with the elevation data.



	Quad Name	County	Accretion	TW Ha	Total TW Ha	% Accretion of Total	Arith Mean STR	Harmonic Mean	Mean SLR Rate
23	Mispillion	Sussex	2	2136.87	2136.87	100	171.53	0.0058	3.21
24	Newark East	New Castle	8	225.36	225.36	100	176.8	0.0057	3.21
25	Rehoboth	Sussex	2	764.37	764.37	100	143.27	0.0070	3.21
26	Saint Georges	New Castle	2	42.66	42.66	100	184.02	0.0054	3.21
27	Seaford East	Sussex	8	90.09	90.09	100	88.21	0.0113	3.21
28	Seaford West	Sussex	8	0.99	0.99	100	88.82	0.0113	3.21
29	Selbyville	Sussex	2	17.46	17.46	100	15	0.0667	3.21
30	Sharptown	Sussex	8	561.06	561.06	100	88.21	0.0113	3.21
31	Smyrna	Kent	0	913.05	1579.77	57.8	196.43	0.0051	3.21
32	Smyrna	Kent	2	666.72	1579.77	42.2	196.43	0.0051	3.21
33	Smyrna	New Castle	2	864.18	864.18	100	194.47	0.0051	3.21
34	TaylorsBridge	New Castle	2	3815.37	3815.37	100	193.74	0.0052	3.21
35	Wilmington_S	New Castle	2	254.43	511.02	49.79	176.24	0.0057	3.21
36	Wilmington_S	New Castle	8	256.59	511.02	50.21	176.24	0.0057	3.21



	Quad Name	County	Accretion	Arith Mean STR	Harmonic Mean STR	Mean SLR Rate
2	Georgetown	Sussex	8	157.78	0.0063	3.21
3	Greenwood	Sussex	8	174.77	0.0057	3.21
4	Hickman	Sussex	8	147.98	0.0075	3.21
5	Laurel	Sussex	8	104.05	0.0098	3.21
6	Marcus Hook	New Castle	8	181.17	0.0055	3.21
7	Marydel	Kent	8	188.28	0.0053	3.21
8	Newark East	New Castle	8	177.75	0.0056	3.21
9	Penns Grove	New Castle	8	180.53	0.0055	3.21
10	Seaford East	Sussex	8	149.74	0.007	3.21
11	Seaford West	Sussex	8	100	0.0104	3.21
12	Sharptown	Sussex	8	87.34	0.0115	3.21
13	Trap Pond	Sussex	8	117.82	0.0085	3.21
14	Wilmington_N	New Castle	8	178.8	0.0056	3.21
15	Wilmington_S	New Castle	8	176.81	0.0057	3.21

Figure 1.2.4. Example of Lookup Tables. Top table: tidal wetland (TW) areas by quadrangle/county/accretion code, total TW for quadrangle/county, percentage of accretion-specific area to total, arithmetic mean of STR, harmonic mean (mean of reciprocal) of STR, and mean SLR rate. Bottom table: dominant accretion code, and arithmetic and harmonic STR means and mean of SLR rate.

Section 1.2 Appendix
Area of Land Close to Sea Level, by State

By James G. Titus, U.S. Environmental Protection Agency
Russell Jones, Stratus Consulting Inc.
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Table A1. New York (square kilometers)

County		0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
		Meters above Spring High Water									
	----------------Dry Land, by half meter elevation increment[a]---------------										
Bronx		2.3	2.3	2.3	2.6	2.8	2.8	2.8	2.8	2.8	1.4
Brooklyn		7.4	6.0	6.0	6.7	9.2	9.2	8.4	5.4	5.4	4.9
Manhattan		1.6	1.6	1.6	1.6	1.7	1.7	1.7	1.7	1.7	1.7
Nassau		13.2	17.8	21.2	21.2	13.3	8.8	8.8	8.6	8.1	7.4
Queens		13.2	8.9	8.9	9.6	9.3	9.3	7.4	5.0	5.0	3.1
Staten Island		5.7	5.7	5.7	4.9	2.7	2.7	2.7	2.7	2.7	2.4
Suffolk		36.8	37.0	38.0	37.6	37.6	34.3	33.9	33.4	30.3	29.5
Westchester		2.1	2.1	2.1	2.2	1.9	1.8	1.8	1.8	1.8	1.3
Ellis & Liberty Islands		0.04	0.04	0.04	0.03	0.00	0.00	0.00	0.00	0.00	0.00
Statewide		82.4	81.5	85.9	86.4	78.5	70.6	67.5	61.4	57.8	51.7
Wetlands	**Tidal**	---------Nontidal Wetlands, by half meter elevation increment---------									
Brooklyn	3.5	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nassau	43.4	0.3	0.3	0.3	0.4	0.3	0.3	0.3	0.3	0.3	0.3
Queens	7.6	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0
Staten Island	5.4	0.3	0.3	0.3	0.3	0.1	0.1	0.1	0.1	0.1	0.1
Suffolk	82.3	4.1	4.0	2.5	2.4	2.3	1.5	1.5	1.4	1.4	1.3
Other[b]	6.9	0.06	0.06	0.06	0.05	0.05	0.04	0.04	0.04	0.04	0.05
Statewide	149.1	5.0	4.8	3.4	3.2	2.8	2.0	1.9	1.9	1.9	1.8
		Cumulative (total) amount of land below a given elevation[c]									
Dry Land		82	164	250	336	415	485	553	614	672	724
Nontidal Wetlands		5	10	13	16	19	21	23	25	27	29
All Land	149	236	323	412	502	583	655	725	788	848	901

[a] For example, Bronx has 2.3 square kilometers of dry land between 0.5 and 1.0 meters above spring high water.
[b] Includes Bronx, Dutchess, Manhattan, Orange, Putnam, Rockland, and Westchester counties.
[c] For example, New York State has 164 square kilometers of dry land less than 1 meter above spring high water.

Table A2. New York jurisdictions not included in shore protection study (hectares)

County		0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
		Meters above Spring High Water									
	Tidal	---------Nontidal Wetlands, by half meter elevation increment---------									
Dutchess	7.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Orange	24.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Putnam	126.6	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Rockland	228.6	1.5	1.5	1.5	1.5	0.9	0.6	0.6	0.6	0.6	0.6

Note: The analysis found no dry land below 5 meters for these jurisdictions.

Table A3. New Jersey (square kilometers)

County		Meters above Spring High Water 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[a]---------------											
Atlantic		8.1	13.7	14.2	10.9	9.3	8.1	7.8	8.1	7.8	7.8
Bergen		11.4	11.4	11.4	7.5	2.2	2.1	2.1	2.1	2.1	2.1
Burlington		4.6	4.6	4.6	4.5	5.6	5.9	5.9	5.9	5.9	7.3
Cape May		16.2	23.0	20.0	16.3	23.0	21.8	20.6	20.7	19.6	18.1
Cumberland		11.8	10.0	10.0	10.1	11.1	11.1	10.6	9.9	9.9	9.6
Gloucester		6.8	6.7	6.7	6.6	6.0	6.0	6.0	6.0	6.0	5.8
Hudson		11.9	11.9	11.9	9.4	3.5	3.5	3.5	3.5	3.5	3.0
Middlesex		6.5	6.5	6.5	5.7	5.2	5.2	5.2	5.2	5.2	4.9
Monmouth		7.3	7.8	9.9	10.4	9.2	9.0	8.1	7.3	8.2	8.0
Ocean		10.1	22.4	25.2	16.6	12.7	12.9	12.3	11.1	10.0	9.0
Salem		20.0	17.3	17.3	16.7	14.2	14.2	13.7	12.1	12.1	11.8
Other[b]		12.4	12.4	12.4	10.8	8.5	8.5	8.5	8.5	8.5	7.7
Statewide		**127.2**	**148.0**	**150.2**	**125.5**	**110.5**	**108.4**	**104.5**	**100.5**	**98.8**	**95.0**
Wetlands	**Tidal**	---------Nontidal Wetlands, by half meter elevation increment---------									
Atlantic	204.0	14.3	9.1	9.1	9.1	8.7	8.6	8.5	8.4	8.3	8.3
Burlington	42.8	7.6	7.5	7.3	7.3	4.7	4.4	4.4	4.4	4.4	4.6
Cape May	201.4	20.5	15.4	14.9	13.7	10.1	9.8	9.5	7.2	7.0	6.6
Cumberland	212.6	18.1	14.1	14.1	12.0	7.2	7.2	6.8	6.3	6.3	6.1
Gloucester	18.0	6.5	6.3	6.3	5.3	1.3	1.3	1.3	1.3	1.3	1.3
Ocean	124.8	7.9	9.2	8.3	7.4	6.6	5.2	4.7	4.3	4.0	3.8
Salem	110.1	21.8	8.5	8.5	7.5	3.1	3.1	3.0	2.7	2.7	2.7
Other[c]	66.7	2.8	2.5	2.5	2.1	1.5	1.4	1.4	1.5	1.6	1.5
Statewide	**980.4**	**99.5**	**72.6**	**70.9**	**64.4**	**43.2**	**41.0**	**39.8**	**36.0**	**35.5**	**35.0**
Cumulative (total) amount of land below a given elevation[d]											
Dry Land		127	275	425	551	661	770	874	975	1073	1169
Nontidal Wetlands		99	172	243	307	351	392	431	467	503	538
All Land	980	1207	1428	1649	1839	1992	2142	2286	2422	2557	2687

[a] For example, Atlantic County has 13.7 square kilometers of dry land between 0.5 and 1.0 meters above spring high water.
[b] Includes Camden, Essex, Mercer, Passaic, Union, and Somerset above 4.5m.
[c] Includes Camden, Essex, Mercer, Passaic, Union, Somerset above 4.5m, Bergen, Hudson, Middlesex, and Monmouth.
[d] For example, New Jersey has 275 square kilometers of dry land less than 1 meter above spring high water.

Table A4. New Jersey jurisdictions not included in shore protection study (hectares)

County		Meters above Spring High Water 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---------------									
Mercer[1]		4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	3.5	0.3
Passaic		11.7	11.7	11.7	14.4	17.7	17.7	17.7	17.7	17.7	18.1
Somerset		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.9
Wetlands	**Tidal**	---------Nontidal Wetlands, by half meter elevation increment---------									
Mercer[a]	178	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.0
Passaic	0	1.2	1.2	1.2	0.7	0.1	0.1	0.1	0.1	0.1	0.3
Somerset	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6

[a] The "not considered" category includes Mercer County because we calculated these statistics before the Mercer County results had been incorporated into our data set.

Table A5. Pennsylvania (square kilometers)

County		Meters above Spring High Water 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[a]---------------									
Bucks		3.2	3.2	3.3	3.6	3.6	3.6	3.6	3.6	3.5	3.4
Delaware		4.4	4.4	4.4	3.3	1.3	1.3	1.3	1.3	1.3	1.2
Philadelphia		4.9[b]	3.5	7.2	6.5	6.4	6.4	5.0	4.3	4.6	4.4
Statewide		12.6	11.1	15.0	13.4	11.3	11.3	9.8	9.2	9.3	9.1
Wetlands	**Tidal**	---------Nontidal Wetlands, by half meter elevation increment---------									
Bucks	1.9	0.7	0.7	0.8	0.9	0.9	0.9	0.9	0.9	0.7	0.3
Delaware	0.6	0.6	0.6	0.6	0.4	0.0	0.0	0.0	0.0	0.0	0.0
Philadelphia	3.6	0.5[c]	0.2	0.3	0.3	0.2	0.1	0.1	0.1	0.1	0.0
Statewide	6.1	1.9	1.5	1.7	1.6	1.1	1.0	1.0	1.0	0.8	0.3
		Cumulative (total) amount of land below a given elevation[d]									
Dry Land		13	24	39	52	63	75	85	94	103	112
Nontidal Wetlands		2	3	5	7	8	9	10	11	11	12
All Land	6	21	33	50	65	77	89	100	110	121	130

[a] For example, Philadelphia has 3.5 square kilometers of dry land between 0.5 and 1.0 meters above spring high water.
[b] This value includes 2.4 square kilometers of dry land below spring high water in Philadelphia, of which 0.87, 0.054, and 0.005 are at least 1, 2, and 3 meters below spring high water, respectively. Most of this land is near Philadelphia International airport.
[c] This value includes 39 hectares below spring high water, of which 3.8 are at least 1 meter below spring high water. Most of this land is near Philadelphia International airport.
[d] For example, Pennsylvania has 24 square kilometers of dry land less than 1 meter above spring high water.

Table A6. Delaware (square kilometers)

County		Meters above Spring High Water 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[a]------------									
Kent		19.2	13.0	13.0	16.2	20.5	20.5	22.0	24.3	24.3	22.2
New Castle		15.4	9.0	9.0	9.6	11.1	11.1	11.3	11.3	11.3	10.7
Sussex: Chesapeake Bay		1.1	1.3	1.6	1.6	2.3	3.4	3.4	4.6	5.7	5.7
Sussex: Delaware Bay		13.7	10.9	10.7	10.8	11.8	11.7	11.6	10.2	10.1	10.2
Sussex: Atlantic Coast		22.7	19.9	18.1	18.1	20.7	22.3	22.3	23.5	24.0	24.0
Statewide		72.2	53.9	52.4	56.3	66.4	68.9	70.5	73.8	75.5	72.9
Wetlands	**Tidal**	**-------Nontidal Wetlands, by half meter elevation increment-------**									
Kent	168.7	9.6	4.3	4.3	4.0	3.1	3.1	3.2	3.3	3.3	3.2
New Castle	73.5	3.5	0.8	0.8	0.8	0.9	0.9	0.8	0.7	0.7	0.7
Sussex: Chesapeake Bay	6.6	1.4	0.9	0.7	0.7	0.9	1.0	1.0	1.5	1.7	1.7
Sussex: Delaware Bay	67.5	4.3	1.2	1.1	1.1	1.0	1.0	1.0	0.7	0.7	0.7
Sussex: Atlantic Coast	40.9	3.5	2.6	2.2	2.2	2.0	1.8	1.8	1.4	1.2	1.2
Statewide	357.1	22.2	9.8	9.2	8.9	7.9	7.8	7.9	7.6	7.5	7.4
		Cumulative (total) amount of land below a given elevation[b]									
Dry Land		72	126	178	235	301	370	441	514	590	663
Nontidal Wetlands		22	32	41	50	58	66	74	81	89	96
All Land	357	452	515	577	642	716	793	871	953	1036	1116

[a] For example, Kent County has 13 square kilometers of dry land between 0.5 and 1.0 meters above spring high water.
[b] For example, Delaware has 126 square kilometers of dry land less than 1 meter above spring high water.

Table A7. Maryland (square kilometers)

County		Meters above Spring High Water 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[a]---------------									
Anne Arundel		5.3	5.3	7.4	11.7	11.7	10.9	8.9	8.9	8.9	8.7
Baltimore County		4.8	5.5	6	7.3	8.9	10.1	10.2	7.8	8.7	8.7
Calvert		1.9	1.9	1.6	1.5	1.6	3.4	3.6	3.6	4.6	4.7
Cecil		1.2	1.5	2.1	2.1	2.6	4.2	4.2	4.3	4.6	4.6
Charles		5.8	5.7	7.5	7.5	7.6	12.7	13.1	13.1	8.2	7.8
Dorchester		74	114.3	62.3	48.1	36.9	37	34	25	19.1	17.4
Harford		9.1	8.9	6.3	6.2	6.3	8.4	8.5	8.4	5.2	5.1
Kent		4	6	6.7	6.8	6.4	11.2	11.2	11.2	12.5	12.9
Queen Anne's		1.9	6.5	9.5	11.2	13.5	16.8	19.3	19.3	18.6	18
Somerset		39.2	47	45.5	52.5	19.9	18.5	27.8	28.4	28.7	29.3
St. Mary's		8.2	8.2	11	11.2	11.2	20.9	21.4	21.4	11.4	10.3
Talbot		4.2	12.2	23.2	41.7	44.1	37.1	35	32.3	23.4	19.5
Wicomico		10	13.1	14.7	15	14.6	13.7	14.3	14.3	14.5	13.5
Worcester		11.5	24.1	31.6	36.7	35	32	27.5	25.7	26	26.6
Other[b]		4.3	4.9	5.4	5.7	6.1	7.1	7.1	7.4	8.4	8.5
Statewide		185.3	265.1	240.7	265.1	226.3	243.8	246.0	231.2	202.8	195.3
Wetlands	**Tidal**	---------Nontidal Wetlands, by half meter elevation increment---------									
Charles	24.2	1.9	1.9	2.2	2.2	2.2	2.4	2.4	2.4	1.5	1.4
Dorchester	424.8	32.5	30.1	20.6	16.2	10.3	6.9	10.1	6.8	4.8	3.1
Harford	29.4	1.4	1.3	1.0	1.0	1.0	1.4	1.4	1.4	0.7	0.6
Somerset	265.4	12.3	7.0	7.2	11.9	3.5	6.0	10.1	7.0	9.3	10.9
St. Mary's	18.7	1.5	1.6	2.1	2.1	2.1	3.9	3.9	3.9	3.0	2.9
Talbot	26.1	0.1	0.6	0.9	1.7	2.2	2.1	2.6	3.8	2.6	2.0
Wicomico	67.0	8.4	3.4	7.3	7.7	5.2	8.9	9.4	8.0	5.5	4.8
Worcester	142.2	2.8	5.4	5.2	6.1	6.1	7.2	6.8	6.4	5.3	5.0
Other[c]	118.0	3.5	5.9	7.2	8.7	8.1	8.5	7.0	7.2	8.6	8.7
Statewide	1115.8	64.5	57.2	53.8	57.6	40.8	47.2	53.7	47.0	41.3	39.5
		Cumulative (total) amount of land below a given elevation[d]									
Dry Land		185	450	691	956	1182	1426	1672	1904	2106	2302
Nontidal Wetlands		64	122	175	233	274	321	375	422	463	503
All Land	1116	1366	1688	1982	2305	2572	2863	3163	3441	3685	3920

[a] For example, Anne Arundel County has 5.3 square kilometers of dry land between 0.5 and 1.0 meters above spring high water.
[b] Includes Baltimore City, Caroline, and Prince George's Counties.
[c] Includes Baltimore City, Caroline, Prince George's, Anne Arundel, Baltimore County, Calvert, Cecil, Kent, and Queen Anne's Counties.
[d] For example, Maryland has 450 square kilometers of dry land less than 1 meter above spring high water.

Table A8. Washington, D.C. (square kilometers)

		Meters above Spring High Water									
		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[a]---------------									
Washington, D.C.		2.43	1.16	1.40	1.42	1.81	1.84	1.83	1.80	1.68	1.65
Wetlands	**Tidal**	---------Nontidal Wetlands, by half meter elevation increment---------									
Washington, D.C.	0.79	0.04	0.02	0.03	0.02	0.02	0.02	0.03	0.03	0.05	0.05
		Cumulative (total) amount of land below a given elevation[b]									
Dry Land		2.43	3.59	4.98	6.40	8.22	10.06	11.88	13.69	15.37	17.01
Nontidal Wetlands		0.04	0.06	0.09	0.11	0.13	0.14	0.17	0.21	0.26	0.31
All Land	0.79	3.26	4.44	5.86	7.31	9.13	10.99	12.85	14.68	16.41	18.12

[a] For example, DC has 1.16 square kilometers of dry land between 0.5 and 1.0 meters above spring high water.
[b] For example, DC has 3.59 square kilometers of dry land less than 1 meter above spring high water.

Table A9. Virginia (square kilometers)

County	Meters above Spring High Water									
	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[a]---------------									
Eastern Shore	**45.5**	**39.8**	**42.9**	**43.1**	**42.6**	**37.1**	**36.4**	**35.6**	**33.5**	**33.5**
Accomack	29.5	29.1	32.7	32.9	31.3	20.7	20.0	19.1	15.3	15.0
Northampton	15.9	10.7	10.2	10.2	11.3	16.4	16.5	16.6	18.1	18.5
Northern Virginia	**2.7**	**2.7**	**2.7**	**2.7**	**2.9**	**3.3**	**3.3**	**3.3**	**3.3**	**3.3**
Rappahannock Area	**3.5**	**3.5**	**3.5**	**3.5**	**3.5**	**6.8**	**6.8**	**6.8**	**6.8**	**6.8**
Northern Neck	**16.2**	**16.2**	**16.5**	**16.5**	**16.7**	**42.4**	**46.9**	**46.9**	**47.0**	**47.0**
Middle Peninsula	**30.6**	**32.5**	**42.3**	**42.5**	**42.7**	**37.3**	**37.4**	**36.7**	**26.6**	**26.4**
Gloucester	11.3	12.4	15.1	15.1	13.5	8.5	8.5	7.9	5.6	5.6
Mathews	10.7	11.5	18.2	18.3	17.8	11.4	11.4	11.2	3.7	3.6
Other[b]	8.5	8.5	9.0	9.1	11.5	17.4	17.6	17.6	17.4	17.3
Hampton Roads[c]	**65.5**	**74.0**	**105.9**	**119.3**	**134.1**	**188.7**	**198.7**	**191.9**	**138.4**	**116.3**
Virginia Beach	24.0	25.2	35.0	44.0	45.3	56.3	54.4	53.6	35.7	25.3
Chesapeake	8.4	10.7	20.2	24.6	29.7	55.7	67.5	68.4	59.9	48.1
Portsmouth	2.7	3.7	5.2	5.2	7.4	11.5	11.5	9.6	4.8	4.8
Hampton	4.1	6.4	12.2	12.2	13.1	14.3	14.3	12.4	4.8	4.8
Norfolk	4.1	6.3	11.3	11.3	14.5	24.5	24.5	20.5	4.2	4.2
York	4.3	5.0	6.5	6.5	6.0	4.8	4.8	4.3	2.7	2.7
Newport News	4.9	4.3	3.2	3.2	3.2	3.5	3.5	3.8	4.7	4.7
Poquoson	3.2	3.4	3.6	3.6	2.7	0.1	0.1	0.1	0.0	0.0
Suffolk	3.4	3.0	2.8	2.8	5.4	8.6	8.6	9.6	11.7	11.8
James City	2.8	2.7	2.5	2.5	2.7	3.8	3.8	3.8	3.9	3.9
Isle of Wight	2.6	2.4	2.4	2.4	3.1	4.9	4.9	5.0	5.2	5.2
Surry	1.0	1.0	1.0	1.0	1.0	0.9	0.9	0.9	0.9	0.9
Other Jurisdictions[d]	**8.1**	**8.1**	**9.3**	**9.3**	**11.0**	**16.5**	**16.6**	**16.7**	**19.4**	**19.7**
Statewide	**172.1**	**176.8**	**223.0**	**236.9**	**253.4**	**332.1**	**346.2**	**337.9**	**275.0**	**253.0**

Table continued on following page

Table A9. Virginia (square kilometers) continued

County		Meters above Spring High Water 0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
Wetlands	**Tidal**	**-----Nontidal Wetlands, by half meter elevation increment------**									
Eastern Shore	**945.5**	**15.8**	**18.2**	**24.3**	**24.5**	**21.8**	**12.2**	**11.7**	**11.3**	**7.9**	**7.6**
Accomack	483.5	15.0	17.0	22.0	22.2	20.0	10.6	10.1	9.7	6.9	6.6
Northampton	462.0	0.8	1.2	2.2	2.3	1.9	1.6	1.6	1.6	1.1	1.0
Northern Virginia	**10.2**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**
Rappahannock Area	**26.7**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**
Northern Neck	**57.3**	**1.8**	**1.8**	**1.8**	**1.8**	**1.8**	**3.5**	**3.9**	**3.9**	**3.9**	**3.9**
Middle Peninsula	**164.4**	**8.7**	**9.4**	**12.5**	**12.5**	**11.9**	**12.0**	**11.9**	**11.7**	**7.7**	**7.6**
Gloucester	43.5	3.9	4.5	5.7	5.7	5.1	2.9	2.9	2.7	1.7	1.7
Mathews	27.1	2.8	3.0	4.8	4.8	4.9	7.5	7.5	7.5	4.5	4.4
Other[e]	93.9	2.0	2.0	2.0	2.0	1.9	1.5	1.5	1.5	1.5	1.5
Hampton Roads[f]	**330.2**	**32.6**	**31.4**	**22.6**	**20.7**	**28.9**	**39.3**	**38.8**	**39.9**	**39.8**	**37.9**
Virginia Beach	112.4	10.5	10.0	7.0	7.5	7.3	4.6	3.4	3.3	2.5	1.8
Chesapeake	39.7	12.2	12.7	10.1	7.7	16.1	30.1	30.7	31.8	32.2	31.0
Portsmouth	3.7	5.3	3.5	0.2	0.2	0.3	0.4	0.4	0.3	0.2	0.2
Hampton	14.4	0.1	0.2	0.2	0.2	0.3	0.7	0.7	0.8	1.1	1.1
Norfolk	4.7	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.0	0.0
York	17.0	0.6	1.0	1.9	1.9	1.5	0.6	0.6	0.6	0.4	0.4
Newport News	15.1	0.2	0.3	0.3	0.3	0.2	0.0	0.0	0.0	0.1	0.1
Poquoson	23.7	0.0	0.1	0.3	0.3	0.2	0.0	0.0	0.0	0.0	0.0
Suffolk	26.3	1.5	1.5	0.7	0.7	0.9	1.0	1.0	1.1	1.6	1.6
James City	32.8	0.6	0.6	0.6	0.6	0.5	0.4	0.4	0.4	0.4	0.4
Isle of Wight	28.9	0.9	0.9	0.7	0.7	0.8	1.1	1.1	1.1	1.2	1.2
Surry	11.5	0.5	0.5	0.5	0.5	0.4	0.2	0.2	0.2	0.2	0.2
Other Jurisdictions[g]	**84.5**	**13.1**	**13.1**	**8.1**	**8.0**	**7.1**	**6.3**	**6.3**	**6.3**	**6.0**	**6.0**
Virginia	**1618.9**	**73.1**	**75.0**	**70.4**	**68.6**	**72.6**	**74.3**	**73.7**	**74.1**	**66.5**	**64.1**
		Cumulative (total) amount of land below a given elevation[h]									
Dry Land		172	349	572	809	1062	1394	1741	2079	2354	2606
Nontidal Wetlands		73	148	218	287	360	434	508	582	648	713
All Land	1619	1864	2116	2409	2715	3041	3447	3867	4279	4621	4938

[a] For example, Gloucester has 12.4 km^2 of dry land between 0.5 and 1.0 meters above spring high water.
[b] Includes Essex, King and Queen, King William, and Middlesex Counties.
[c]Excludes Southampton, Franklin, and Williamsburg.
[d]Includes Charles City, Chesterfield, Hanover, Henrico, New Kent, Prince George, Southampton, and Sussex Counties and the cities of Colonial Heights, Franklin, Hopewell, Petersburg, and Williamsburg.
[e]Includes Essex, King and Queen, King William, and Middlesex Counties.
[f]Excludes Southampton, Franklin, and Williamsburg.
[g]Includes Charles City, Chesterfield, Hanover, Henrico, New Kent, Prince George, Southampton, and Sussex Counties and the cities of Colonial Heights, Franklin, Hopewell, Petersburg, and Williamsburg.
[h]For example, Virginia has a total of 349 square kilometers of dry land less than 1 meter above spring high water.

Table A10. Virginia jurisdictions not included in shore protection study (hectares)

County		Meters above Spring High Water									
		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---------------									
Charles City		237.9	237.9	237.9	237.9	296.2	445.5	445.5	445.5	445.5	445.5
Chesterfield		97.5	97.5	97.5	97.5	78.0	67.2	67.2	67.2	67.2	67.2
Colonial Heights		2.6	2.6	2.6	2.6	1.7	1.1	1.1	1.1	1.1	1.1
Franklin		5.1	5.1	19.5	19.7	19.7	24.2	24.5	24.5	35.1	36.4
Hanover		1.8	1.8	1.8	1.8	7.6	9.9	9.9	9.9	9.9	9.9
Henrico		57.0	57.0	57.0	57.0	47.4	40.8	40.8	40.8	40.8	40.8
Hopewell		28.1	28.1	28.1	28.1	18.0	10.9	10.9	10.9	10.9	10.9
New Kent		154.0	154.0	154.0	154.0	257.5	372.5	372.5	372.5	372.5	372.5
Petersburg		0.0	0.0	0.0	0.0	0.2	0.3	0.3	0.3	0.3	0.3
Prince George		140.5	140.5	140.5	140.5	178.4	287.8	287.8	287.8	287.8	287.8
Southampton		82.3	82.3	184.4	185.7	185.7	379.0	391.6	391.6	653.7	686.0
Williamsburg		3.7	3.7	3.7	3.7	4.0	5.7	5.7	5.7	5.7	5.7
Wetlands	**Tidal**	---------Nontidal Wetlands, by half meter elevation increment---------									
Charles City	2215.5	138.8	138.8	138.8	138.8	108.2	57.9	57.9	57.9	57.9	57.9
Chesterfield	1052.3	26.1	26.1	26.1	26.1	11.2	2.7	2.7	2.7	2.7	2.7
Colonial Heights	52.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Franklin	0.0	67.6	67.6	23.2	22.7	22.7	2.9	1.6	1.6	0.8	0.7
Hanover	114.2	0.0	0.0	0.0	0.0	0.1	0.2	0.2	0.2	0.2	0.2
Henrico	422.5	3.0	3.0	3.0	3.0	3.4	3.8	3.8	3.8	3.8	3.8
Hopewell	73.1	7.4	7.4	7.4	7.4	3.9	1.3	1.3	1.3	1.3	1.3
New Kent	3390.9	169.5	169.5	169.5	169.5	120.1	55.6	55.6	55.6	55.6	55.6
Petersburg	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Prince George	1091.1	57.6	57.6	57.6	57.6	59.3	76.2	76.2	76.2	76.2	76.2
Southampton	0.0	835.8	835.8	383.9	378.3	378.3	421.1	423.9	423.9	399.9	396.9
Williamsburg	39.7	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1

Table A11. North Carolina (square kilometers)

County		Meters above Spring High Water 0.5[a]	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[b]---------------									
Beaufort		50.4	61.0	66.2	81.9	84.7	80.9	83.3	96.7	68.9	48.8
Camden		16.8	11.3	50.0	39.0	46.5	52.8	26.4	23.1	35.8	22.3
Carteret		51.2	69.8	90.0	107.5	79.1	21.7	15.1	16.5	17.4	13.3
Currituck		19.8	26.4	36.6	57.4	57.2	51.8	32.7	21.6	9.1	5.4
Dare		45.4	22.2	17.9	15.2	15.2	11.7	8.8	5.3	3.3	2.1
Hyde		295.7	141.3	56.4	52.9	51.6	39.5	25.2	18.4	12.0	5.7
Onslow		24.6	10.1	9.9	11.5	14.7	11.6	15.5	17.9	13.6	21.8
Pamlico		24.2	35.4	52.2	53.4	38.6	34.8	30.7	22.7	15.7	9.2
Pasquotank		10.6	28.8	43.4	48.7	47.3	40.6	71.8	93.7	47.8	25.3
Tyrrell		139.9	143.4	49.6	26.1	12.6	3.5	3.2	1.3	0.5	0.0
Other[c]		60.3	73.7	105.6	138.2	177.8	213.7	292.6	380.4	319.8	227.9
Not Considered[d]		3.0	2.7	3.8	5.1	7.1	9.4	12.9	18.0	22.5	30.5
Statewide		741.9	626.1	581.6	636.9	632.5	572	618.2	715.6	566.4	412.3
Wetlands	**Tidal**	---------Nontidal Wetlands, by half meter elevation increment---------									
Beaufort	35.1	68.0	40.9	32.3	32.4	44.6	37.0	24.2	16.4	15.3	12.7
Brunswick	109.2	38.5	8.7	7.4	6.1	6.3	6.2	5.7	5.9	5.0	4.8
Camden	7.1	142.5	7.5	10.6	7.6	10.2	11.8	7.2	7.4	12.5	30.1
Carteret	334.3	34.3	53.0	48.1	44.7	36.2	20.5	10.6	10.9	15.6	12.7
Currituck	124.6	131.8	18.3	13.2	14.6	9.7	8.9	4.2	3.3	4.4	10.6
Dare	167.8	402.2	162.2	61.4	33.8	5.0	1.1	0.4	0.2	0.1	0.1
Hyde	199.3	345.6	153.3	52.9	27.5	19.7	22.1	18.0	22.4	13.7	10.2
Pamlico	111.6	52.8	20.8	12.1	20.8	25.6	16.4	22.5	22.1	13.0	15.2
Pender	38.2	87.2	28.2	18.0	17.5	14.6	14.3	13.6	13.1	13.9	12.2
Tyrrell	3.8	433.4	95.7	32.3	10.7	11.4	10.6	12.8	9.7	5.0	1.1
Other[e]	137.5	605.1	119.8	96.1	93.4	98.3	94.6	95.7	105.4	100.8	98.7
Not Considered[d]	3.5	30.9	10.2	10.0	11.7	14.2	15.8	18.7	21.2	19.6	26.3
Statewide	1272.0	2372.3	718.6	394.4	320.8	295.8	259.3	233.6	238	218.9	234.7
		Cumulative (total) amount of land below a given elevation[f]									
Dry Land		742	1368	1950	2587	3219	3791	4410	5125	5692	6104
Nontidal Wetlands		2372	3091	3485	3806	4102	4361	4595	4833	5052	5286
All Land	1272	4386	5731	6707	7665	8593	9425	10276	11230	12016	12662

[a] Includes land below spring high water.
[b] For example, Beaufort County has 61 square kilometers of dry land between 0.5 and 1.0 meters above spring high water.
[c] Includes Bertie, Brunswick, Chowan, Craven, Gates, Hertford, Martin, New Hanover, Pender, Perquimans, and Washington Counties.
[d] Includes Bladen, Columbus, Duplin, Jones, Lenoir, Northampton, Pitt and Sampson Counties.
[e] Includes Bertie, Chowan, Craven, Gates, Hertford, Martin, New Hanover, Onslow, Pasquotank, Perquimans, and Washington Counties.
[f] For example, North Carolina has 1368 square kilometers of dry land less than 1 meter above spring high water.

Table A12. North Carolina jurisdictions not included in shore protection study (hectares)

County		Meters above Spring High Water									
		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---------------									
Bladen		0.0	0.0	0.1	1.7	6.8	12.2	33.7	112.2	225.0	691.0
Columbus		0.2	2.1	2.8	8.8	13.9	18.5	21.2	22.9	32.9	39.3
Duplin		0.2	0.1	0.1	0.0	0.5	2.3	6.2	13.7	19.3	55.2
Jones		190.4	116.3	140.3	178.4	224.2	312.0	388.4	525.8	676.4	762.9
Lenoir		0.0	0.0	0.0	0.0	0.5	5.1	11.3	21.2	50.9	96.2
Northampton		6.5	10.4	11.1	19.8	47.7	83.2	114.2	124.7	131.6	140.1
Pitt		105.8	137.0	230.2	303.5	421.4	508.0	710.1	973.0	1106.3	1233.4
Sampson		0.0	0.0	0.0	0.0	0.0	2.5	5.0	8.2	11.4	34.1
Wetlands	**Tidal**	---------Nontidal Wetlands, by half meter elevation increment---------									
Bladen	0.0	0.3	20.3	70.1	125.9	214.1	277.6	432.4	644.7	461.4	895.1
Columbus	0.0	20.1	58.2	104.9	134.7	126.8	108.1	86.3	58.1	47.3	143.5
Duplin	0.0	0.0	0.0	0.0	0.0	5.0	9.5	65.3	134.6	112.4	221.9
Jones	350.8	811.1	332.6	246.7	263.8	244.8	251.8	241.0	271.4	242.4	220.7
Lenoir	0.0	0.0	0.0	13.6	40.3	108.4	168.4	246.9	205.3	361.9	405.4
Northampton	0.0	119.8	85.7	73.5	125.2	224.1	192.9	194.0	133.7	82.8	80.3
Pitt	0.0	2142.9	526.3	490.1	479.3	497.3	497.0	500.9	557.6	550.0	456.0
Sampson	0.0	0.0	0.0	0.0	0.0	0.1	70.1	99.5	115.9	100.5	202.1

1.3. Uncertainty Ranges Associated with EPA's Estimates of the Area of Land Close to Sea Level

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Dave Cacela, Stratus Consulting Inc.

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Section 1.3.1. Approach

Author: James G. Titus

Introduction

Digital Elevation Model output allows one to easily generate a point estimate ("best guess") of the amount of land below a particular elevation X by simply tabulating the number of points below X and multiplying by the cell size that each point represents. The accuracy of available elevation data varies, however, so the accuracy of these point estimates of the area estimates will vary as well. For some purposes, it may be sufficient to have a "best guess" estimate. But for other purposes, one needs some sort of uncertainty range. Fortunately, most elevation data come with a precision estimate, which makes it possible to develop an uncertainty range.

Section 1.3 explains how Dave Cacela and this author generated an uncertainty range for the estimates of the amount of land close to sea level within different shore protection categories and different elevations, which form the basis of this report. Section 1.3.1 explains the assumptions and the basic approach for estimating uncertainty; Section 1.3.2 explains how the approach was implemented. Section 1.3.3 provides the results. The final results constitute the three appendices to this section.

Like Section 1.2, by Jones and Wang, the starting point is the elevation data set developed in Section 1.1 by Titus and Wang. The approach for specifying uncertainty is based on the most important sources of error in that analysis. The actual implementation, however, uses the output from Section 1.2, in which Jones and Wang overlay the elevation study by Titus and Wang with the eight state-specific shore protection studies that Titus and Hudgens developed in their unpublished analysis mentioned in Section 1.2. Section 1.1 provided cumulative elevation distributions for dry land and nontidal wetlands; Section 1.2 subdivided the dry land into the various shore protection categories. Our exposition of the approach taken focuses on the elevation distribution of dry land. But not only did we apply the procedure to the totals for dry land, we also applied it to all the other shore protection categories and nontidal wetlands.

We warn the reader at the outset that this section switches between metric (standard international) and English (imperial) units of measurement. The final results are in metric units—but most of the underlying elevation data were based on topographic maps with contour intervals measured in feet. The point of measurements provided in this section is generally to explain the relationship between input data and assumptions, not to inform the reader about the magnitude of any particular effect. Therefore, the reader unfamiliar with one or the other system of measurements need not attempt to make conversions. In the few cases where that actual magnitude may matter, our convention is metric.

Background

Previous assessments of the land vulnerable to sea level rise have provided an uncertainty range; but the uncertainty range did not include uncertainty associated with topographic information. EPA's 1989 *Report to Congress* provided an uncertainty range about the area of land lost for a rise in sea level of 50, 100, or 200 cm. In Appendix B to that *Report to Congress*, Titus and Greene (1989) developed the uncertainty range, based on a study by Park et al. (1989), who used a sample of study area sites, and calculated a point estimate of land loss of each site. The published uncertainty range used a simple sampling error approach, treating the study sites as a random sample from the entire population of USGS quads. Because Park et al. did not report an uncertainty range for their sample sites, Titus and Greene made no attempt to include that uncertainty. In effect, Titus and Greene assumed that Park et al. accurately estimated the amount of land at particular elevations in those areas they assessed. The true uncertainty associated with their estimates included both sampling and measurement error; but the published uncertainty range considered only the sampling error.

This study uses the elevation data from Section 1.1, as formatted by the analysis explained in Section 1.2. That data set estimated the elevations of all land above spring high water. That is, it estimated elevations for dry land and nontidal wetlands, but did not estimate elevations for tidal wetlands. (Knowing that land is tidal wetland tells us that the land elevation is below spring high water and above mean low water, which provides a narrower uncertainty range about the elevation than if we know only that the land is below, for example, the 10-ft contour on a topographic map.) Because they obtained data for the entirety of the study area, there is no sampling error. The source of error stems entirely from the limitations in precision of the Section 1.1 results.

The overall approach is to make an assumption about the potential vertical error of the elevation data and the extent to which that error is random versus systematic. The magnitude of the error varies by data source: because we assume that error is a function of contour interval, which in turn varies by topographic quad, we calculate error separately for each topographic quad. Let us first explain our basis for focusing on vertical error of the elevation data, and then explain how low and high estimates for areas were calculated where the input data were USGS contour maps and other data with relatively coarse contour intervals (1 meter or worse), as well as our procedure for when the data had higher quality (2 feet or better).

Horizontal and Vertical Precision

Figure 1.3.1 depicts the various sources of data used to estimate elevations and the areas of land at particular elevations. In most locations, Titus and Wang relied on USGS 1:24,000 scale maps with various contour intervals. The second most common source of data was LIDAR provided by Maryland or North Carolina, which give elevations at various points in a grid.

USGS maps follow the national mapping standards for vertical and horizontal precision. The vertical standard is that 90 percent of the well-defined points along a contour must be within one-half the contour interval above or below the stated elevation of the contour. The horizontal standard is that 90 percent of the points should be within one fiftieth of an inch (about half a millimeter). On a 1:24,000 scale map, the allowable horizontal accuracy would be 12 meters. The LIDAR data sources generally have vertical precision on the order of 10–30 cm and horizontal error of less than 1 meter.

To keep the analysis reasonably manageable, this study ignores the horizontal error and focuses entirely on the vertical errors. Inspection of the USGS maps and the maps produced by Titus and Wang shows that most lowland is in an area where the contours are hundreds—and often thousands—of meters apart. Random error on the order of 12 meters is very small by comparison and not likely to substantially change an estimated error range. The horizontal error of LIDAR seemed even less likely to matter. In an assessment of the impacts of rising sea level, what matters is that most of the input data had contour intervals of 5 feet (150 cm) or worse, and we are interested in the implications of a 50-cm rise.

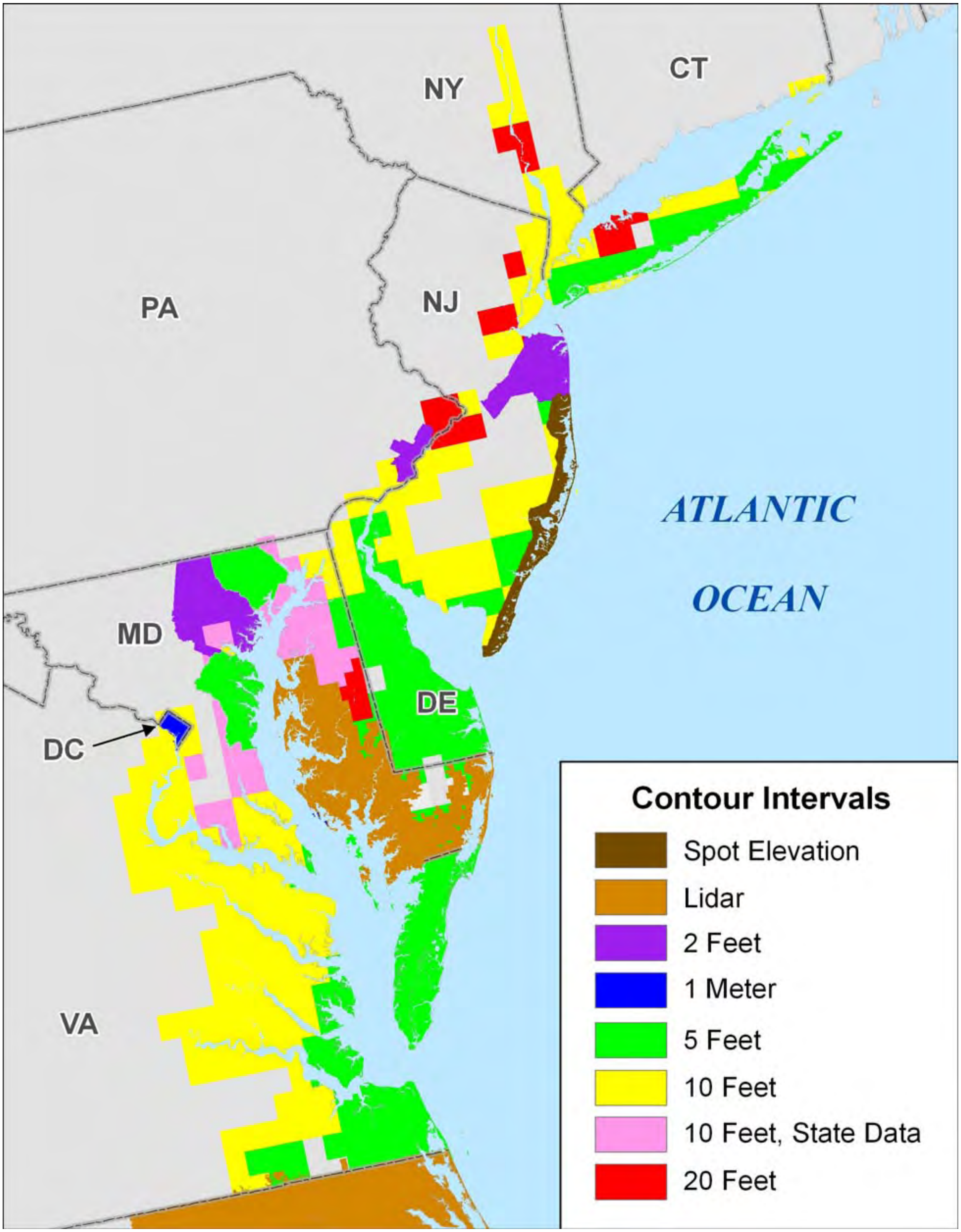

Figure 1.3.1. Input Elevation Data used in Section 1.1 to Estimate Area of Land Close to Sea Level. Quadrangles with a 10-ft contour interval and a 5-ft supplemental contour are shown as 5 feet. The Maryland data included 5-ft contours drawn from spot elevation with RMS error of 5 feet; hence the legend calls the data "10 feet, State Data"; USGS 5-ft contours have an RMS error of 2.5 feet.

Areas with USGS Maps as the Input Data

This analysis assumes that the standard deviation of error within a neighborhood is one-half the contour interval, based on National Map Accuracy standards. For reasons discussed below, the calculations also assume that half the error is random and half is systematic, so that the standard deviation of the uncertainty is one-quarter the contour interval for areas the size of a county or larger. These assumptions are adjusted to address possible error in the estimate of spring high water (SHW).

Our Initial Model of Vertical Error

Based on a comparison of their model results with LIDAR from Maryland and North Carolina (see Section 1.1, Jones 2007, and Jones et al. 2008), Titus and Wang report that the root mean square (RMS) error[1] of their elevation data sets tended to be approximately one-half the contour interval of the input contour. (Strictly speaking, their comparison measured the root mean square of the difference between the DEM and the LIDAR, which overestimates the error of the DEM.[2]) That finding seems roughly consistent with the National Map Accuracy Standard that 90 percent of the well-defined points should be within one-half contour interval of the stated elevation (Bureau of the Budget 1947)—"roughly" because they are not identical: If mean error is zero, a 90 percent confidence limit will almost always be a wider interval than the range defined by an estimate plus or minus the RMS error. In a normal distribution, the 90 percent interval would encompass a range ±1.64 times the RMS error (generally called standard deviation or σ in this case).[3] But one would expect the error across all elevations to be greater than the error at those elevations where we have a contour. For example, if a USGS map says that one contour is 5 feet above the vertical datum and that another contour is 10 feet above the vertical datum, and then one estimates an 8-ft contour through interpolation, we would expect the USGS contours to be somewhat more accurate than the 8-ft contour derived from the two USGS contours. So the assumption that 90 percent of the points along the contour are within one-half the contour interval of the stated elevation would be roughly consistent with the assumption that the standard deviation of error for all elevations is one-half the contour interval.[4] Because Titus and Wang did not know whether their estimates have a mean error or not, the more general term "RMS error" better describes the uncertainty. The contour intervals vary from place to place—but we know the contour interval at all locations. Therefore, this study assumes that RMS error equals one-half the contour interval for all locations where contour maps were the underlying source of the data.

Given that the availability of an estimate of the RMS error, this author's first thought was that the low and high estimates could be derived by simply (a) adding and subtracting the RMS error from the DEM[5] data set developed by Titus and Wang, cell by cell, and then (b) retabulating the data. In effect, this approach would add and

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[1]RMS error is calculated by taking the difference between the estimated and actual values for each point, squaring that difference, taking the sum of squares, dividing that sum by the total number of data points, and taking the square root. If the mean error is zero, RMS error is equal to the standard deviation of the error. If the mean error is not zero, then RMS error is equal to the square root of the sum of (a) the square of the mean error plus (b) the square of the standard deviation of the error.

[2] In general, whenever one has two independent measurements M_1 and M_2, with random error e_1 and e_2,

$$\text{variance}(M_1\text{-}M_2) = \text{variance }(e_1) + \text{variance }(e_2).$$

Thus, the variance of one error is equal to the variance of the difference minus the variance of the other error.

[3]The RMS error band includes about 68 percent of all data points.

[4]In the case of normally distributed error, we are saying, in effect, that 90 percent of the points along the contour are within 0.5 contour interval, while 90 percent of all points are within 0.82 (1.64/2) the contour interval of the stated elevation.

[5]DEM is an abbreviation for digital elevation model. Literally, that means the model used to calculate elevations. People in the business of making elevation maps, however, often use this term when referring to the actual set of elevation data points calculated by their model. The Titus and Wang data set we used has data points on a 30-m grid.

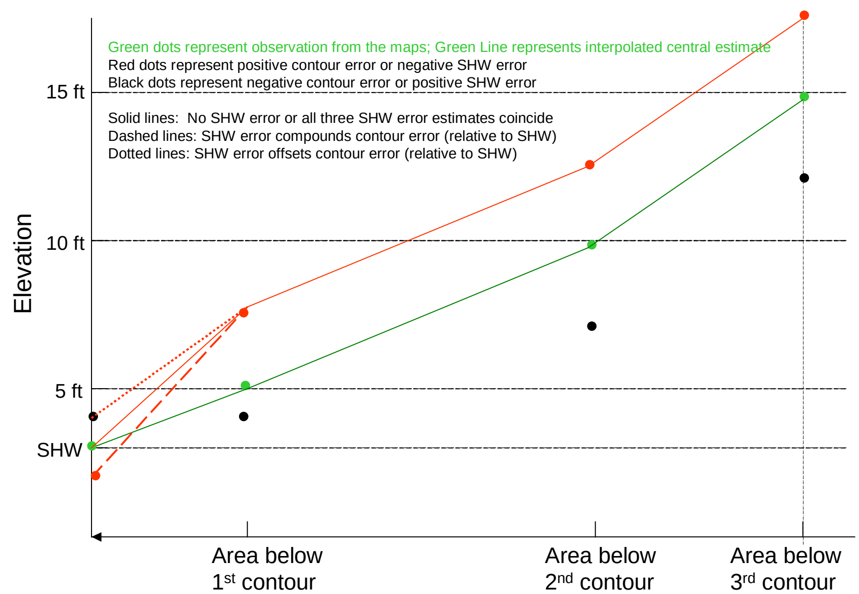

Figure 1.3.2. Interpolated Elevation Estimates Relative to NGVD29. Central estimate and high contour error (with and without SHW error, relative to NGVD, ignoring model error). This case assumes a 5-ft contour interval, a 1-ft error in estimating the elevation of spring high water, and contour error of 2.5 feet. Red dots represent positive contour error and negative SHW error, both of which cause a positive error in our estimates of elevation relative to SHW.

subtract the RMS error from the cumulative distribution of elevations. However, as those authors discuss in Section 1.1, their DEM contained plateaus along the input contours, which were artifacts of the interpolation algorithm, with no physical basis.[6] Therefore, they concluded that a linear interpolation of elevations between the contours would give a better estimate of the area of land below a particular elevation than the cumulative distribution of their cell-by-cell DEM output. Therefore, their elevation density distribution

assumed that elevations were uniformly distributed between contours. If the input data said that there are 100 ha of land between the 5- and 10-ft contours, for example, then there are 20 ha between the 5- and 6-ft contours, they assumed. Thus, their cumulative elevation distribution function was a series of line segments connecting a few points that represent actual observations based on the contour interval and the area of land above spring high water land below specific contours.[7] (See the green line in Figure 1.3.2, discussed below.)

This study assumes that the same logic that applies for the "point estimates" would apply to EPA's effort to estimate an uncertainty range. Choosing instead to add or subtract one-half contour interval from the DEM, would (for example) create data sets with plateaus at 2.5, 7.5, 12.5, and 17.5 feet in those areas where the USGS data had a contour interval of 5 feet, just as the Titus and Wang output had plateaus at SHW, 5, 10, 15, and 20 feet.[8]

Let us go back to the source information. For each quad, Titus and Wang provide

- the areas of land that lie below specific elevation contours from the input data set (e.g., the area between the 5- and 10-ft contours in a given quad), and
- their estimate of the elevation of spring high water relative to NGVD29 (derived from NOAA tidal datum).

[6]See Section 1.1.3 at Step 4, and especially Table 1.1.3 in Section 1.1.4. The large horizontal error but small vertical error in replicating contours is indicative of large plateaus.

[7]In an area with a 5-ft contour interval, those points would be (SHW, 0) , (5, A(5)), (10, A(10)), (15, A(15)), (20, A(20)) … etc., where A(x) is the area of land between spring high water and elevation x.

[8]Their data set also created plateaus just above their spring high water supplemental contour. Thus, if spring high water is 2 feet (NGVD29), then the high-elevation estimate would have a plateau at 4.5 feet; the low-elevation estimate would have a plateau at 2.5 feet below spring high water, that is, –0.5 feet (NGVD29).

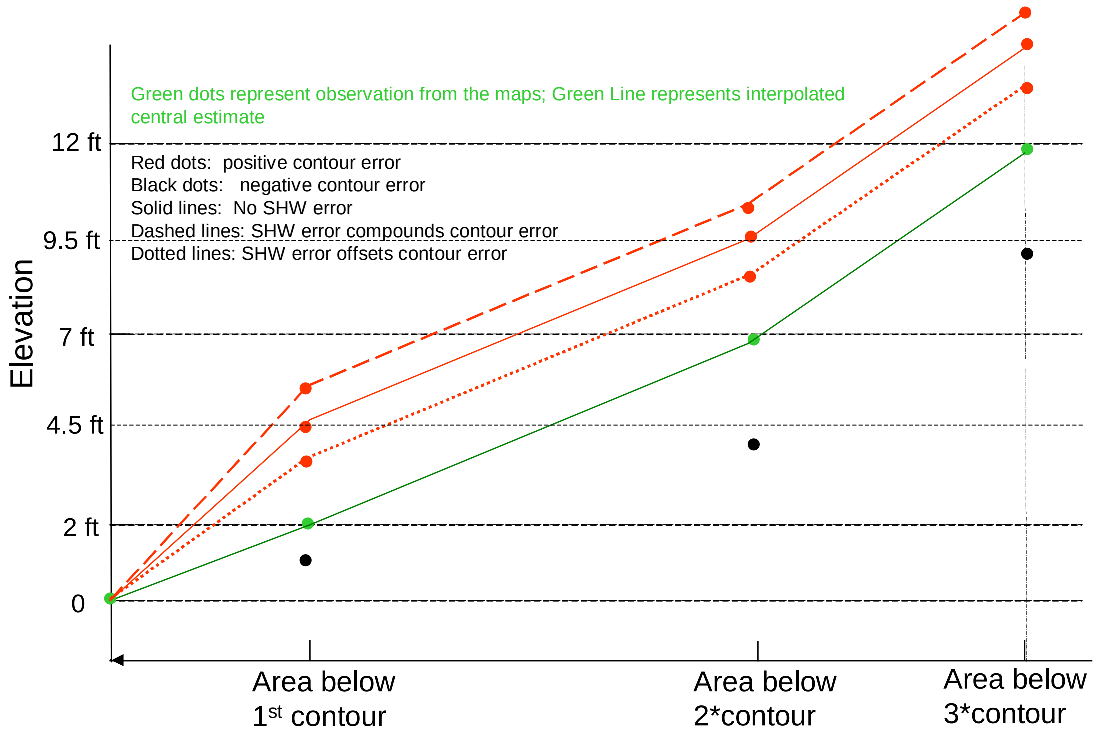

Figure 1.3.3. Interpolated Elevation Estimates Relative to Spring High Water. Central estimate and high contour error (with and without SHW error, relative to SHW, ignoring model error). This case assumes a 5-ft contour interval, a 1-ft error in estimating the elevation of spring high water, and contour error of 2.5 feet.

The estimates of the land below various elevations were based on simple linear interpolation of this information.[9] Figures 1.3.2 through 1.3.4 illustrate a proposed approach to generating high and low elevation estimates, respectively. But before discussing that approach, let us examine a depiction of the Titus and Wang analysis (see Section 1.1) used as input to this study. In Figure 1.3.2 (as well as Figures 1.3.3 and 1.3.4), the four green dots represent the values of the input data. This example quad has a 5-ft contour interval, and spring high water is estimated to be 3 feet above NGVD29. The first green dot shows the estimated elevation of spring high water; this dot appears along the vertical axis because all the dry land and nontidal wetlands are above spring high water (by definition). The other three points show the amount of land (other than tidal wetlands) below the 5-, 10-, and 15-ft contours. The green line is the cumulative elevation distributions that Titus and Wang derived through interpolation—but transposed so that the cumulative elevation is on the horizontal axis and elevation on the vertical axis. The figures are transposed from the traditional way of depicting cumulative distribution functions, because the transposed version gives us the actual profile of a typical transect or cross section of the land.

Now let us consider a possible way to think about high and low error. In Figure 1.3.2, the three red dots with elevations of 7.5, 12.5, and 17.5 feet represent high estimates of the elevation of the contours. That is, given the RMS error of one-half the contour interval (2.5 feet), the 5-ft contour could actually be as high as 7.5 feet. Along the vertical axis, we see three dots.

[9]In some cases, the 5-ft contour was seaward of the wetland boundary and the Titus and Wang interpolation disregarded the 5-ft contour on the assumption that it was obsolete. In those cases, the interpolation created—in effect—a new 5-ft contour farther inland, which was used in quantifying the land below 5 feet in a given quad.

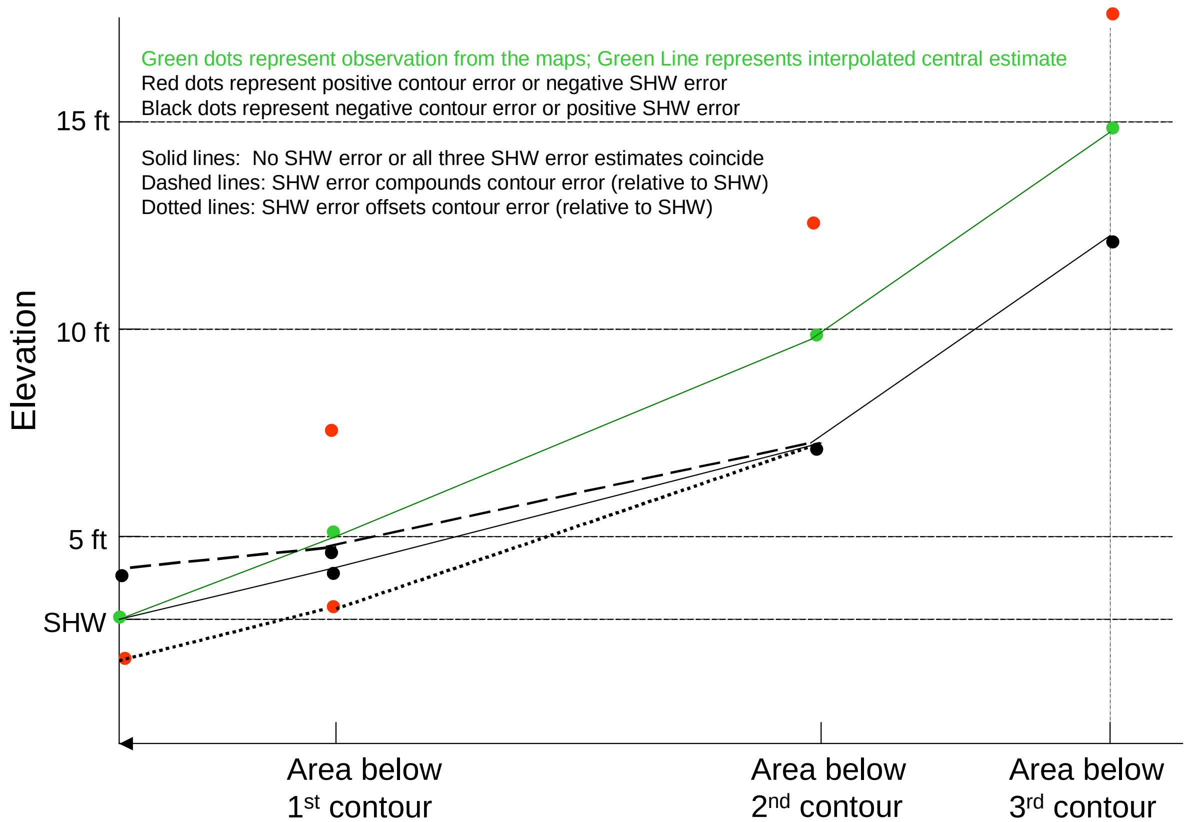

Figure 1.3.4. Interpolated Elevation Estimates Relative to NGVD29. Central estimate and low contour error (with and without SHW error, relative to NGVD, ignoring model error). This case assumes a 5-ft contour interval, a 1-ft error in estimating the elevation of SHW, and contour error of 2.5 feet

As previously mentioned, the green dot is the estimate of spring high water (3 feet). The red and black dots at 2 and 4 feet, respectively, represent the possibility that Titus and Wang over- or underestimated SHW, respectively. The three red lines represent the alternative high-elevation cumulative elevation distributions (and average profile) implied by the three different estimates of the elevation of SHW. In all these cases, the profile is steeper than the profile implied by the input data. The dashed line—where spring high water is less than estimated—provides the steepest profile and hence the greatest error. Put another way, the dashed line assumes that SHW is lower—and the contour is higher—than assumed by Titus and Wang; i.e., the errors compound. Figure 1.3.3 shows the same four cases, but with elevations relative to spring high water instead of NGVD29. Comparing Figures 1.3.2 and 1.3.3 may help one visualize the impact of SHW error on the land profile (cumulative elevation distribution) assumed in the calculations. Each of the four profiles has the same shape in Figure 1.3.3 as it has in Figure 1.3.2. When measured against NGVD (Figure 1.3.2), the three high-contour error profiles start at different elevations (reflecting uncertainty about the elevation of the lowest spot of dry land, SHW) but coincide after the first contour (because SHW error has no impact on the topographic contours). When measured against SHW (Figure 1.3.3), the profiles all start out at zero, because error in estimating SHW has no impact on the definitional assumption that dry land extends down to SHW. But the profiles diverge because errors in SHW have a 1:1 impact on elevations measured relative to SHW. Whatever the true elevation of the 5-ft contour relative to NGVD29, overestimating SHW by 1 foot lowers the estimated elevation relative to SHW by 1 foot.[10]

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[10]The error of elevations relative to spring high water would be 1 foot greater if the red dot (in Figure 1.3.2) was

All the figures show the implications of errors in spring high water and elevation estimates. There is no reason to think that these errors are correlated and every reason to assume that they are independent: two different federal agencies (USGS and NOAA) compiled the underlying data.[11] Therefore, when calculating uncertainty, we should assume that these errors are independent. It follows that the total elevation error is calculated as the square root of the sum of squares. Thus, in areas where the contour error is significant, the error in spring high water makes very little difference. But in areas with precise elevation data, error in spring high water can account for about one-half the total error.

Figure 1.3.4 presents a story similar to Figure 1.3.2 but for the low elevation case. The story is not completely symmetrical because of the first contour. The contour interval of the USGS maps at this location is 5 feet; but it is almost impossible for the USGS contour to have overestimated the actual elevations by 2.5 feet. Substantial dry land ("area below 1st contour") is above SHW (approximately 3 feet NGVD) and below the first contour. If the low elevation estimate were to assume that the lowest contour is at 2.5 feet, there would be an impossible result: the land above SHW (3 feet) cannot also be below 2.5 feet. This analysis avoids such an anomaly by assuming that RMS error is one-half the actual contour interval used. Thus, if SHW is between 2 and 4 feet, the lowest contour interval is 1 to 3 feet; so the low case assumes that the lowest contour is between 3.5 and 4.5 feet above NGVD (depending on the error in estimating SHW) rather than at 2.5 feet.

Although map accuracy standards provide a basis for the contour-error assumption, the literature does not provide a good estimate of uncertainty for SHW. This exposition has looked at the case where the error in SHW is 1 foot, because whole numbers can help simplify numerical illustrations. Our final results, however, assume that uncertainty for spring high water is approximately 15 cm (6 inches). Section 1.1 suggests that error is likely to be less than 6 inches, pointing out that the estimates are based on interpolation of spring tide ranges from more than 750 sites, and that the variation from site to site tends to be about 5 cm (2 to 3 inches), or less. Within a given quad—the unit of analysis for this study—those errors should cancel to some extent, causing the error to be less.

Using an Error Function to Represent Low and High Cumulative Distributions

The previous discussion explains the low and high estimates as alternative possibilities for the average shore profile, given the points along the profile for which observations are available. That is, the discussion compared the "best guess" profile estimated by Titus and Wang, with proposed high and low profiles. Recall, however, that although one usually displays y = f(x), in this case, the argument of the function is shown on the vertical axis. That is, in Section 1.1, Titus and Wang estimated the area as a function of elevation. Similarly, this study needs to estimate the low and high estimates as a function of elevation.

For computational purposes, it may be useful to think of error as a function of the best-guess central estimate. Viewed together, Sections 1.1 and Section 1.2 estimate the area of land within each shore protection category within each quad by 0.1-ft elevation increments. Thus, if one can express low = f(central estimate) and high = g(central estimate), then one need merely assign low and high elevations to each area. That is:

$$A\_low_{ik,low,f(E)} = A_{ik,E}$$

$$A\_high_{ik,high,g(E)} = A_{ik,E}$$

the actual value, and 1 foot less if the black dot was the actual value.

[11]The Section 1.1 estimates of spring high water are based entirely on NOAA tidal observations and NOAA analysis relating mean sea level to the fixed reference elevations used by topographic data (i.e., NAVD88 and NGVD29).

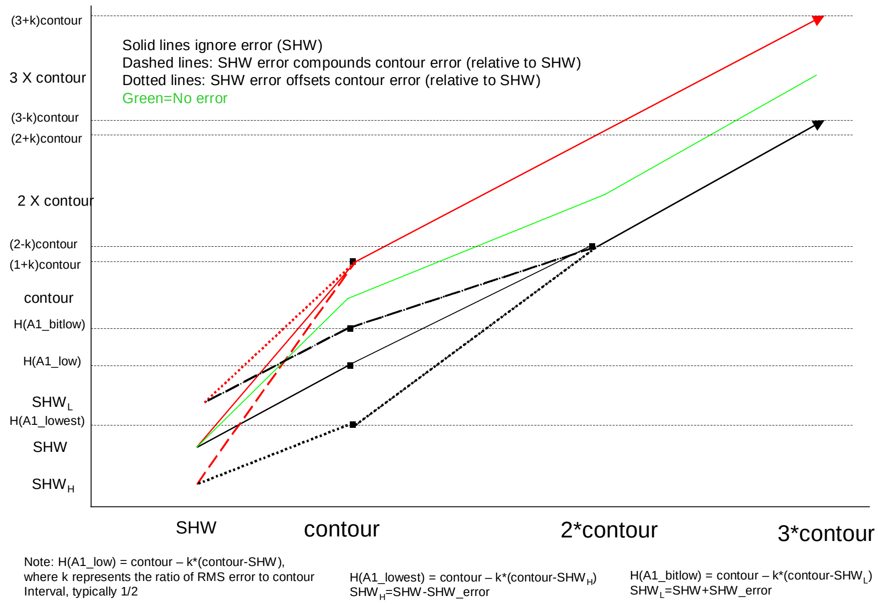


Figure 1.3.5. High and Low Estimates as a Function of the Best Guess. The difference between the red line and the green is the high vertical error; the difference between the black line and the green is the low vertical error. High error is constant beyond the first contour; low error is constant beyond the second contour. The vertical scale of this drawing is exaggerated below one contour to better display the relationships at low elevations.

where $A_{ij,E}$ represents the area of land in the i^{th} shore protection category in the k^{th} USGS quad at elevation E, as estimated in Section 1.2[12]; f and g are the error functions that express low and high elevation estimates as a function of the central estimate of elevation, and A_low and A_high represent the areas of land at elevation E in the low and high elevation cases. Figure 1.3.5 shows the low and high elevations as a function of the central estimate of elevation, i.e., functions f and g.

Refinements

Our initial model has two important flaws: it assumes that precision in modeling a single point is the same as our precision in estimating the total, and it ignores the model error of our linear interpolation. Let us examine each of these issues.

Systematic and random error. Intuitively, one might assume that the precision with which one can reasonably estimate the area of vulnerable land is the same as the precision of the input data. But that is true only if all errors are perfectly correlated. If we think that all elevations are likely to have been over- or underestimated by the same amount, then the ability to estimate the total is no more precise than the ability to estimate the elevation of a particular location. In such a case, there is no random error; all error is systematic. But that should rarely be the case.

Most elevation estimates include both a random and a systematic component. Along the contour, random errors would be expected as a human being attempts to trace a contour while viewing aerial photographs through a stereoplotter; systematic error might occur through biases caused by settings in the instrumentation or by subsiding benchmark elevations. Between the contours, systematic errors are likely because the actual "lay of the land" often departs from what one would expect from a linear interpolation. In developed areas, people have often filled and

[12]Jones and Wang overlaid the elevation data from Titus and Wang with the shore protection likelihood maps from an unpublished analysis to create cumulative elevation distribution functions for each of the shore protection categories. In effect, they subdivided the cumulative elevation distribution functions estimated by Titus and Wang, into the separate cumulative distribution functions for the different categories of likelihood of shore protection. Thus, all the uncertainties we analyze here result from the Titus and Wang analysis; but the actual input data came from Jones and Wang.

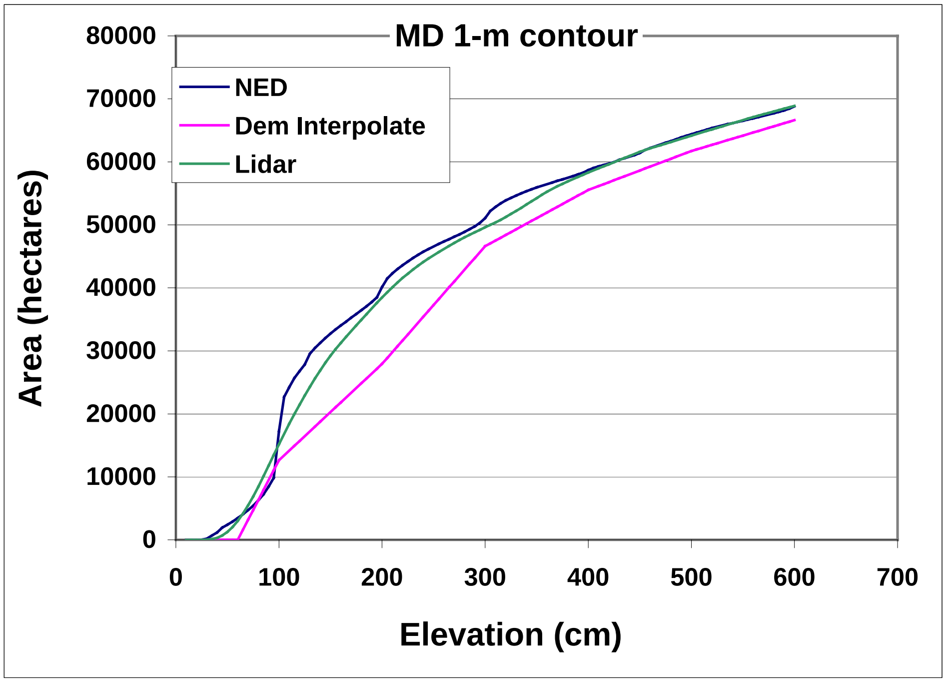
bulkheaded the shore, increasing the amount of land 50–100 cm above the tides at the expense of land 0–50 cm above the tides; in undeveloped areas bluffs occur in some areas, and the land follows a more gentle slope in other areas.

A sophisticated treatment of this question is beyond our time and budget constraints. Therefore, we need a simple parameterization. Figures 1.3.6 compares the cumulative elevation distributions of LIDAR collected by the state of Maryland (see Section 1.1, Jones 2007, and Jones et al. 2008 for additional details) to the interpolated results for the area on the Eastern Shore of Maryland where LIDAR was available (see Figure 1.3.1), subdivided into four subareas with varying data quality. The vertical axes omit magnitudes, which are unimportant for the purposes here.

The four figures all suggest that systematic error is well less than one-half the contour interval. In the areas with a 5-ft contour interval (Figure 1.3.6a), the DEM interpolation is about 1 foot lower (to the left) than the LIDAR below 3 feet; but above 4 feet the interpolation and LIDAR are less than 0.5 feet (15 cm) apart. In the areas with a 1-m contour (Figure 1.3.6b), the DEM interpolation and LIDAR are less than 10 cm (4 inches) apart below 1 meter. Above that point, the DEM interpolation increases to 50 cm greater than the LIDAR, but the difference is generally 25 cm. In the area that used the Maryland DNR data—which have an RMS error of 5 feet—the difference is less than 1 foot (30 cm) below the 10-ft contour (Figure 1.3.6c). It increases to 2.5 feet at the 15-ft contour before declining. In those areas that rely on USGS 20-ft contours (Figure 1.3.6d), the DEM underestimates the elevation by 2 to 3 feet, on average.

These comparisons (as well as the comparison with North Carolina LIDAR reported by Jones [2007] and Section 1.1.) lead to two insights worth applying in this error assessment. First, in areas the size of a county or two, the cumulative elevation distribution is within one-half the nominal RMS error of the data most of the time; and it almost never exceeds the reported RMS error. Therefore, one would expect that when there are many counties (e.g. results for entire states), the cumulative elevation distribution would continue to converge and almost never exceed one-half the nominal RMS error of the data set. That is, *it seems safe to assume that the systematic error over a large area is no more than one-half the reported RMS error of the data*. Therefore, this error assessment assumes that when USGS maps are the input data set, the low and high estimates are one-quarter the contour below and above the central estimates derived by interpolating between those contours in Section 1.2. that the high error may be greater than the low error, as displayed in Figures 1.3.2 and 1.3.4.

Model error from linear interpolation. The potential for linear interpolation to understate elevations appears to be particularly pronounced at very low elevations. The approach described so far assumes, in effect, that below the first contour, error is proportional to elevation (relative to SHW). But there is no reason to assume that precision increases at low elevations; that was simply an artifact of linear interpolation in a scheme designed to prevent assuming the impossible, such as dry land being below spring high water. These assumptions seem more defensible on the low end than on the high end. That is, assuming that the area of land below elevation X is proportional to X below the first contour is more unreasonable for the high-elevation uncertainty than the low-elevation uncertainty:



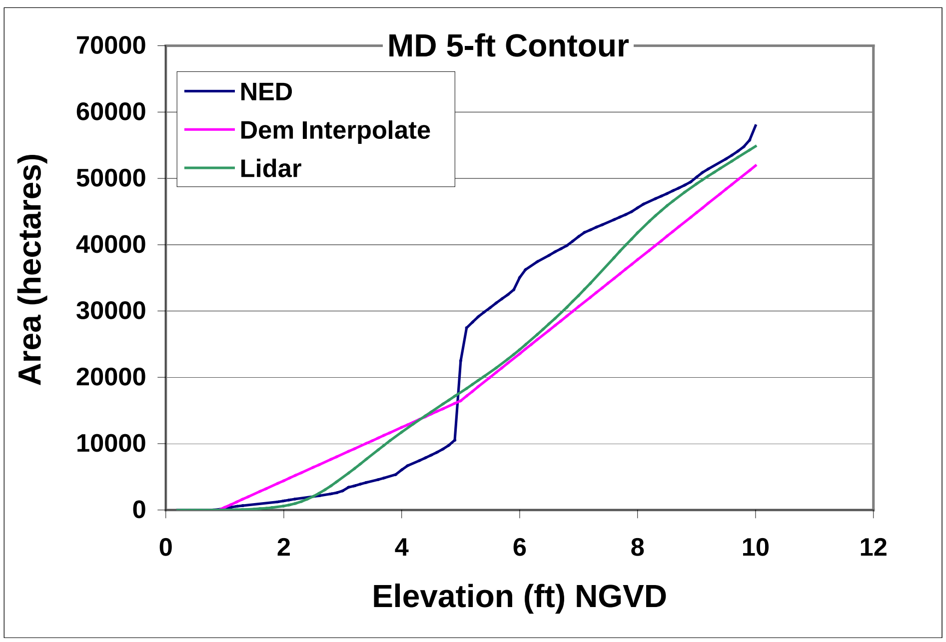


Figure 1.3.6. Cumulative Area of Land Close to Sea Level according to USGS National Elevation Data (NED), interpolation of the Titus and Wang DEM, and State of Maryland's LIDAR in the area where LIDAR was available (see Figure 1.3.1). The data are divided according to the best available data other than LIDAR: (a) USGS maps with 5- ft contours; (b) USGS maps with 1 meter contours, (c) 5-foot contours created from MD-DNR data in areas where USGS maps had 20-ft contours; and (d) USGS 20-ft contours. See Section 1.1 and accompanying metadata for more details.

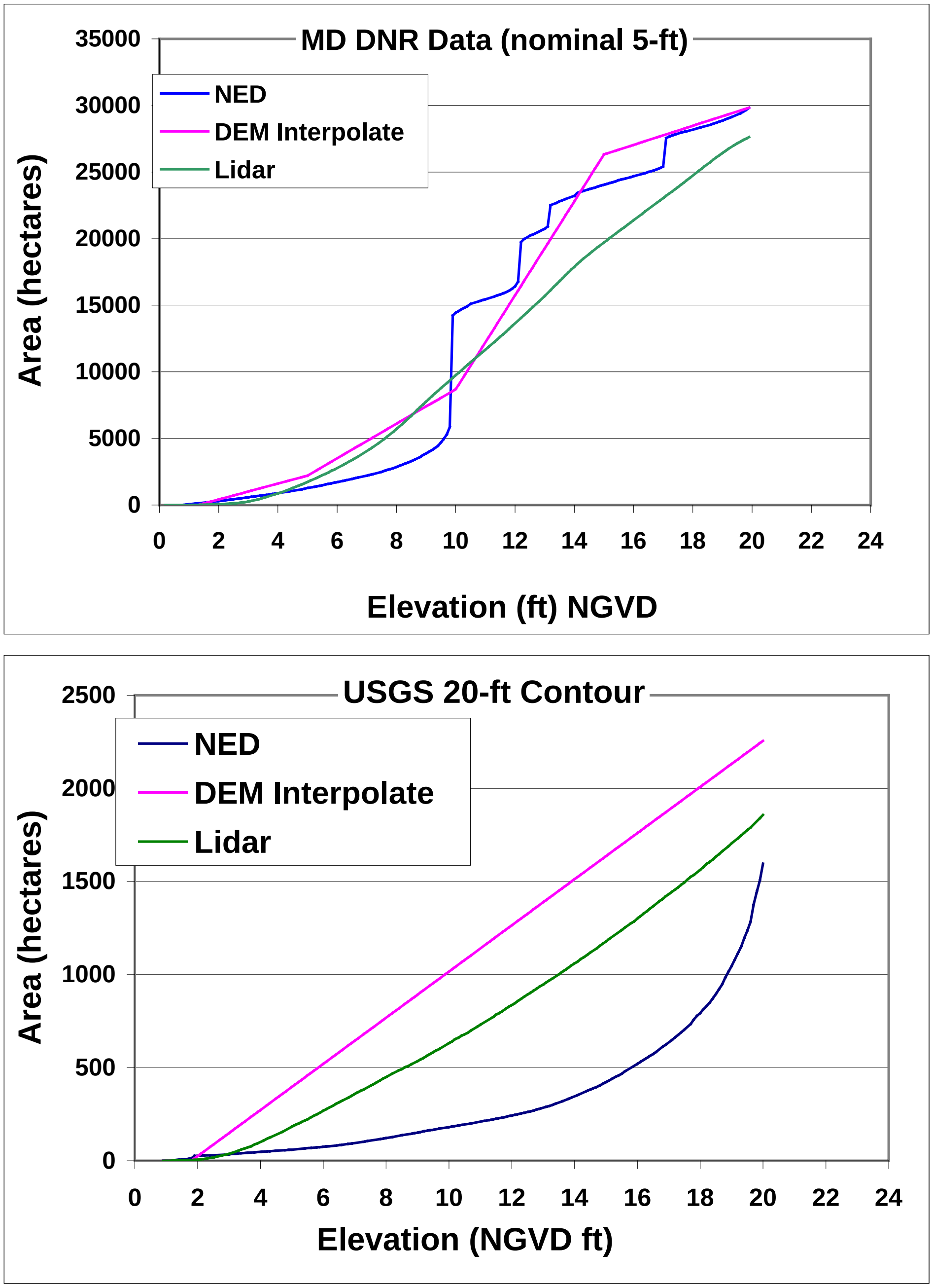


Figure 1.3.6. Cumulative Area of Land Close to Sea Level according to USGS National Elevation Data (NED), interpolation of the Titus and Wang DEM, and State of Maryland's LIDAR in the area where LIDAR was available (see Figure 1.3.1). The data are divided according to the best available data other than LIDAR: (a) USGS maps with 5- ft contours; (b) USGS maps with 1 meter contours, (c) 5-foot contours created from MD-DNR data in areas where USGS maps had 20-ft contours; and (d) USGS 20-ft contours. See Section 1.1 and accompanying metadata for more details.

Second, the tendency for the DEM interpolation to underestimate elevations appears to be somewhat more pronounced than any tendency to overestimate elevations. In Maryland this is clearly the case. (Titus and Wang, and Jones, found that in North Carolina, the interpolation overestimated elevations of very low land; but they concluded that the unique situation of North Carolina was probably to blame in that case. [13]) That tends to reinforce our inclination to assume

- The wetlands boundary is at the kink of the most common concave-up profile. So the use of wetlands data means that interpolation already accounts for cases where the profile is below a linear trend.

- The accuracy assessment shows the Section 1.1 DEM to underestimate elevations close to spring high water (see Figure 1.3.6):

  – In Maryland, they generally found that more than half of the land between spring high water and the first contour was above the midpoint between spring high water and the elevation of the first contour.

  – The error was particularly great when the contour interval was large.

- USGS contour selection also creates a downward bias: Consider an area with a 10-ft contour. If there is much land below the 5-ft contour, USGS is likely to reduce the contour interval to 5 feet or at least collect a 5-ft supplemental contour. This does not always occur, but the tendency is enough for a high-elevation scenario to assume that there is no land below the 2.5-ft contour.

- The mathematics limits downside uncertainty: Because elevations must be above spring high water, they can only be a little bit less than the very low elevations under consideration, while they could be much higher.

Thus, if the point estimate assumes 100 hectares within 0.5 feet above spring high water, it is desirable that the low estimate does not assume 100 hectares to be 2 feet below spring high water. That does not mean, however, that the high estimate ought to rule out the possibility that this land is actually 3 feet above spring high water. Low bluffs really are common along the coast—so a high scenario that assumes a low bluff with an elevation of contour/4 is actually quite realistic. (By contrast, a high scenario that assumes an unmapped dike protecting low land that it contour/4 below spring high water is not realistic.) Put another way, there is good reason to not think that there is a large amount of dry land below high tide—but there is no reason to think that there is a significant amount of land just above spring high water. Therefore, the high scenario should allow for the possibility that there is no significant amount land barely above the tides.

Figure 1.3.6 supports this concern. In Figures 1.3.6a and 1.3.6c, the interpolation understates elevations by about 1 foot below 4 feet in elevation, and then declines. In Figure 1.3.6d, where the underlying USGS maps have a 20-ft contour interval, the interpolation finds as much land below 3 feet as LIDAR finds below 5 feet, and as much land below 17 feet as the LIDAR finds below 20 feet. Thus, at an elevation of one-quarter the contour interval, the error is about two-thirds the error seen at the contour. (In Figure 1.3.6b, the error is fairly minor at all elevations.)

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[13]Much of North Carolinas coastal wetlands are truly are classified as nontidal wetlands, and hence the interpolations in Section 1.1 treated them as uniformly distributed between SHW and the 5-ft contour, which is generally more than 1 meter above SHW. (The final results used LIDAR and hence are not affected directly by this problem.) Much of those wetlands are at sea level, and classified as nontidal because the rivers and sounds along which they are found have an astronomical tide so small that, for most practical purposes, it is nontidal. When considering the impact of sea level rise, it would be more accurate to consider these areas to be "nanotidal wetlands."

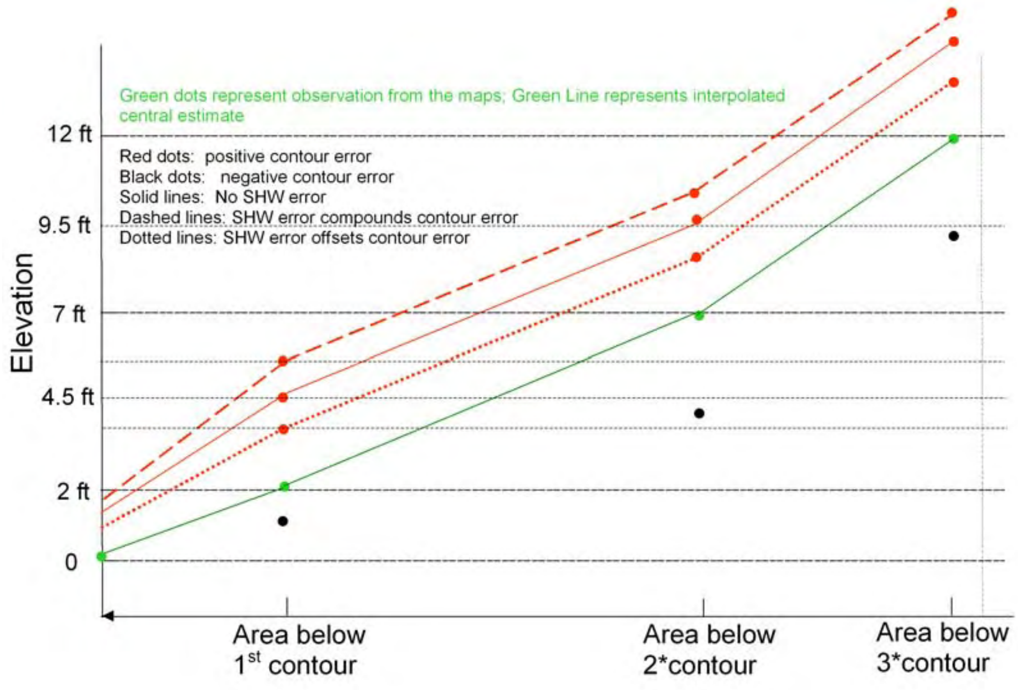

Figure 1.3.7. High Elevation Estimates Relative to Spring High Water, including Possible Model Error (with and without SHW error, relative to NGVD, ignoring model error). This case assumes a 5-ft contour interval, a 1-ft error in estimating the elevation of SHW, a contour error of 2.5 feet, and a high-end error that is always at least one-quarter the contour interval

There is no completely satisfactory way to model this possibility. The simplest approach would have been to simply add and subtract one-quarter the contour interval to the entire distribution, but this analysis employs a more complicated approach in part to avoid impossible results in the low case (e.g., dry land up to one-quarter the contour interval below SHW). But this is not a problem with the high scenario. Therefore, *the high scenario assumes that all land is at least one-quarter times the contour interval above SHW*. In effect, the high estimate assumes that one can not rule out a bluff with an elevation at one-quarter the lowest contour interval. Comparing Figure 1.3.7 to Figure 1.3.3 shows that this assumption has no impact on elevations above the first contour.

Areas with Higher Precision Data

In areas with higher precision data, these considerations are less important. They mostly apply to problems between contours; and EPA does not need elevations in increments finer than 50 cm. What is important is that no matter how precise the elevation data, we will report some uncertainty because LIDAR measures elevations relative to a fixed reference plane, while we report elevations relative to spring high water, which we estimate imprecisely. As mentioned above, this analysis assumes that the estimates of spring high water have an error of 15 cm (6 inches).

In Section 1.1, Titus and Wang used the LIDAR, spot elevation, and actual DEM results where contour intervals were 2 feet (60 cm) or less. Therefore, the interpolation model did not apply and it would be reasonable to simply add or subtract the systematic error. We saved some time, however, by applying the algorithm developed for USGS data to these results as well rather than rewriting a separate algorithm.

Section 1.3.2. Implementing the Approach using Geographically Specific Error Functions Approach

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The objective of elevation uncertainty analyses is to acknowledge uncertainty about the actual elevation of any particular geographic region and to quantify it so that the elevation in a particular region can be expressed as a range of plausible values. Consequently, estimates of flooded areas under any particular scenario of sea level rise can also be expressed as a range of plausible values.

This section reports the actual methods used to calculate ranges of plausible elevation that reflect the reasoning about landscapes, interpretation of map accuracy, and between-contour interpolation methods described in Section 1.3.1. It is intended to describe the essential features of methodology introduced in Section 1.3.1 that were actually applied in the uncertainty analysis in a manner that includes specific mathematical definitions that allow for reproducibility.

The reasoning in Section 1.3.1 about uncertainty is described in terms of two generalized error functions. One of the functions defines the lower limit of plausible elevation and the other defines the upper limit. Considered jointly, the error functions define the amount of uncertainty about elevation (vertical error) associated with any geographic point. To quantify uncertainty in a particular geographic location, the generalized error functions are used with parameters that are specific to that particular location to define plausible ranges of elevation for that location. Plausible ranges of elevation determine in this manner are subsequently translated into plausible ranges of area that may be inundated by various sea level rise scenarios.

Magnitude of Uncertainty in the Data Sources

Uncertainty analyses consider two main sources of uncertainty. The analyses consider both types of uncertainty jointly to generate an estimate of total uncertainty that is specific to each geographic area in the study.

One source of uncertainty derives from imprecision in elevation values in the source data. Each location in the study area is represented by one of several types of source data with differing amounts of inherent precision. As described in Section 1.3.1, the inherent precision of each type of source data is a known value that is expressed as the root mean square error (RMSE) and in the same units of measure as the vertical units provided (Table 1.3.1). Data with greater inherent precision have less uncertainty with regard to the true elevation of a particular geographic point and, conversely, source data with lesser inherent precision have more uncertainty with regard to the true elevation of a particular point. (See Figure 1.3.8 and Table 1.3.1; and Section 1.1 and Section 1.2 for additional details concerning the precision of the source data used in the study area.)

The second source of uncertainty derives from the estimated elevation of SHW relative to the NGVD29 for any particular section of coastline as derived from local tide gage data. The elevation of SHW is relevant because the elevations provided by the source data are expressed relative to the NGVD29 datum, but the estimation of inundation is expressed relative to SHW (see Section 1.1 for a description of how the elevations relative to SHW were derived).

Aggregate Uncertainty

All NGVD29 elevations from the source data are converted to elevations relative to SHW by:

$E_{jk} = E_{ngvd,jk} - SHW_k$ (1)

where:

E_{jk} is the derived nominal elevation of point j in region k relative to SHW
$E_{ngvd,jk}$ is the nominal elevation of point j in region k relative to NGVD29, as provided in the source data
SHW_k is the estimated (NGVD29) elevation of SHW for region k.

SHW_k is not known with absolute certainty; thus the precision of E_{jk} is a function of two sources of uncertainty: (1) the magnitude of uncertainty inherent in $E_{ngvd,jk}$ and (2) the magnitude of uncertainty in SHW_k. In principle, the magnitude of uncertainty in SHW_k could vary by region k, but in this study SHW_k is defined as a constant value of 0.5 feet. These two sources of uncertainty were assumed to be statistically independent; thus, the magnitude of total uncertainty is estimated with the basic equation:

$$P_{jk} = \sqrt{P_{mshw,k}{}^2 + P_{ngvd,jk}{}^2} \quad (2)$$

where:

$P_{mshw,k}$ is the magnitude of uncertainty in SHW_k expressed as RMSE, defined as a constant value of 0.5 feet
$P_{ngvd,jk} = kC_{jk}$ or
$P_{ngvd,jk}$ is a specified the magnitude of uncertainty in $E_{ngvd,jk}$ expressed as RMSE (feet)[14]
P_{jk} is the magnitude of total effective uncertainty in E_{jk} (feet)
C_{jk} is the magnitude of contour intervals represented in the relevant source data for point j,k[15]
k is a scalar that varies by source data (e.g., 0.5; see Table 1.3.1).
(1)

The basic definition of P_{jk} was not applied universally to all points in region k. In some subregions within region k, P_{jk} is associated with points j,k, but in other subregions, particularly regions of low elevation, P_{jk} is redefined by an ad hoc function of E_{jk} that is described below.

Estimating Elevation Uncertainty

The magnitude of uncertainty about E_{jk} was defined as P_{jk} at all relatively high elevations. In such regions, upper and lower bounds on E_{jk} were defined simply as:

$$E_{jk,l} = E_{jk} - P_{jk} \quad (3)$$

$$E_{jk,u} = E_{jk} + P_{jk} \quad (4)$$

where:

E_{jk} is the nominal elevation of point j,k [16]
$E_{jk,l}$ and $E_{jk,u}$ represent the lower and upper bounds on E_{jk}, respectively.

(2)

However, the simple formulations in Equations 3 and 4 were considered inadequate for providing realistic bounds for E_{jk} in locations with low elevation, where "low elevations" are defined to be lower than selected reference elevations. For estimating $E_{jk,u}$, a reference elevation was taken to be E'_{jk}, the elevation of "first contour," which is E_{jk} corresponding to $E_{ngvd,jk}$ equal to the lowest nonzero elevation contour in the source data for region k. For estimating $E_{jk,l}$, an additional reference elevation was taken to be E''_{jk}, the elevation of "second contour," which is E_{jk} corresponding to $E_{ngvd,jk}$ equal to the second-lowest nonzero elevation contour in the source data for region k.

[14] For areas described by some types of source data, e.g., USGS topographic maps, $P_{ngvd,jk}$ is defined as a certain fraction of the contour intervals used in the base maps, but for other types of source elevation data not based on contour intervals, e.g., elevations derived from LIDAR data, $P_{ngvd,jk}$ is a constant (Table 1.3.1). For USGS maps, $P_{ngvd,jk} = kC$.

[15] For source data not based on a contour interval, such as SPOT and LIDAR, contour interval was derived from the RMSE of the source data.

[16] Nominal elevations were determined from the source data using interpolation methods described in Section 1.1.

The general uncertainty modeling procedure can be succinctly described as two complex error functions. One such function describes the error in a positive direction, i.e., the amount by which the "true" elevation, E^*_{jk}, could exceed the nominal elevation E_{jk}. The other such function describes the error in a negative direction, i.e., the amount by which the "true" elevation, E^*_{jk}, could lie below the nominal elevation E_{jk}. The functions are asymmetrical because of the assumption that the magnitude of errors in the negative direction will tend to be relatively dampened if E_{jk} is lower than E'_{jk} or E''_{jk} (defined below; see Section 1.3.1 for the justification of this assumption).

The error function for determining an upper bound on E_{jk} is a set of line segments defined as:

$$E'_{jk} = (C_{jk} - MSWH_k) \tag{5}$$

$$P_{jk,u} = \begin{cases} gE'_{jk} + E_{jk} \times (P_{jk} - gE'_{jk}) / E'_{jk} & \text{If } E_{jk} < E'_{jk} \\ P_{jk} & \text{If } E_{jk} \geq E'_{jk} \end{cases} \tag{6}$$

$$E_{jk,u} = E_{jk} + P_{jk,u} \tag{7}$$

where:

SHW is the elevation of mean spring high water for point j,k

g is a constant (e.g., 0.25)

E'_{jk} is the elevation (relative to SHW) of "first contour"

$P_{jk,u}$ is the magnitude of error in a positive direction

$E_{jk,u}$ is the upper bound on E_{jk}.

The error function for determining a lower bound on E_{jk} is a set of line segments defined by:

$$E''_{jk} = (2C_{jk} - MSWH_k) \tag{8}$$

$$P'_{jk} = \sqrt{((1-k)P_{mshw})^2 + (kE'_{jk})^2} \tag{9}$$

$$P_{jk,l} = \begin{cases} P'_{jk} E_{jk} / E'_{jk} & \text{If } E_{jk} > 0 \text{ and } E_{jk} < E'_{jk} \\ P'_{jk} + ((E_{jk} - E'_{jk})(P_{jk} - P'_{jk})) / (E''_{jk} - E'_{jk}) & \text{If } E_{jk} \geq E'_{jk} \text{ and } E_{jk} < E''_{jk} \\ P_{jk} & \text{If } E_{jk} \geq E''_{jk} \end{cases} \tag{10}$$

$$E_{jk,l} = \max(0, (E_{jk} - P_{jk,l})) \tag{11}$$

where:

P'_{jk} is a measure of uncertainty analogous to P_{jk}

E''_{jk} is E_{jk} corresponding to $E''_{ngvd,jk}$, the elevation of the second-lowest non-zero elevation contour in the base map for region k

$P_{jk,l}$ is the magnitude of error in a negative direction

$E_{jk,l}$ is the lower bound on E_{jk}.

The typical shape of the error functions defined by Equations 1 through 11 are depicted in Figure 1.3.8.

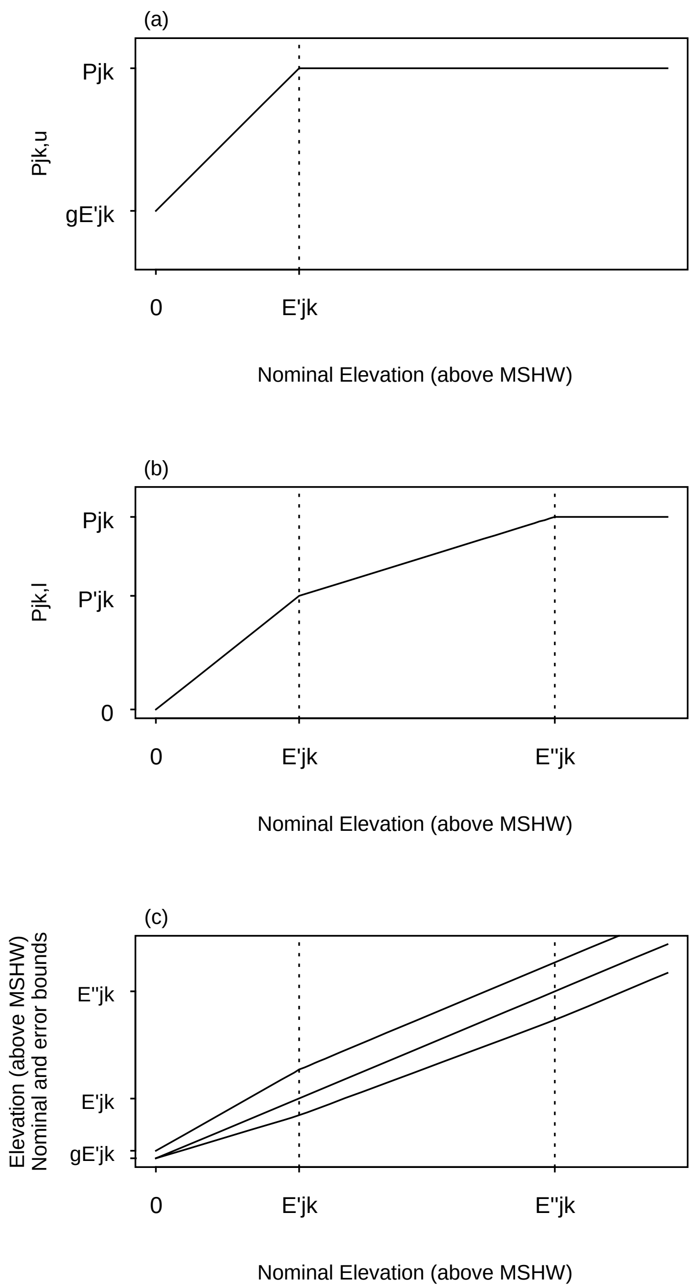

Figure 1.3.8. Generalized Error Functions Used to Estimate Uncertainty Bounds on Elevation. Panel (a) depicts magnitude of uncertainty in a positive direction; panel (b) depicts magnitude of uncertainty in a negative direction; and panel (c) describes the net effect of the functions depicted in panels (a) and (b), expressed as positive and negative uncertainty bounds relative to the nominal elevation.

Estimating Ranges of Plausible Elevation

Before the uncertainty analyses, acreages for a particular region and protection scenario were compiled into bins corresponding to elevations above SHW 0.1-ft increments.[17] For example, for scenarios,

$A_{k,s,0.1}$ = area between E_{jk} = 0 feet and E_{jk} = 0.1 foot (hectares)

$A_{k,s,0.2}$ = area between E_{jk} = 0.1 feet and E_{jk} = 0.2 foot (hectares), etc.

Thus, collectively the $A_{k,s}$ values can be considered as a density[18] with each element associated with a particular E_{jk}. Considering the meaning of $E_{jk,l}$ and $E_{jk,u}$, each $A_{k,s}$ can be associated with all three values: E_{jk}, $E_{jk,l}$, and $E_{jk,u}$. By extension, each E_{jk} elevation can be associated with three alternative values of $A_{k,s}$ by aligning with cases where $E_{jk} = E_{jk,l}$ and $E_{jk} = E_{jk,u}$. In this manner, two additional "densities" are generated such that for each E_{jk} there are three alternative corresponding $A_{k,s}$. The alternative densities have little implicit meaning, but converting each of the alternative densities to cumulative distributions provides alternative elevation profiles that are meaningful for generating a range of estimates of total flooded area under various amounts of sea level rise.

Procedural Notes

Data processing and calculations related to the elevation uncertainty analyses were conducted with S-Plus software (Professional Developer version 7; Insightful Corporation, Seattle, WA). In addition to quality control procedures used during development of the S-Plus algorithms used to solve for the uncertainty endpoints, quality control procedures were conducted independently from the S-Plus algorithms using MS-Excel spreadsheets for selected test cases.

[17]The data used as the basis for the uncertainty analyses were expressed with a resolution of 0.1 feet (see footnote 14), and the general processing of those data to develop uncertainty limits were conducted with a resolution of 0.1 feet. Prior to comparisons with elevations of interest (e.g., a selected amount of sea level rise), the basic results with 0.1 foot resolution were further subdivided into 10 bins of equal size to provide a quasi-resolution of 0.01 feet.

[18]Not strictly a probability density because the sum of all H_k,s equal a total area in region k for scenarios, not one.

Table 1.3.1. Features of distinct base map data sources related to estimation of elevation uncertainty

State	Quadrangle	County	Source	Contour interval (ft)	k (base)[a]	g	RMS cm (base)	SHW (ft)[b]
DC	Alexandria	Washington DC	1 m	3.280839	0.5	0.25	50	3.49
DC	Anacostia	Washington DC	1 m	3.280839	0.5	0.25	50	3.51
DC	Washington East	Washington DC	1 m	3.280839	0.5	0.25	50	3.39
DC	Washington West	Washington DC	1 m	3.280839	0.5	0.25	50	3.22
DE	Assawoman Bay	Sussex	5 ft	5	0.5	0.25	76.2	2.71
DE	Bennetts Pier	Kent	5 ft	5	0.5	0.25	76.2	3.89
DE	Bethany	Sussex	5 ft	5	0.5	0.25	76.2	2.76
DE	Bombay Hook	Kent	5 ft	5	0.5	0.25	76.2	4.22
DE	Cape Henlopen	Sussex	5 ft	5	0.5	0.25	76.2	2.89
DE	Clayton	Kent	5 ft	5	0.5	0.25	76.2	4.07
DE	Delaware City	New Castle	5 ft	5	0.5	0.25	76.2	3.89
DE	Dover	Kent	5 ft	5	0.5	0.25	76.2	4.13
DE	Ellendale	Sussex	5 ft	5	0.5	0.25	76.2	3.67
DE	Fairmount	Sussex	5 ft	5	0.5	0.25	76.2	2.88
DE	Frankford	Sussex	5 ft	5	0.5	0.25	76.2	2.78
DE	Frederica	Kent	5 ft	5	0.5	0.25	76.2	3.95
DE	Georgetown	Sussex	5 ft	5	0.5	0.25	76.2	3.2
DE	Greenwood	Kent	5 ft	5	0.5	0.25	76.2	3.79
DE	Greenwood	Sussex	5 ft	5	0.5	0.25	76.2	3.79
DE	Harbeson	Sussex	5 ft	5	0.5	0.25	76.2	3.01
DE	Harrington	Kent	5 ft	5	0.5	0.25	76.2	3.92
DE	Hickman	Kent	5 ft	5	0.5	0.25	76.2	3.82
DE	Kenton	Kent	5 ft	5	0.5	0.25	76.2	4.18
DE	Laurel	Sussex	5 ft	5	0.5	0.25	76.2	2.53
DE	Lewes	Sussex	5 ft	5	0.5	0.25	76.2	3.13
DE	Little Creek	Kent	5 ft	5	0.5	0.25	76.2	4.06
DE	Marydel	Kent	5 ft	5	0.5	0.25	76.2	4.03
DE	Milford	Kent	5 ft	5	0.5	0.25	76.2	3.89
DE	Millsboro	Sussex	5 ft	5	0.5	0.25	76.2	2.8
DE	Milton	Sussex	5 ft	5	0.5	0.25	76.2	3.45
DE	Mispillion	Kent	5 ft	5	0.5	0.25	76.2	3.85
DE	Penns Grove	New Castle	5 ft	5	0.5	0.25	76.2	4.06
DE	Rehoboth	Sussex	5 ft	5	0.5	0.25	76.2	2.83
DE	Seaford East	Sussex	5 ft	5	0.5	0.25	76.2	3.37
DE	Seaford West	Sussex	5 ft	5	0.5	0.25	76.2	2.5
DE	Selbyville	Sussex	5 ft	5	0.5	0.25	76.2	2.75
DE	Sharptown	Sussex	5 ft	5	0.5	0.25	76.2	2.24
DE	Smyrna	Kent	5 ft	5	0.5	0.25	76.2	4.2
DE	Taylorsbridge	New Castle	5 ft	5	0.5	0.25	76.2	4.05
DE	Trap Pond	Kent	5 ft	5	0.5	0.25	76.2	2.79
DE	Trap Pond	Sussex	5 ft	5	0.5	0.25	76.2	2.79
DE	Wilmington S	New Castle	5 ft	5	0.5	0.25	76.2	3.89
DE	Wyoming	Kent	5 ft	5	0.5	0.25	76.2	3.98
DE	Cecilton	New Castle	10 ft	10	0.5	0.25	152.4	3.92
DE	Elkton	New Castle	10 ft	10	0.5	0.25	152.4	3.83
DE	Marcus Hook	New Castle	10 ft	10	0.5	0.25	152.4	4.05
DE	Middletown	New Castle	10 ft	10	0.5	0.25	152.4	3.98
DE	Newark East	New Castle	10 ft	10	0.5	0.25	152.4	3.84
DE	Saint Georges	New Castle	10 ft	10	0.5	0.25	152.4	3.85
DE	Wilmington N	New Castle	10 ft	10	0.5	0.25	152.4	3.99
MD	Aberdeen	Cecil	20 ft DNR	5	1	0.5	152.4	2.36
MD	Anacostia	Prince George S	20 ft DNR	5	1	0.5	152.4	2.5

Table 1.3.1. Features of distinct base map data sources related to estimation of elevation uncertainty

State	Quadrangle	County	Source	Contour interval (ft)	k (base)[a]	g	RMS cm (base)	SHW (ft)[b]
MD	Baltimore East	Baltimore City	20 ft DNR	5	1	0.5	152.4	1.6
MD	Baltimore West	Baltimore City	20 ft DNR	5	1	0.5	152.4	1.6
MD	Benedict	Calvert	20 ft DNR	5	1	0.5	152.4	1.9
MD	Betterton	Kent	20 ft DNR	5	1	0.5	152.4	2
MD	Bowie	Prince George S	20 ft DNR	5	1	0.5	152.4	2.1
MD	Bristol	Calvert	20 ft DNR	5	1	0.5	152.4	2.1
MD	Centreville	Kent	20 ft DNR	5	1	0.5	152.4	1.6
MD	Charlotte Hall	Charles	20 ft DNR	5	1	0.5	152.4	1.7
MD	Chestertown	Kent	20 ft DNR	5	1	0.5	152.4	1.8
MD	Church Hill	Kent	20 ft DNR	5	1	0.5	152.4	2.2
MD	Claiborne	Talbot	20 ft DNR	5	1	0.5	152.4	1.5
MD	Conowingo Dam	Cecil	20 ft DNR	5	1	0.5	152.4	2.4
MD	Earleville	Cecil	20 ft DNR	5	1	0.5	152.4	2.1
MD	Edgewood	Harford	20 ft DNR	5	1	0.5	152.4	1.9
MD	Galena	Cecil	20 ft DNR	5	1	0.5	152.4	2.3
MD	Gunpowder Neck	Harford	20 ft DNR	5	1	0.5	152.4	1.6
MD	Hanesville	Harford	20 ft DNR	5	1	0.5	152.4	1.6
MD	Havre De Grace	Cecil	20 ft DNR	5	1	0.5	152.4	2.2
MD	Langford Creek	Kent	20 ft DNR	5	1	0.5	152.4	1.5
MD	Lower Marlboro	Calvert	20 ft DNR	5	1	0.5	152.4	2.1
MD	North Beach	Calvert	20 ft DNR	5	1	0.5	152.4	1.5
MD	Perryman	Harford	20 ft DNR	5	1	0.5	152.4	1.9
MD	Piscataway	Prince George S	20 ft DNR	5	1	0.5	152.4	2.5
MD	Popes Creek	Charles	20 ft DNR	5	1	0.5	152.4	1.7
MD	Price	Caroline	20 ft DNR	5	1	0.5	152.4	2.4
MD	Prince Frederick	Calvert	20 ft DNR	5	1	0.5	152.4	1.7
MD	Relay	Baltimore City	20 ft DNR	5	1	0.5	152.4	1.5
MD	Ridgely	Caroline	20 ft DNR	5	1	0.5	152.4	2.3
MD	Rock Hall	Kent	20 ft DNR	5	1	0.5	152.4	1.6
MD	Rock Point	Charles	20 ft DNR	5	1	0.5	152.4	1.8
MD	Spesutie	Cecil	20 ft DNR	5	1	0.5	152.4	1.8
MD	Swan Point	Kent	20 ft DNR	5	1	0.5	152.4	1.5
MD	Washington East	Prince George S	20 ft DNR	5	1	0.5	152.4	2.6
MD	Aberdeen	Harford	5 ft	5	0.5	0.25	76.2	2.2
MD	Annapolis	Anne Arundel	5 ft	5	0.5	0.25	76.2	0.5
MD	Bloodsworth Island	Somerset	5 ft	5	0.5	0.25	76.2	1.8
MD	Bowie	Anne Arundel	5 ft	5	0.5	0.25	76.2	1.2
MD	Bristol	Anne Arundel	5 ft	5	0.5	0.25	76.2	1.3
MD	Conowingo Dam	Harford	5 ft	5	0.5	0.25	76.2	2.4
MD	Curtis Bay	Anne Arundel	5 ft	5	0.5	0.25	76.2	0.7
MD	Deale	Anne Arundel	5 ft	5	0.5	0.25	76.2	0.6
MD	Deale Oe E	Anne Arundel	5 ft	5	0.5	0.25	76.2	0.5
MD	Edgewood	Harford	5 ft	5	0.5	0.25	76.2	1.9
MD	Gibson Island	Anne Arundel	5 ft	5	0.5	0.25	76.2	0.6
MD	Havre De Grace	Harford	5 ft	5	0.5	0.25	76.2	2.1
MD	Kedges Straits	Somerset	5 ft	5	0.5	0.25	76.2	1.6
MD	Millington	Cecil	5 ft	5	0.5	0.25	76.2	2.3
MD	North Beach	Anne Arundel	5 ft	5	0.5	0.25	76.2	0.6
MD	Odenton	Anne Arundel	5 ft	5	0.5	0.25	76.2	1
MD	Perryman	Harford	5 ft	5	0.5	0.25	76.2	1.9
MD	Point Lookout	St. Mary S	5 ft	5	0.5	0.25	76.2	1.6
MD	Point No Point	St. Mary S	5 ft	5	0.5	0.25	76.2	1.6

Table 1.3.1. Features of distinct base map data sources related to estimation of elevation uncertainty

State	Quadrangle	County	Source	Contour interval (ft)	k (base)[a]	g	RMS cm (base)	SHW (ft)[b]
MD	Relay	Anne Arundel	5 ft	5	0.5	0.25	76.2	0.7
MD	Round Bay	Anne Arundel	5 ft	5	0.5	0.25	76.2	0.6
MD	Saxis	Somerset	5 ft	5	0.5	0.25	76.2	2
MD	South River	Anne Arundel	5 ft	5	0.5	0.25	76.2	0.6
MD	Sparrows Point	Anne Arundel	5 ft	5	0.5	0.25	76.2	0.6
MD	Spesutie	Harford	5 ft	5	0.5	0.25	76.2	2
MD	Sudlersville	Kent	5 ft	5	0.5	0.25	76.2	2.2
MD	White Marsh	Harford	5 ft	5	0.5	0.25	76.2	1.8
MD	Alexandria	Prince George S	10 ft	5	1	0.25	152.4	2.6
MD	Broomes Island	Calvert	10 ft	5	1	0.25	152.4	1.7
MD	Cecilton	Cecil	10 ft	5	1	0.25	152.4	2.3
MD	Colonial Beach North	Charles	10 ft	5	1	0.25	152.4	1.7
MD	Cove Point	Calvert	10 ft	5	1	0.25	152.4	1.5
MD	Curtis Bay	Baltimore City	10 ft	5	1	0.25	152.4	1.5
MD	Elkton	Cecil	10 ft	5	1	0.25	152.4	2.3
MD	Hollywood	St. Mary S	10 ft	5	1	0.25	152.4	1.7
MD	Indian Head	Charles	10 ft	5	1	0.25	152.4	1.9
MD	King George	Charles	10 ft	5	1	0.25	152.4	1.5
MD	Leonardtown	St. Mary S	10 ft	5	1	0.25	152.4	1.8
MD	Mathias Point	Charles	10 ft	5	1	0.25	152.4	1.7
MD	Mechanicsville	Calvert	10 ft	5	1	0.25	152.4	1.8
MD	Mount Vernon	Charles	10 ft	5	1	0.25	152.4	2.2
MD	Nanjemoy	Charles	10 ft	5	1	0.25	152.4	1.6
MD	North East	Cecil	10 ft	5	1	0.25	152.4	2.2
MD	Piney Point	St. Mary S	10 ft	5	1	0.25	152.4	1.8
MD	Port Tobacco	Charles	10 ft	5	1	0.25	152.4	2
MD	Quantico	Charles	10 ft	5	1	0.25	152.4	1.8
MD	Saint Clements Island	St. Mary S	10 ft	5	1	0.25	152.4	1.8
MD	Saint George Island	St. Mary S	10 ft	5	1	0.25	152.4	1.6
MD	Saint Marys City	St. Mary S	10 ft	5	1	0.25	152.4	1.7
MD	Solomons Island	Calvert	10 ft	5	1	0.25	152.4	1.6
MD	Stratford Hall	St. Mary S	10 ft	5	1	0.25	152.4	1.8
MD	Widewater	Charles	10 ft	5	1	0.25	152.4	1.6
MD	Barren Island	Dorchester	Lidar	1[b]	0.47	0.25	14.3	0[b]
MD	Blackwater River	Dorchester	Lidar	1[b]	0.47	0.25	14.3	0[b]
MD	Bloodsworth Island	Dorchester	Lidar	1[b]	0.47	0.25	14.3	0[b]
MD	Cambridge	Dorchester	Lidar	1[b]	0.47	0.25	14.3	0[b]
MD	Centreville	Kent	Lidar	1[b]	0.47	0.25	14.3	0[b]
MD	Chicamacomico River	Dorchester	Lidar	1[b]	0.47	0.25	14.3	0[b]
MD	Church Creek	Dorchester	Lidar	1[b]	0.47	0.25	14.3	0[b]
MD	Claiborne	Queen Anne S	Lidar	1[b]	0.47	0.25	14.3	0[b]
MD	Crisfield	Somerset	Lidar	1[b]	0.47	0.25	14.3	0[b]
MD	Deal Island	Somerset	Lidar	1[b]	0.47	0.25	14.3	0[b]
MD	Delmar	Wicomico	Lidar	1[b]	0.47	0.25	14.3	0[b]
MD	Dividing Creek	Somerset	Lidar	1[c]	0.47	0.25	14.3	0[b]
MD	East New Market	Dorchester	Lidar	1[b]	0.47	0.25	14.3	0[b]
MD	Easton	Talbot	Lidar	1[b]	0.47	0.25	14.3	0[b]
MD	Eden	Somerset	Lidar	1[b]	0.47	0.25	14.3	0[b]
MD	Ewell	Somerset	Lidar	1[b]	0.47	0.25	14.3	0[b]
MD	Federalsburg	Caroline	Lidar	1[b]	0.47	0.25	14.3	0[b]
MD	Fowling Creek	Caroline	Lidar	1[b]	0.47	0.25	14.3	0[b]
MD	Golden Hill	Dorchester	Lidar	1[b]	0.47	0.25	14.3	0[b]

Table 1.3.1. Features of distinct base map data sources related to estimation of elevation uncertainty

State	Quadrangle	County	Source	Contour interval (ft)	k (base)[a]	g	RMS cm (base)	SHW (ft)[b]
MD	Hebron	Wicomico	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Honga	Dorchester	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Hudson	Dorchester	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Kedges Straits	Somerset	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Kent Island	Queen Anne S	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Kingston	Somerset	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Langford Creek	Kent	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Love Point	Queen Anne S	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Mardela Springs	Dorchester	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Marion	Somerset	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Monie	Somerset	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Nanticoke	Dorchester	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Ninepin Branch	Wicomico	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Oxford	Dorchester	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Pocomoke City	Somerset	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Preston	Caroline	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Princess Anne	Somerset	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Queenstown	Queen Anne S	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Rhodesdale	Dorchester	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Richland Point	Dorchester	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Ridgely	Caroline	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Saint Michaels	Queen Anne S	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Salisbury	Wicomico	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Saxis	Somerset	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Seaford West	Caroline	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Sharptown	Dorchester	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Taylors Island	Dorchester	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Terrapin Sand Point	Somerset	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Tilghman	Dorchester	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Trappe	Caroline	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Wango	Wicomico	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Wetipquin	Dorchester	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Whaleyville	Wicomico	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Wingate	Dorchester	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Wye Mills	Queen Anne S	Lidar	1 [b]	0.47	0.25	14.3	0 [b]
MD	Assawoman Bay	Worcester	Lidar	1 [b]	0.98	0.25	30	0 [b]
MD	Berlin	Worcester	Lidar	1 [b]	0.98	0.25	30	0 [b]
MD	Boxiron	Worcester	Lidar	1 [b]	0.98	0.25	30	0 [b]
MD	Dividing Creek	Worcester	Lidar	1 [b]	0.98	0.25	30	0 [b]
MD	Girdletree	Worcester	Lidar	1 [b]	0.98	0.25	30	0 [b]
MD	Hallwood	Worcester	Lidar	1 [b]	0.98	0.25	30	0 [b]
MD	Kingston	Worcester	Lidar	1 [b]	0.98	0.25	30	0 [b]
MD	Ninepin Branch	Worcester	Lidar	1 [b]	0.98	0.25	30	0 [b]
MD	Ocean City	Worcester	Lidar	1 [b]	0.98	0.25	30	0 [b]
MD	Pocomoke City	Worcester	Lidar	1 [b]	0.98	0.25	30	0 [b]
MD	Public Landing	Worcester	Lidar	1 [b]	0.98	0.25	30	0 [b]
MD	Selbyville	Worcester	Lidar	1 [b]	0.98	0.25	30	0 [b]
MD	Snow Hill	Worcester	Lidar	1 [b]	0.98	0.25	30	0 [b]
MD	Tingles Island	Worcester	Lidar	1 [b]	0.98	0.25	30	0 [b]
MD	Wango	Worcester	Lidar	1 [b]	0.98	0.25	30	0 [b]
MD	Whaleyville	Worcester	Lidar	1 [b]	0.98	0.25	30	0 [b]
MD	Whittington Point	Worcester	Lidar	1 [b]	0.98	0.25	30	0 [b]

Table 1.3.1. Features of distinct base map data sources related to estimation of elevation uncertainty

State	Quadrangle	County	Source	Contour interval (ft)	k (base)[a]	g	RMS cm (base)	SHW (ft)[b]
MD	Baltimore East	Baltimore	2 ft	1 [b]	1	0.5	30.5	0 [b]
MD	Curtis Bay	Baltimore	2 ft	1 [b]	1	0.5	30.5	0 [b]
MD	Edgewood	Baltimore	2 ft	1 [b]	1	0.5	30.5	0 [b]
MD	Gunpowder Neck	Baltimore	2 ft	1 [b]	1	0.5	30.5	0 [b]
MD	Middle River	Baltimore	2 ft	1 [b]	1	0.5	30.5	0 [b]
MD	Relay	Baltimore	2 ft	1 [b]	1	0.5	30.5	0 [b]
MD	Sparrows Point	Baltimore	2 ft	1 [b]	1	0.5	30.5	0 [b]
MD	White Marsh	Baltimore	2 ft	1 [b]	1	0.5	30.5	0 [b]
MD	Barren Island	Dorchester	MTR	3.28084	0.5	0.25	50	1.6
MD	Honga	Dorchester	MTR	3.28084	0.5	0.25	50	1.4
MD	Hudson	Dorchester	MTR	3.28084	0.5	0.25	50	1.5
MD	Taylors Island	Dorchester	MTR	3.28084	0.5	0.25	50	1.5
MD	Burrsville	Caroline	20 ft USGS	20	0.5	0.25	304.8	2.4
MD	Denton	Caroline	20 ft USGS	20	0.5	0.25	304.8	2.3
MD	Federalsburg	Caroline	20 ft USGS	20	0.5	0.25	304.8	2.3
MD	Fowling Creek	Caroline	20 ft USGS	20	0.5	0.25	304.8	2.1
MD	Goldsboro	Caroline	20 ft USGS	20	0.5	0.25	304.8	2.4
MD	Hickman	Caroline	20 ft USGS	20	0.5	0.25	304.8	2.37
MD	Hobbs	Caroline	20 ft USGS	20	0.5	0.25	304.8	2.2
MD	Marydel	Caroline	20 ft USGS	20	0.5	0.25	304.8	2.3
MD	Preston	Caroline	20 ft USGS	20	0.5	0.25	304.8	2.1
MD	Ridgely	Caroline	20 ft USGS	20	0.5	0.25	304.8	2.3
MD	Seaford West	Caroline	20 ft USGS	20	0.5	0.25	304.8	2.3
NC	Fictitious Nocar	Chowan	Lidar	1 [b]	0.36	0.089	10.9	0 [b]
NC	Fictitious Nocar	Carteret	Lidar	1 [b]	0.37	0.092	11.2	0 [b]
NC	Fictitious Nocar	Bertie	Lidar	1 [b]	0.37	0.093	11.3	0 [b]
NC	Fictitious Nocar	Pitt	Lidar	1 [b]	0.38	0.096	11.7	0 [b]
NC	Fictitious Nocar	Currituck	Lidar	1 [b]	0.4	0.099	12.1	0 [b]
NC	Fictitious Nocar	Washington	Lidar	1 [b]	0.4	0.101	12.3	0 [b]
NC	Fictitious Nocar	Brunswick	Lidar	1 [b]	0.41	0.102	12.4	0 [b]
NC	Fictitious Nocar	Columbus	Lidar	1 [b]	0.41	0.103	12.5	0 [b]
NC	Fictitious Nocar	Pasquotank	Lidar	1 [b]	0.42	0.105	12.8	0 [b]
NC	Fictitious Nocar	Perquimans	Lidar	1 [b]	0.42	0.106	12.9	0 [b]
NC	Fictitious Nocar	Pamlico	Lidar	1 [b]	0.45	0.112	13.7	0 [b]
NC	Fictitious Nocar	Martin	Lidar	1 [b]	0.47	0.118	14.4	0 [b]
NC	Fictitious Nocar	Hyde	Lidar	1 [b]	0.48	0.119	14.5	0 [b]
NC	Fictitious Nocar	Camden	Lidar	1 [b]	0.48	0.12	14.6	0 [b]
NC	Fictitious Nocar	Duplin	Lidar	1 [b]	0.48	0.121	14.7	0 [b]
NC	Fictitious Nocar	Craven	Lidar	1 [b]	0.49	0.121	14.8	0 [b]
NC	Fictitious Nocar	Bladen	Lidar	1 [b]	0.49	0.122	14.9	0 [b]
NC	Fictitious Nocar	Dare	Lidar	1 [b]	0.52	0.131	16	0 [b]
NC	Fictitious Nocar	Onslow	Lidar	1 [b]	0.54	0.135	16.4	0 [b]
NC	Fictitious Nocar	Lenoir	Lidar	1 [b]	0.57	0.144	17.5	0 [b]
NC	Fictitious Nocar	New Han	Lidar	1 [b]	0.59	0.147	17.9	0 [b]
NC	Fictitious Nocar	Pender	Lidar	1 [b]	0.61	0.152	18.5	0 [b]
NC	Fictitious Nocar	Beaufort	Lidar	1 [b]	0.66	0.164	20	0 [b]
NC	Fictitious Nocar	Halifax	Lidar	1 [b]	0.66	0.165	20.12	0 [b]
NC	Fictitious Nocar	Northampton	Lidar	1 [b]	0.87	0.217	26.5	0 [b]
NC	Fictitious Nocar	Gates	Lidar	1 [b]	1.06	0.265	32.3	0 [b]
NC	Fictitious Nocar	Hertford	Lidar	1 [b]	1.11	0.276	33.7	0 [b]
NJ	Alloway	Salem	10 ft	10	0.5	0.25	152.4	3.7
NJ	Arthur Kill	Middlesex	10 ft	10	0.5	0.25	152.4	4.09

Table 1.3.1. Features of distinct base map data sources related to estimation of elevation uncertainty

State	Quadrangle	County	Source	Contour interval (ft)	k (base)[a]	g	RMS cm (base)	SHW (ft)[b]
NJ	Atsion	Atlantic	10 ft	10	0.5	0.25	152.4	2.93
NJ	Bridgeport	Gloucester	10 ft	10	0.5	0.25	152.4	3.77
NJ	Bridgeton	Cumberland	10 ft	10	0.5	0.25	152.4	4.48
NJ	Cape May	Cape May	10 ft	10	0.5	0.25	152.4	3.79
NJ	Cedarville	Cumberland	10 ft	10	0.5	0.25	152.4	3.72
NJ	Central Park	Bergen	10 ft	10	0.5	0.25	152.4	3.34
NJ	Dividing Creek	Cumberland	10 ft	10	0.5	0.25	152.4	3.75
NJ	Dorothy	Atlantic	10 ft	10	0.5	0.25	152.4	5
NJ	Egg Harbor City	Atlantic	10 ft	10	0.5	0.25	152.4	3.19
NJ	Elizabeth	Essex	10 ft	10	0.5	0.25	152.4	4.15
NJ	Five Points	Cumberland	10 ft	10	0.5	0.25	152.4	4.23
NJ	Forked River	Ocean	10 ft	10	0.5	0.25	152.4	1.67
NJ	Frankford	Burlington	10 ft	10	0.5	0.25	152.4	4.74
NJ	Green Bank	Atlantic	10 ft	10	0.5	0.25	152.4	3.15
NJ	Hackensack	Bergen	10 ft	10	0.5	0.25	152.4	4.24
NJ	Jenkins	Atlantic	10 ft	10	0.5	0.25	152.4	3.04
NJ	Jersey City	Essex	10 ft	10	0.5	0.25	152.4	4.16
NJ	Marcus Hook	Gloucester	10 ft	10	0.5	0.25	152.4	3.78
NJ	Millville	Cumberland	10 ft	10	0.5	0.25	152.4	4.37
NJ	New Brunswick	Middlesex	10 ft	10	0.5	0.25	152.4	4.54
NJ	New Gretna	Atlantic	10 ft	10	0.5	0.25	152.4	3.24
NJ	Nyack	Bergen	10 ft	10	0.5	0.25	152.4	3.59
NJ	Oswego Lake	Burlington	10 ft	10	0.5	0.25	152.4	3.01
NJ	Park Ridge	Bergen	10 ft	10	0.5	0.25	152.4	4.24
NJ	Port Elizabeth	Cape May	10 ft	10	0.5	0.25	152.4	3.83
NJ	Rio Grande	Cape May	10 ft	10	0.5	0.25	152.4	3.93
NJ	Runnemede	Camden	10 ft	10	0.5	0.25	152.4	3.66
NJ	Salem	Salem	10 ft	10	0.5	0.25	152.4	3.68
NJ	Sea Isle City	Cape May	10 ft	10	0.5	0.25	152.4	3.4
NJ	Shiloh	Cumberland	10 ft	10	0.5	0.25	152.4	4.06
NJ	Ship Bottom	Ocean	10 ft	10	0.5	0.25	152.4	2.03
NJ	South Amboy	Middlesex	10 ft	10	0.5	0.25	152.4	4.25
NJ	Stone Harbor	Cape May	10 ft	10	0.5	0.25	152.4	3.53
NJ	Toms River	Ocean	10 ft	10	0.5	0.25	152.4	1.68
NJ	Tuckahoe	Atlantic	10 ft	10	0.5	0.25	152.4	3.39
NJ	Tuckerton	Ocean	10 ft	10	0.5	0.25	152.4	2.94
NJ	Weehawken	Bergen	10 ft	10	0.5	0.25	152.4	4.2
NJ	West Creek	Ocean	10 ft	10	0.5	0.25	152.4	2.43
NJ	Wildwood	Cape May	10 ft	10	0.5	0.25	152.4	3.65
NJ	Woodbury	Gloucester	10 ft	10	0.5	0.25	152.4	3.83
NJ	Woodstown	Gloucester	10 ft	10	0.5	0.25	152.4	3.33
NJ	Yonkers	Bergen	10 ft	10	0.5	0.25	152.4	3.59
NJ	Asbury Park	Monmouth	5 ft	5	0.5	0.25	76.2	3.56
NJ	Atlantic City	Atlantic	5 ft	5	0.5	0.25	76.2	3.58
NJ	Ben Davis Point	Cumberland	5 ft	5	0.5	0.25	76.2	4.16
NJ	Bombay Hook Island	Cumberland	5 ft	5	0.5	0.25	76.2	4.24
NJ	Brigantine Inlet	Atlantic	5 ft	5	0.5	0.25	76.2	3.32
NJ	Canton	Cumberland	5 ft	5	0.5	0.25	76.2	3.81
NJ	Delaware City	Salem	5 ft	5	0.5	0.25	76.2	3.92
NJ	Heislerville	Cape May	5 ft	5	0.5	0.25	76.2	3.99
NJ	Lakewood	Monmouth	5 ft	5	0.5	0.25	76.2	1.68
NJ	Marmora	Atlantic	5 ft	5	0.5	0.25	76.2	3.39

Table 1.3.1. Features of distinct base map data sources related to estimation of elevation uncertainty

State	Quadrangle	County	Source	Contour interval (ft)	k (base)[a]	g	RMS cm (base)	SHW (ft)[b]
NJ	Mays Landing	Atlantic	5 ft	5	0.5	0.25	76.2	3.69
NJ	Ocean City	Atlantic	5 ft	5	0.5	0.25	76.2	3.5
NJ	Oceanville	Atlantic	5 ft	5	0.5	0.25	76.2	3.46
NJ	Penns Grove	Gloucester	5 ft	5	0.5	0.25	76.2	3.42
NJ	Pleasantville	Atlantic	5 ft	5	0.5	0.25	76.2	3.62
NJ	Point Pleasant	Ocean	5 ft	5	0.5	0.25	76.2	2.01
NJ	Port Norris	Cumberland	5 ft	5	0.5	0.25	76.2	4.32
NJ	Taylors Bridge	Salem	5 ft	5	0.5	0.25	76.2	4.05
NJ	Wilmington South	Salem	5 ft	5	0.5	0.25	76.2	3.82
NJ	Woodbine	Cape May	5 ft	5	0.5	0.25	76.2	3.58
NJ	Asbury Park	Monmouth	MMTH	1 [b]	1	0.5	30.48	0 [b]
NJ	Asbury Park Oe E	Monmouth	MMTH	1 [b]	1	0.5	30.48	0 [b]
NJ	Farmingdale	Monmouth	MMTH	1 [b]	1	0.5	30.48	0 [b]
NJ	Keyport	Monmouth	MMTH	1 [b]	1	0.5	30.48	0 [b]
NJ	Lakewood	Monmouth	MMTH	1 [b]	1	0.5	30.48	0 [b]
NJ	Long Branch East	Monmouth	MMTH	1 [b]	1	0.5	30.48	0 [b]
NJ	Long Branch West	Monmouth	MMTH	1 [b]	1	0.5	30.48	0 [b]
NJ	Point Pleasant	Monmouth	MMTH	1 [b]	1	0.5	30.48	0 [b]
NJ	Sandy Hook East	Monmouth	MMTH	1 [b]	1	0.5	30.48	0 [b]
NJ	Sandy Hook West	Monmouth	MMTH	1 [b]	1	0.5	30.48	0 [b]
NJ	Atlantic City	Atlantic	SPOT	1 [b]	1	0.5	30.48	0 [b]
NJ	Avalon	Cape May	SPOT	1 [b]	1	0.5	30.48	0 [b]
NJ	Barnegat Light	Ocean	SPOT	1 [b]	1	0.5	30.48	0 [b]
NJ	Beach Haven	Ocean	SPOT	1 [b]	1	0.5	30.48	0 [b]
NJ	Brigantine Inlet	Atlantic	SPOT	1 [b]	1	0.5	30.48	0 [b]
NJ	Cape May	Cape May	SPOT	1 [b]	1	0.5	30.48	0 [b]
NJ	Forked River	Ocean	SPOT	1 [b]	1	0.5	30.48	0 [b]
NJ	Lakewood	Ocean	SPOT	1 [b]	1	0.5	30.48	0 [b]
NJ	Long Beach NE	Ocean	SPOT	1 [b]	1	0.5	30.48	0 [b]
NJ	Marmora	Cape May	SPOT	1 [b]	1	0.5	30.48	0 [b]
NJ	New Gretna	Atlantic	SPOT	1 [b]	1	0.5	30.48	0 [b]
NJ	Ocean City	Atlantic	SPOT	1 [b]	1	0.5	30.48	0 [b]
NJ	Oceanville	Atlantic	SPOT	1 [b]	1	0.5	30.48	0 [b]
NJ	Pleasantville	Atlantic	SPOT	1 [b]	1	0.5	30.48	0 [b]
NJ	Point Pleasant	Ocean	SPOT	1 [b]	1	0.5	30.48	0 [b]
NJ	Rio Grande	Cape May	SPOT	1 [b]	1	0.5	30.48	0 [b]
NJ	Sea Isle City	Cape May	SPOT	1 [b]	1	0.5	30.48	0 [b]
NJ	Sea Isle City Oe E	Cape May	SPOT	1 [b]	1	0.5	30.48	0 [b]
NJ	Seaside Park	Ocean	SPOT	1 [b]	1	0.5	30.48	0 [b]
NJ	Ship Bottom	Ocean	SPOT	1 [b]	1	0.5	30.48	0 [b]
NJ	Stone Harbor	Cape May	SPOT	1 [b]	1	0.5	30.48	0 [b]
NJ	Toms River	Ocean	SPOT	1 [b]	1	0.5	30.48	0 [b]
NJ	Tuckerton	Ocean	SPOT	1 [b]	1	0.5	30.48	0 [b]
NJ	West Creek	Ocean	SPOT	1 [b]	1	0.5	30.48	0 [b]
NJ	Wildwood	Cape May	SPOT	1 [b]	1	0.5	30.48	0 [b]
NJ	Woodbine	Cape May	SPOT	1 [b]	1	0.5	30.48	0 [b]
NJ	Beverly	Burlington	20 ft	20	0.5	0.25	304.8	4.9
NJ	Bristol	Burlington	20 ft	20	0.5	0.25	304.8	5.3
NJ	Camden	Burlington	20 ft	20	0.5	0.25	304.8	4.05
NJ	Keyport	Middlesex	20 ft	20	0.5	0.25	304.8	3.94
NJ	Orange	Bergen	20 ft	20	0.5	0.25	304.8	4.28
NJ	Perth Amboy	Middlesex	20 ft	20	0.5	0.25	304.8	4.07

Table 1.3.1. Features of distinct base map data sources related to estimation of elevation uncertainty

State	Quadrangle	County	Source	Contour interval (ft)	k (base)[a]	g	RMS cm (base)	SHW (ft)[b]
NJ	Plainfield	Middlesex	20 ft	20	0.5	0.25	304.8	4.27
NJ	Roselle	Union	20 ft	20	0.5	0.25	304.8	4.09
NJ	Trenton West	Burlington	20 ft	20	0.5	0.25	304.8	5.63
NY	Amityville	Nassau	5 ft	5	0.5	0.25	76.2	1.88
NY	Bay Shore East	Suffolk	5 ft	5	0.5	0.25	76.2	1.51
NY	Bay Shore East Oe S	Suffolk	5 ft	5	0.5	0.25	76.2	3.28
NY	Bay Shore West	Suffolk	5 ft	5	0.5	0.25	76.2	1.44
NY	Bay Shore West Oe S	Suffolk	5 ft	5	0.5	0.25	76.2	3.06
NY	Bellport	Suffolk	5 ft	5	0.5	0.25	76.2	1.39
NY	Brooklyn	Kings	5 ft	5	0.5	0.25	76.2	3.69
NY	Coney Island	Kings	5 ft	5	0.5	0.25	76.2	3.88
NY	East Hampton	Suffolk	5 ft	5	0.5	0.25	76.2	2.24
NY	Eastport	Suffolk	5 ft	5	0.5	0.25	76.2	1.69
NY	Far Rockaway	Kings	5 ft	5	0.5	0.25	76.2	3.98
NY	Freeport	Nassau	5 ft	5	0.5	0.25	76.2	2.52
NY	Gardiners Island East	Suffolk	5 ft	5	0.5	0.25	76.2	2.12
NY	Greenport	Suffolk	5 ft	5	0.5	0.25	76.2	2.46
NY	Howells Point	Suffolk	5 ft	5	0.5	0.25	76.2	2.19
NY	Jamaica	Kings	5 ft	5	0.5	0.25	76.2	4.08
NY	Lynbrook	Nassau	5 ft	5	0.5	0.25	76.2	3.5
NY	Mattituck	Suffolk	5 ft	5	0.5	0.25	76.2	2.66
NY	Mattituck Hills	Suffolk	5 ft	5	0.5	0.25	76.2	3.53
NY	Montauk Point	Suffolk	5 ft	5	0.5	0.25	76.2	2.05
NY	Montauk Point Oe E	Suffolk	5 ft	5	0.5	0.25	76.2	2.25
NY	Moriches	Suffolk	5 ft	5	0.5	0.25	76.2	1.62
NY	Napeague Beach	Suffolk	5 ft	5	0.5	0.25	76.2	2.12
NY	Orient	Suffolk	5 ft	5	0.5	0.25	76.2	2.55
NY	Patchogue	Suffolk	5 ft	5	0.5	0.25	76.2	1.96
NY	Pattersquash Island	Suffolk	5 ft	5	0.5	0.25	76.2	2.48
NY	Quogue	Suffolk	5 ft	5	0.5	0.25	76.2	2.18
NY	Sag Harbor	Suffolk	5 ft	5	0.5	0.25	76.2	2.29
NY	Sayville	Suffolk	5 ft	5	0.5	0.25	76.2	1.83
NY	Southampton	Suffolk	5 ft	5	0.5	0.25	76.2	2.35
NY	Southold	Suffolk	5 ft	5	0.5	0.25	76.2	2.77
NY	Arthur Kill	Richmond	10 ft	10	0.5	0.25	152.4	3.93
NY	Brooklyn	New York	10 ft	10	0.5	0.25	152.4	3.42
NY	Central Islip	Suffolk	10 ft	10	0.5	0.25	152.4	3.07
NY	Central Park	Bronx	10 ft	10	0.5	0.25	152.4	4.21
NY	Elizabeth	Richmond	10 ft	10	0.5	0.25	152.4	3.97
NY	Flushing	Bronx	10 ft	10	0.5	0.25	152.4	5.09
NY	Gardiners Island West	Suffolk	10 ft	10	0.5	0.25	152.4	2.34
NY	Glenville	Westchester	10 ft	10	0.5	0.25	152.4	4.34
NY	Haverstraw	Rockland	10 ft	10	0.5	0.25	152.4	2.82
NY	Jersey City	Ellis	10 ft	10	0.5	0.25	152.4	3.61
NY	Jones Inlet	Nassau	10 ft	10	0.5	0.25	152.4	2.72
NY	Keyport	Richmond	10 ft	10	0.5	0.25	152.4	3.83
NY	Lawrence	Nassau	10 ft	10	0.5	0.25	152.4	3.37
NY	Mamaroneck	Nassau	10 ft	10	0.5	0.25	152.4	5.2
NY	Middle Island	Suffolk	10 ft	10	0.5	0.25	152.4	4.12
NY	Mount Vernon	Bronx	10 ft	10	0.5	0.25	152.4	4.64
NY	Mystic	Suffolk	10 ft	10	0.5	0.25	152.4	2.23
NY	New London	Suffolk	10 ft	10	0.5	0.25	152.4	2.15

Table 1.3.1. Features of distinct base map data sources related to estimation of elevation uncertainty

State	Quadrangle	County	Source	Contour interval (ft)	k (base)[a]	g	RMS cm (base)	SHW (ft)[b]
NY	Nyack	Rockland	10 ft	10	0.5	0.25	152.4	3.02
NY	Ossining	Westchester	10 ft	10	0.5	0.25	152.4	2.87
NY	Perth Amboy	Richmond	10 ft	10	0.5	0.25	152.4	4.04
NY	Plum Island	Suffolk	10 ft	10	0.5	0.25	152.4	2.27
NY	Plum Island Oe E	Suffolk	10 ft	10	0.5	0.25	152.4	2.09
NY	Port Jefferson	Suffolk	10 ft	10	0.5	0.25	152.4	4.6
NY	Riverhead	Suffolk	10 ft	10	0.5	0.25	152.4	3.06
NY	Saint James	Suffolk	10 ft	10	0.5	0.25	152.4	4.65
NY	Sea Cliff	Nassau	10 ft	10	0.5	0.25	152.4	5.15
NY	Shinnecock Inlet	Suffolk	10 ft	10	0.5	0.25	152.4	2.42
NY	South Amboy	Richmond	10 ft	10	0.5	0.25	152.4	4
NY	The Narrows	Kings	10 ft	10	0.5	0.25	152.4	3.72
NY	Wading River	Suffolk	10 ft	10	0.5	0.25	152.4	3.47
NY	Weehawken	New York	10 ft	10	0.5	0.25	152.4	3.45
NY	West Gilgo Beach	Nassau	10 ft	10	0.5	0.25	152.4	2.15
NY	White Plains	Westchester	10 ft	10	0.5	0.25	152.4	3.04
NY	Yonkers	Bronx	10 ft	10	0.5	0.25	152.4	3.33
PA	Beverly	Bucks	20 ft	20	0.5	0.25	304.8	5.25
PA	Bristol	Bucks	20 ft	20	0.5	0.25	304.8	5.42
PA	Langhorne	Bucks	20 ft	20	0.5	0.25	304.8	5.4
PA	Trenton West	Bucks	20 ft	20	0.5	0.25	304.8	5.59
PA	Beverly	Philadelphia	2 ft	2[c]	0.5	0.25	30.48	0[c]
PA	Camden	Philadelphia	2 ft	2[c]	0.5	0.25	30.48	0[c]
PA	Frankford	Philadelphia	2 ft	2[c]	0.5	0.25	30.48	0[c]
PA	Langhorne	Philadelphia	2 ft	2[c]	0.5	0.25	30.48	0[c]
PA	Lansdowne	Philadelphia	2 ft	2[c]	0.5	0.25	30.48	0[c]
PA	Philadelphia	Philadelphia	2 ft	2[c]	0.5	0.25	30.48	0[c]
PA	Woodbury	Philadelphia	2 ft	2[c]	0.5	0.25	30.48	0[c]
PA	Bridgeport	Delaware	10 ft	10	0.5	0.25	152.4	4.02
PA	Lansdowne	Delaware	10 ft	10	0.5	0.25	152.4	4.12
PA	Marcus Hook	Delaware	10 ft	10	0.5	0.25	152.4	3.99
PA	Philadelphia	Delaware	10 ft	10	0.5	0.25	152.4	4.2
PA	Trenton East	Bucks	10 ft	10	0.5	0.25	152.4	5.65
PA	Woodbury	Delaware	10 ft	10	0.5	0.25	152.4	4.08
PA	Ficticious	Philadelphia	2 ft	2[c]	0.5	0.25	30.48	0[c]
VA	Accomac	Accomack	5 ft	5	0.5	0.25	76.2	2.2
VA	Achilles	Gloucester	5 ft	5	0.5	0.25	76.2	2.2
VA	Bethel Beach	Mathews	5 ft	5	0.5	0.25	76.2	1.51
VA	Bloxom	Accomack	5 ft	5	0.5	0.25	76.2	2.37
VA	Bowers Hill	Chesapeake	5 ft	5	0.5	0.25	76.2	2.47
VA	Boxiron	Accomack	5 ft	5	0.5	0.25	76.2	1.22
VA	Cape Charles	Northampton	5 ft	5	0.5	0.25	76.2	1.79
VA	Cape Henry	Virginia Beach	5 ft	5	0.5	0.25	76.2	1.78
VA	Cheriton	Northampton	5 ft	5	0.5	0.25	76.2	2.29
VA	Chesapeake Channel	Virginia Beach	5 ft	5	0.5	0.25	76.2	2.08
VA	Chesconessex	Accomack	5 ft	5	0.5	0.25	76.2	1.75
VA	Chincoteague East	Accomack	5 ft	5	0.5	0.25	76.2	2.09
VA	Chincoteague East Oe S	Accomack	5 ft	5	0.5	0.25	76.2	2.81
VA	Chincoteague West	Accomack	5 ft	5	0.5	0.25	76.2	1.71
VA	Cobb Island	Northampton	5 ft	5	0.5	0.25	76.2	2.84
VA	Courtland	Southampton	5 ft	5	0.5	0.25	76.2	1.7

Table 1.3.1. Features of distinct base map data sources related to estimation of elevation uncertainty

State	Quadrangle	County	Source	Contour interval (ft)	k (base)[a]	g	RMS cm (base)	SHW (ft)[b]
VA	Creeds	Chesapeake	5 ft	5	0.5	0.25	76.2	0.88
VA	Crisfield	Accomack	5 ft	5	0.5	0.25	76.2	1.82
VA	Deep Creek	Chesapeake	5 ft	5	0.5	0.25	76.2	2.16
VA	Deltaville	Lancaster	5 ft	5	0.5	0.25	76.2	1.38
VA	Elliotts Creek	Northampton	5 ft	5	0.5	0.25	76.2	1.93
VA	Ewell	Accomack	5 ft	5	0.5	0.25	76.2	1.56
VA	Exmore	Accomack	5 ft	5	0.5	0.25	76.2	2.02
VA	Fentress	Chesapeake	5 ft	5	0.5	0.25	76.2	1.15
VA	Fishermans Island	Northampton	5 ft	5	0.5	0.25	76.2	2.37
VA	Franklin	Franklin City	5 ft	5	0.5	0.25	76.2	1.7
VA	Franktown	Northampton	5 ft	5	0.5	0.25	76.2	1.73
VA	Gates	Suffolk City	5 ft	5	0.5	0.25	76.2	1.7
VA	Girdletree	Accomack	5 ft	5	0.5	0.25	76.2	1.31
VA	Great Machipongo Inlet	Northampton	5 ft	5	0.5	0.25	76.2	2.85
VA	Hallwood	Accomack	5 ft	5	0.5	0.25	76.2	2.12
VA	Hampton	Hampton City	5 ft	5	0.5	0.25	76.2	2.17
VA	Holland	Isle of Wight	5 ft	5	0.5	0.25	76.2	15
VA	Jamesville	Accomack	5 ft	5	0.5	0.25	76.2	1.55
VA	Kempsville	Chesapeake	5 ft	5	0.5	0.25	76.2	2.21
VA	Knotts Island	Virginia Beach	5 ft	5	0.5	0.25	76.2	0.94
VA	Knotts Island Oe E	Virginia Beach	5 ft	5	0.5	0.25	76.2	2.58
VA	Lake Drummond SE	Chesapeake	5 ft	5	0.5	0.25	76.2	1.04
VA	Little Creek	Norfolk City	5 ft	5	0.5	0.25	76.2	2.13
VA	Mathews	Mathews	5 ft	5	0.5	0.25	76.2	1.83
VA	Metompkin Inlet	Accomack	5 ft	5	0.5	0.25	76.2	2.72
VA	Moyock	Chesapeake	5 ft	5	0.5	0.25	76.2	0.9
VA	Mulberry Island	Isle of Wight	5 ft	5	0.5	0.25	76.2	2.37
VA	Nandua Creek	Accomack	5 ft	5	0.5	0.25	76.2	1.57
VA	Nassawadox	Accomack	5 ft	5	0.5	0.25	76.2	3.1
VA	New Point Comfort	Mathews	5 ft	5	0.5	0.25	76.2	2.08
VA	Newport News North	Hampton City	5 ft	5	0.5	0.25	76.2	2.29
VA	Newport News South	Hampton City	5 ft	5	0.5	0.25	76.2	2.27
VA	Norfolk North	Hampton City	5 ft	5	0.5	0.25	76.2	2.22
VA	Norfolk South	Chesapeake	5 ft	5	0.5	0.25	76.2	2.39
VA	North Bay	Virginia Beach	5 ft	5	0.5	0.25	76.2	1.54
VA	North Virginia Beach	Virginia Beach	5 ft	5	0.5	0.25	76.2	2.24
VA	Parksley	Accomack	5 ft	5	0.5	0.25	76.2	2.01
VA	Pleasant Ridge	Chesapeake	5 ft	5	0.5	0.25	76.2	0.88
VA	Pocomoke City	Accomack	5 ft	5	0.5	0.25	76.2	5
VA	Poquoson East	Poquoson City	5 ft	5	0.5	0.25	76.2	2.13
VA	Poquoson West	Gloucester	5 ft	5	0.5	0.25	76.2	2.14
VA	Princess Anne	Virginia Beach	5 ft	5	0.5	0.25	76.2	1.31
VA	Pungoteague	Accomack	5 ft	5	0.5	0.25	76.2	1.63
VA	Quinby Inlet	Accomack	5 ft	5	0.5	0.25	76.2	2.91
VA	Riverdale	Southampton	5 ft	5	0.5	0.25	76.2	1.7
VA	Saxis	Accomack	5 ft	5	0.5	0.25	76.2	2.05
VA	Ship Shoal Inlet	Northampton	5 ft	5	0.5	0.25	76.2	2.74
VA	Tangier Island	Accomack	5 ft	5	0.5	0.25	76.2	1.62
VA	Townsend	Northampton	5 ft	5	0.5	0.25	76.2	2.42
VA	Virginia Beach	Virginia Beach	5 ft	5	0.5	0.25	76.2	2.07
VA	Wachapreague	Accomack	5 ft	5	0.5	0.25	76.2	2.79
VA	Wachapreague Oe E	Accomack	5 ft	5	0.5	0.25	76.2	2.83

Table 1.3.1. Features of distinct base map data sources related to estimation of elevation uncertainty

State	Quadrangle	County	Source	Contour interval (ft)	k (base)[a]	g	RMS cm (base)	SHW (ft)[b]
VA	Wallops Island	Accomack	5 ft	5	0.5	0.25	76.2	2.78
VA	Ware Neck	Gloucester	5 ft	5	0.5	0.25	76.2	2.18
VA	Whittington Point	Accomack	5 ft	5	0.5	0.25	76.2	2.79
VA	Yorktown	Gloucester	5 ft	5	0.5	0.25	76.2	2.2
VA	Alexandria	Alexandria	10 ft	10	0.5	0.25	152.4	2.63
VA	Aylett	King and Queen	10 ft	10	0.5	0.25	152.4	3.32
VA	Bacons Castle	Isle of Wight	10 ft	10	0.5	0.25	152.4	2.25
VA	Benns Church	Isle of Wight	10 ft	10	0.5	0.25	152.4	2.47
VA	Boykins	Southampton	10 ft	10	0.5	0.25	152.4	1.7
VA	Brandon	Charles City	10 ft	10	0.5	0.25	152.4	2.12
VA	Buckhorn	Suffolk City	10 ft	10	0.5	0.25	152.4	20
VA	Burgess	Northumberland	10 ft	10	0.5	0.25	152.4	1.39
VA	Capron	Southampton	10 ft	10	0.5	0.25	152.4	1.7
VA	Champlain	Essex	10 ft	10	0.5	0.25	152.4	1.84
VA	Charles City	Charles City	10 ft	10	0.5	0.25	152.4	2.38
VA	Chuckatuck	Isle of Wight	10 ft	10	0.5	0.25	152.4	10
VA	Church View	King and Queen	10 ft	10	0.5	0.25	152.4	20
VA	Claremont	Charles City	10 ft	10	0.5	0.25	152.4	1.98
VA	Clay Bank	Gloucester	10 ft	10	0.5	0.25	152.4	2.34
VA	Colonial Beach North	Westmoreland	10 ft	10	0.5	0.25	152.4	1.89
VA	Colonial Beach South	Westmoreland	10 ft	10	0.5	0.25	152.4	1.87
VA	Corapeake	Suffolk City	10 ft	10	0.5	0.25	152.4	20
VA	Dahlgren	King George	10 ft	10	0.5	0.25	152.4	1.78
VA	Disputanta North	Prince George	10 ft	10	0.5	0.25	152.4	2.48
VA	Drewrys Bluff	Chesterfield	10 ft	10	0.5	0.25	152.4	10
VA	Dunnsville	Essex	10 ft	10	0.5	0.25	152.4	1.84
VA	Dutch Gap	Charles City	10 ft	10	0.5	0.25	152.4	2.87
VA	East of Reedville	Northumberland	10 ft	10	0.5	0.25	152.4	1.33
VA	Fleets Bay	Lancaster	10 ft	10	0.5	0.25	152.4	1.4
VA	Fort Belvoir	Fairfax	10 ft	10	0.5	0.25	152.4	2.25
VA	Fredericksburg	Fredericksburg	10 ft	10	0.5	0.25	152.4	2.84
VA	Gloucester	Gloucester	10 ft	10	0.5	0.25	152.4	2.38
VA	Gressitt	Gloucester	10 ft	10	0.5	0.25	152.4	2.46
VA	Guinea	Spotsylvania	10 ft	10	0.5	0.25	152.4	2.73
VA	Haynesville	Richmond	10 ft	10	0.5	0.25	152.4	1.82
VA	Heathsville	Northumberland	10 ft	10	0.5	0.25	152.4	1.45
VA	Hog Island	Isle of Wight	10 ft	10	0.5	0.25	152.4	2.19
VA	Hopewell	Charles City	10 ft	10	0.5	0.25	152.4	2.72
VA	Indian Head	Fairfax	10 ft	10	0.5	0.25	152.4	1.91
VA	Irvington	Lancaster	10 ft	10	0.5	0.25	152.4	1.5
VA	King and Queen Court House	King and Queen	10 ft	10	0.5	0.25	152.4	2.98
VA	King George	King George	10 ft	10	0.5	0.25	152.4	1.74
VA	King William	Hanover	10 ft	10	0.5	0.25	152.4	10
VA	Kinsale	Northumberland	10 ft	10	0.5	0.25	152.4	1.5
VA	Lake Drummond	Chesapeake	10 ft	10	0.5	0.25	152.4	10
VA	Lake Drummond NW	Chesapeake	10 ft	10	0.5	0.25	152.4	10
VA	Lancaster	Lancaster	10 ft	10	0.5	0.25	152.4	1.59
VA	Lively	Lancaster	10 ft	10	0.5	0.25	152.4	1.65
VA	Loretto	Caroline	10 ft	10	0.5	0.25	152.4	1.97
VA	Lottsburg	Northumberland	10 ft	10	0.5	0.25	152.4	1.49
VA	Machodoc	Westmoreland	10 ft	10	0.5	0.25	152.4	1.61

Table 1.3.1. Features of distinct base map data sources related to estimation of elevation uncertainty

State	Quadrangle	County	Source	Contour interval (ft)	k (base)[a]	g	RMS cm (base)	SHW (ft)[b]
VA	Mathias Point	King George	10 ft	10	0.5	0.25	152.4	1.7
VA	Millers Tavern	Essex	10 ft	10	0.5	0.25	152.4	1.9
VA	Montross	Richmond	10 ft	10	0.5	0.25	152.4	1.79
VA	Morattico	Essex	10 ft	10	0.5	0.25	152.4	1.77
VA	Mount Landing	Essex	10 ft	10	0.5	0.25	152.4	1.83
VA	Mount Vernon	Fairfax	10 ft	10	0.5	0.25	152.4	2.42
VA	New Kent	King William	10 ft	10	0.5	0.25	152.4	2.55
VA	Norge	James City	10 ft	10	0.5	0.25	152.4	2.04
VA	Occoquan	Fairfax	10 ft	10	0.5	0.25	152.4	2.34
VA	Passapatanzy	Caroline	10 ft	10	0.5	0.25	152.4	2.6
VA	Piney Point	Westmoreland	10 ft	10	0.5	0.25	152.4	1.76
VA	Port Royal	Caroline	10 ft	10	0.5	0.25	152.4	2.23
VA	Prince George	Petersburg	10 ft	10	0.5	0.25	152.4	10
VA	Providence Forge	Charles City	10 ft	10	0.5	0.25	152.4	2.56
VA	Quantico	Prince William	10 ft	10	0.5	0.25	152.4	1.87
VA	Rappahannock Academy	Caroline	10 ft	10	0.5	0.25	152.4	2.56
VA	Raynor	Isle of Wight	10 ft	10	0.5	0.25	152.4	10
VA	Reedville	Northumberland	10 ft	10	0.5	0.25	152.4	1.33
VA	Rollins Fork	Caroline	10 ft	10	0.5	0.25	152.4	2.1
VA	Roxbury	Charles City	10 ft	10	0.5	0.25	152.4	2.68
VA	Runnymede	Surry	10 ft	10	0.5	0.25	152.4	20
VA	Saint Clements Island	Westmoreland	10 ft	10	0.5	0.25	152.4	1.81
VA	Saint George Island	Northumberland	10 ft	10	0.5	0.25	152.4	1.52
VA	Saluda	Gloucester	10 ft	10	0.5	0.25	152.4	1.7
VA	Savedge	Prince George	10 ft	10	0.5	0.25	152.4	2.23
VA	Sebrell	Southampton	10 ft	10	0.5	0.25	152.4	1.7
VA	Sedley	Isle of Wight	10 ft	10	0.5	0.25	152.4	1.7
VA	Shacklefords	Gloucester	10 ft	10	0.5	0.25	152.4	2.14
VA	Smith Point	Northumberland	10 ft	10	0.5	0.25	152.4	1.34
VA	Smithfield	Isle of Wight	10 ft	10	0.5	0.25	152.4	2.52
VA	Stafford	Stafford	10 ft	10	0.5	0.25	152.4	1.93
VA	Stratford Hall	Westmoreland	10 ft	10	0.5	0.25	152.4	1.84
VA	Suffolk	Suffolk City	10 ft	10	0.5	0.25	152.4	2.99
VA	Sunbeam	Southampton	10 ft	10	0.5	0.25	152.4	1.7
VA	Supply	Caroline	10 ft	10	0.5	0.25	152.4	10
VA	Surry	James City	10 ft	10	0.5	0.25	152.4	1.9
VA	Tappahannock	Essex	10 ft	10	0.5	0.25	152.4	1.82
VA	Toano	James City	10 ft	10	0.5	0.25	152.4	2.42
VA	Truhart	King and Queen	10 ft	10	0.5	0.25	152.4	2.31
VA	Tunstall	King William	10 ft	10	0.5	0.25	152.4	2.76
VA	Urbanna	Lancaster	10 ft	10	0.5	0.25	152.4	1.55
VA	Vicksville	Southampton	10 ft	10	0.5	0.25	152.4	10
VA	Walkers	Charles City	10 ft	10	0.5	0.25	152.4	2.43
VA	Washington West	Arlington	10 ft	10	0.5	0.25	152.4	2.64
VA	West Point	King and Queen	10 ft	10	0.5	0.25	152.4	2.57
VA	Westover	Charles City	10 ft	10	0.5	0.25	152.4	2.59
VA	Whaleyville	Suffolk City	10 ft	10	0.5	0.25	152.4	20
VA	Widewater	Stafford	10 ft	10	0.5	0.25	152.4	1.79
VA	Williamsburg	Gloucester	10 ft	10	0.5	0.25	152.4	2.46
VA	Wilton	Gloucester	10 ft	10	0.5	0.25	152.4	1.48
VA	Windsor	Isle of Wight	10 ft	10	0.5	0.25	152.4	20

Table 1.3.1. Features of distinct base map data sources related to estimation of elevation uncertainty

State	Quadrangle	County	Source	Contour interval (ft)	k (base)[a]	g	RMS cm (base)	SHW (ft)[b]
VA	Zuni	Isle of Wight	10 ft	10	0.5	0.25	152.4	1.76

a. The values of k listed here are the "base" value of k that relates contour interval to RMS as RMS = k(base) H contour interval. The procedures for conducting uncertainty analyses allow for universal rescaling of k. These values were scaled by a factor of 0.5 in the analysis; i.e., we assume that error = 0.25 times the contour interval in most quads.

b. For these locations, the values of 1 for contour interval and 0 for SHW were provided to trick the algorithm into calculating "contour error" as RMSE/2. This was necessary because of the format in which Jones and Wang had saved the central estimate results for those areas with high precision data. The value of g doe not matter because g had no effect above the contour interval, which is less than the 50 cm increment with which our results are reported.

c. For these locations, the values of 2 for contour interval and 0 for SHW were provided to trick the algorithm into calculating "contour error" as RMSE/2. This was necessary because of the format in which Jones and Wang had saved the central estimate results for those areas with high precision data.

Section 1.3.3. Results

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The results from this section are displayed in Appendices A, B, and C (along with regional summaries). *What we call "low" and "high"(elevation) as we explain our approach in this section are reversed in the tables, because the high elevation means less vulnerability and a lower area close to sea level, and vice versa.*

We encourage the reader to examine these tables and think about both the ratio of the high to the low estimate and the vertical error implied by a given line in the table. If the high estimate at 50 cm is greater than the low estimate for 100 cm, then the vertical error is greater than 25 cm. If the high estimate at 50 cm is greater than the low estimate for 150 cm, then the vertical error is greater than 50 cm.

If the ratio of high to low at 50 cm is great, that may mean that the uncertainty is great; but it may also mean that there is an inflection point nearby. For example, if the data (e.g., LIDAR) show several times as much land between 50 and 65 cm as between 0 and 50 cm, then even if the error is only 15 cm, the ratio of high to low could be very large.[19] This happens in some areas with LIDAR. As a result, if one considers only the ratio of high to low, one might be surprised that the areas with LIDAR do not always seem much more precise than the areas that relied on USGS 5-ft contours. (A second reason that the LIDAR does not always appear more precise than areas with 5-ft contours is that the first contour interval is only 2–3 feet in areas where spring high water is 2–3 feet above NGVD29. Although the subsequent contour intervals are greater, the ratios of high to low get closer to 1 as elevations increase.) Nevertheless, variations in precision are palpable when one looks at areas with a 10- or 20-ft contour interval. See the Pennsylvania tables in Appendix A, where Bucks County has mostly 20-ft contours but Philadelphia has 2-ft contours.

Overall, we estimate between 8,792 and 10,882 square kilometers of land within 50 cm above the tides, and 11,032 to 12,985 square kilometers within 1 meter above the tides in the middle Atlantic (see Appendix C). Our input data and assumptions are based on RMS error; but at the state and regionwide level, much of the errors should cancel. The true amount of land close to sea level is very likely to fall within the ranges we have estimated.

One final warning: The available output provided by Jones and Wang (explained in Section 1.2), which this effort used as input, extended only to an elevation of 20 feet above SHW. Therefore, we cannot literally apply our formula for the high-elevation (low-area) case for elevations above 20 feet minus "error." In cases with a 20-ft contour interval, error is 5 feet; so we cannot apply the low-area formula above 15 feet. The algorithm explained in Section 1.3.2 treats no data as zero, assuming in effect that there is no land above 20-ft SHW. We considered suppressing all calculations above 4.5 meters in such cases, but opted instead to provide the results with an asterisk. That approach seems more reasonable: In these cases, assuming that there is no land above 20-ft SHW is clearly an extreme lower bound. But we doubt that it seriously distorts the statewide results. Typically, a state has only a few quads with a 20-ft contour interval—generally in areas that have very little low land. So even if we had been able to correctly apply our formula (i.e., if Jones and Wang in Section 1.2 had interpolated above 20-ft SHW) the calculated area would not be much

[19] For example, if the LIDAR shows 10 ha between 0 and 50, and 100 ha between 50 and 65, if error is 15 cm, the high estimate would be 110 ha, and the low estimate would be less than 10. The ratio of high to low would this be more than 11.

greater than zero when considered at the statewide level. Thus, instead of suppressing our "low area" estimate, we provide an estimate that is slightly lower than a rigorous application of our approach.

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Appendix A

Low and High Estimates of the Area of Land Close to Sea Level, by State[a]
(square kilometers)

[a]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. For a discussion of these calculations, see Section 1.3 of this report.

Table A.1 Low and High Estimates of the Area of Land Close to Sea Level in New York

County	Tidal	Meters above Spring High Water																			
		low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high
		0.5		1.0		1.5		2.0		2.5		3.0		3.5		4.0		4.5		5.0	
		----------------Cumulative (total) amount of Dry Land below a given elevation---------------																			
Bronx		0.4	3.2	2.2	6.3	4.1	9.4	5.9	13	8.1	16	11	19	14	22	17	25	19	26	22	27
Brooklyn		3.1	10	8.5	17	14	24	20	34	28	43	37	52	46	57	53	63	59	68	64	69
Manhattan		0.03	2.2	1.4	4.3	2.8	6.4	4.2	8.3	5.5	10	7.2	12	8.9	14	11	16	12	17	14	17
Nassau		2.2	19	13	44	31	70	51	85	71	95	85	104	94	113	103	121	111	128*	119	132*
Queens		6.2	17	15	28	23	39	32	49	41	58	51	67	60	72	66	77	71	80	77	81
Staten Island		0.3	7.8	5.1	15	10	22	15	25	20	28	23	31	26	34	29	37	31	38	34	39
Suffolk[2]		14	51	43	97	78	140	115	181	152	217	189	251	222	286	256	316	289	345*	319	371*
Westchester		0.2	2.9	1.7	5.7	3.4	8.4	5.2	11	7.1	13	9.2	15	11	17	13	19	15	20*	16	21*
Ellis & Liberty Islands		<0.01	0.05	0.03	0.1	0.06	0.14	0.09	0.14	0.13	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Statewide		**26**	**114**	**90**	**218**	**166**	**320**	**248**	**405**	**333**	**479**	**412**	**551**	**482**	**615**	**548**	**672**	**608**	**722***	**665**	**757***
Wetlands	Tidal	---------Cumulative (total) amount of Nontidal Wetlands below a given elevation---------																			
Bronx	1.2	0.00	0.01	0.01	0.02	0.01	0.03	0.02	0.06	0.03	0.09	0.04	0.11	0.07	0.14	0.1	0.2	0.1	0.2	0.1	0.2
Brooklyn	10	0.03	0.08	0.07	0.11	0.09	0.14	0.12	0.15	0.14	0.16	0.15	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Nassau	44	0.1	0.4	0.3	0.7	0.5	1.2	0.8	1.5	1.1	1.8	1.4	2.1	1.7	2.3	2.0	2.6	2.2	2.9*	2.6	3.2*
Putnam	1.3	0	<0.01	0.00	<0.01	<0.01	0.01	<0.01	0.01	<0.01	0.01	<0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.02*	0.01	0.02*
Queens	12	0.0	0.2	0.1	0.3	0.2	0.4	0.4	0.5	0.4	0.6	0.5	0.6	0.6	0.7	0.6	0.7	0.6	0.7	0.67	0.69
Rockland	2.3	0.0	0.02	0.01	0.04	0.02	0.06	0.03	0.07	0.05	0.08	0.06	0.09	0.07	0.09	0.07	0.10	0.08	0.11*	0.1	0.2*
Staten Island	4.0	0.01	0.5	0.3	0.9	0.6	1.3	0.9	1.4	1.2	1.5	1.3	1.6	1.4	1.7	1.5	1.8	1.6	1.9	1.7	1.9
Suffolk	72	1.5	5.7	4.9	9.8	8.5	13	11	15	13	17	15	18	17	20	18	21	19	23*	21	24*
Westchester	1.7	<0.01	0.04	0.03	0.08	0.05	0.12	0.08	0.13	0.10	0.14	0.1	0.2	0.1	0.2	0.1	0.2	0.15	0.21*	0.16	0.23*
Statewide	**149**	**1.7**	**6.9**	**5.7**	**12**	**10**	**16**	**13**	**19**	**16**	**21**	**19**	**23**	**21**	**25**	**23**	**27**	**25**	**29***	**26**	**30***
		Cumulative (total) amount of land below a given elevation[3]																			
Dry Land		26	114	90	218	166	320	248	405	333	479	412	551	482	615	548	672	608	722*	665	757*
Nontidal Wetlands		2	7	6	12	10	16	13	19	16	21	19	23	21	25	23	27	25	29*	26	30*
All Land	**149**	**176**	**269**	**244**	**379**	**325**	**485**	**410**	**573**	**498**	**649**	**579**	**722**	**652**	**788**	**719**	**848**	**781**	**899***	**840**	**936***

*This value is probably too low because of a data limitation. See Section 1.3 of this report.

Note: A peer reviewer noticed that the draft maps showed Gardiners Island as "likely" even though the text said that it had been changed to "unlikely". The effect of that error was to overstate the area of land below one meter where shore protection is likely, and understate the area where shore protection is unlikely, by 0.7, 0.9, and 1.1 square miles for the land within 50, 100, and 200 cm above spring high water. We corrected the maps, but not the quantitative results in this report.

Table A.2 Low and High Estimates of the Area of Land Close to Sea Level in New Jersey

	Meters above Spring High Water																			
	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high
	0.5		1.0		1.5		2.0		2.5		3.0		3.5		4.0		4.5		5.0	
County	**----------------Cumulative (total) amount of dry land below a given elevation---------------**																			
Atlantic	4	13	14	29	29	42	41	54	50	63	57	71	65	79	73	88	81	96	88	106
Bergen	0.9	16	10	31	20	42	29	44	39	47	43	49	45	51	47	54	49	56*	51	58*
Burlington	0.1	6.3	1.7	12	5.1	18	9.3	25	13	33	18	40	24	47	29	55	35	63*	41	69*
Camden	<0.01	3.8	0.1	7.3	1.7	11	4.3	15	6.9	19	9.5	22	12	26	15	29	18	32*	20	35*
Cape May	8	25	26	50	48	69	65	93	80	117	99	139	120	161	141	182	161	199	180	212
Cumberland	3	16	12	29	21	41	30	53	39	65	50	77	61	88	71	98	81	107	91	114
Essex	0.4	6.1	3.9	12	7.6	17	11	20	15	23	18	25	20	28	23	31	25	32*	28	32*
Gloucester	0.2	9.2	6.1	18	12	27	18	33	23	40	30	47	36	53	42	60	48	65	54	69
Hudson	0.6	16	10	32	21	45	31	49	41	53	46	57	50	61	53	65	57	66*	60	67*
Mercer	0	0.1	0	0.1	0.03	0.19	0.1	0.2	0.1	0.3	0.2	0.4	0.2	0.4	0.2	0.4	0.3	0.4*	0.3	0.4*
Middlesex	0.4	8.8	4.3	17	9.2	25	15	31	20	37	25	44	30	50	36	55	41	59*	46	62*
Monmouth	4.1	10	11	20	21	30	31	39	40	47	49	57	58	65	66	73	74	80	82	87
Ocean	4.6	19	22	44	47	66	67	81	81	94	93	107	105	119	117	129	127	139	137	149
Passaic	0	0.2	0.1	0.3	0.2	0.5	0.3	0.7	0.4	0.9	0.6	1.1	0.7	1.3	0.9	1.5	1.1	1.7*	1.3	1.9*
Salem	5.9	27	21	49	38	70	54	84	69	99	84	114	98	127	111	139	123	151	135	160
Somerset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0.1*	0	0.2*
Union	0.4	6.9	4.2	14	8.4	19	13	23	17	26	20	29	23	33	26	36	29	39*	32	41*
Statewide	**32**	**184**	**148**	**365**	**289**	**522**	**418**	**645**	**536**	**764**	**642**	**878**	**748**	**989**	**850**	**1096**	**949**	**1185***	**1046**	**1265***

*This value is probably too low because of a data limitation. See Section 1.3 of this report.

Table A.2 Low and High Estimates of the Area of Land Close to Sea Level in New Jersey (continued)

		low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high
		0.5		1.0		1.5		2.0		2.5		3.0		3.5		4.0		4.5		5.0	
Wetlands	Tidal	---------Cumulative (total) amount of Nontidal Wetlands below a given elevation---------																			
Atlantic	204	4.8	18	15	29	23	41	32	50	40	59	48	68	57	77	65	86	74	94	82	103
Bergen	15	0.04	0.6	0.4	1.2	0.8	1.5	1.1	1.5	1.48	1.54	1.52	1.55	1.5	1.6	1.5	1.6	1.5	1.8*	1.6	2.1*
Burlington	43	0.2	10	6.2	20	13	30	19	35	26	40	32	45	36	50	40	54	45	59*	49	63*
Camden	2	<0.01	0.3	0.1	0.7	0.3	1	0.5	1.3	0.7	1.6	0.9	1.9	1.2	2.2	1.4	2.4	1.6	2.5*	1.8	2.7*
Cape May	201	7.2	27	22	45	37	63	50	73	63	84	74	94	83	102	92	109	99	115	106	119
Cumberland	213	4.7	24	18	42	31	58	44	65	55	73	63	81	71	87	77	94	84	99	90	103
Essex	0	<0.01	0.03	0.02	0.05	0.04	0.07	0.05	0.07	0.07	0.07	0.07	0.08	0.07	0.08	0.07	0.08	<0.08	0.08*	<0.08	0.08*
Gloucester	18	0.2	8.8	5.9	17	11	24	17	26	22	27	25	29	26	30	28	32	29	33	30	34
Hudson	12	0.01	0.2	0.1	0.3	0.19	0.42	0.3	0.4	0.38	0.45	0.4	0.5	0.4	0.5	0.4	0.5	0.46	0.49*	0.47	0.49*
Mercer	2	0	<0.01	0	0.01	<0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.03	0.01	0.03	0.02	0.03	0.02	0.03*	0.02	0.03*
Middlesex	22	0.1	1.2	0.7	2.3	1.4	3.3	2.1	3.9	2.9	4.6	3.5	5.3	4	5.9	4.6	6.5	5.1	7.2*	5.7	7.8*
Monmouth	12	0.6	1.3	1.4	2	2.1	2.6	2.7	3.3	3.4	3.9	4	4.5	4.5	5	5.1	5.7	5.8	6.3	6.4	6.9
Ocean	125	2.3	12	10	22	19	31	26	38	33	44	39	49	44	54	48	58	53	63	56	66
Passaic	0	<0.01	0.02	0.01	0.03	0.02	0.04	0.03	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.05*	0.04	0.05*
Salem	110	9.6	25	22	36	30	46	38	49	45	52	49	55	52	58	55	61	58	64	60	68
Somerset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.01	0	0.03*	0	0.04*
Union	2	0.01	0.2	0.1	0.3	0.2	0.4	0.3	0.5	0.4	0.6	0.4	0.6	0.5	0.7	0.5	0.7	0.6	0.8*	0.6	0.8*
Statewide	**980**	**30**	**128**	**102**	**219**	**169**	**301**	**233**	**348**	**293**	**393**	**341**	**436**	**381**	**474**	**420**	**513**	**455**	**546***	**491**	**576***
		Cumulative (total) amount of land below a given elevation																			
Dry Land		32	184	148	365	289	522	418	645	536	764	642	878	748	989	850	1096	949	1185*	1046	1265*
Nontidal Wetlands		30	128	102	219	169	301	233	348	293	393	341	436	381	474	420	513	455	546*	491	576*
All Land	980	1043	1292	1231	1564	1438	1803	1632	1974	1810	2137	1964	2294	2109	2443	2250	2589	2385	2712*	2517	2822*

*This value is probably too low because of a data limitation. See Section 1.3 of this report.

Table A.3 Low and High Estimates of the Area of Land Close to Sea Level in Pennsylvania

		Meters above Spring High Water																			
		low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high
County		**0.5**		**1.0**		**1.5**		**2.0**		**2.5**		**3.0**		**3.5**		**4.0**		**4.5**		**5.0**	
		----------------Cumulative (total) amount of Dry Land below a given elevation---------------																			
Bucks		0.04	4.4	0.2	8.5	2.5	13	5.3	18	9	23	12	27	15	32	19	36	22	39*	25	42*
Delaware		0.4	6.1	4	12	7.9	17	12	18	15	19	17	21	18	22	20	24	21	25	22	26
Philadelphia		3.6	6.1	6.8	12	13	19	20	25	26	31	32	37	37	42	42	46	47	51	51	55
Statewide		**4**	**17**	**11**	**33**	**24**	**49**	**37**	**61**	**50**	**73**	**61**	**85**	**71**	**96**	**81**	**106**	**90**	**115***	**99**	**123***
Wetlands	Tidal	---------Cumulative (total) amount of Nontidal Wetlands below a given elevation---------																			
Bucks	1.9	0.04	0.9	0.1	1.9	0.6	3	1.2	4.1	2	5.2	2.9	6.3	3.7	7.2	4.5	7.6	5.4	7.9*	6.2	8.2*
Delaware	3.6	0.1	0.8	0.6	1.7	1.1	2.2	1.6	2.2	2.1	2.2	2.2	2.3	2.2	2.3	2.2	2.3	2.25	2.27	2.26	2.28
Philadelphia	0.6	0.5	0.6	0.6	0.9	0.9	1.2	1.2	1.4	1.5	1.61	1.62	1.69	1.71	1.78	1.79	1.84	1.85	1.89	1.89	1.93
Statewide	**6.1**	**0.6**	**2.4**	**1.3**	**4.5**	**2.7**	**6.4**	**4.1**	**7.7**	**5.6**	**9.1**	**6.7**	**10**	**7.7**	**11**	**8.6**	**12**	**9.5**	**12***	**10**	**12***
		Cumulative (total) amount of land below a given elevation																			
Dry Land		4	17	11	33	24	49	37	61	50	73	61	85	71	96	81	106	90	115*	99	123*
Nontidal Wetlands		1	2	1	4	3	6	4	8	6	9	7	10	8	11	9	12	9	12*	10	12*
All Land	6	11	25	18	44	32	61	47	75	62	88	74	101	85	113	95	124	106	133*	115	141*

*This value is probably too low because of a data limitation. See Section 1.3 of this report

Table A.4 Low and High Estimates of the Area of Land Close to Sea Level in Delaware

		Meters above Spring High Water																			
		low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high
County		0.5		1.0		1.5		2.0		2.5		3.0		3.5		4.0		4.5		5.0	
		----------------Cumulative (total) amount of Dry Land below a given elevation---------------																			
Kent		8.8	25	22	41	35	57	48	78	66	98	86	119	107	144	129	168	154	191	178	210
New Castle		7.1	19	17	30	26	41	34	52	44	64	54	75	65	87	77	98	88	110	99	119
Sussex: Chesapeake Bay		0.5	1.6	1.4	3.3	2.7	5.2	4.3	7.1	6	11	8.5	14	12	18	15	24	20	29	26	36
Sussex: Delaware Bay		6.4	18	16	31	27	43	37	55	48	67	60	79	72	89	83	99	93	109	103	120
Sussex: Atlantic Coast		11	32	28	54	46	74	65	95	83	117	104	140	126	163	149	187	173	211	197	234
Statewide		**34**	**96**	**84**	**158**	**136**	**221**	**188**	**287**	**246**	**356**	**313**	**426**	**382**	**499**	**453**	**575**	**527**	**647**	**603**	**719**
Wetlands	Tidal	---------Cumulative (total) amount of Nontidal Wetlands below a given elevation---------																			
Kent	169	4.9	11	10	17	15	22	19	25	23	28	26	31	29	34	32	37	36	41	39	44
New Castle	74	1.8	3.8	3.5	4.8	4.3	5.8	5.1	6.7	5.8	7.6	6.7	8.4	7.5	9.2	8.3	9.9	9	11	9.7	11
Sussex: Chesapeake Bay	6.7	0.6	1.8	1.6	2.7	2.4	3.5	3.1	4.4	3.8	5.4	4.8	6.4	5.8	7.7	6.9	9.4	8.4	11	10	13
Sussex: Delaware Bay	67	2.1	4.8	4.6	6.2	5.7	7.5	6.8	8.6	8	9.6	9	11	10	11	11	12	12	13	12	13
Sussex: Atlantic Coast	41	1.7	4.9	4.2	7.5	6.6	10	8.8	12	11	14	13	16	15	17	16	18	18	20	19	21
Statewide	**357**	**11**	**27**	**24**	**38**	**34**	**48**	**43**	**56**	**52**	**64**	**59**	**72**	**67**	**80**	**75**	**87**	**82**	**95**	**90**	**102**
		Cumulative (total) amount of land below a given elevation																			
Dry Land		34	96	84	158	136	221	188	287	246	356	313	426	382	499	453	575	527	650	603	719
Nontidal Wetlands		11	27	24	38	34	48	43	56	51	64	59	72	67	80	75	87	82	95	90	102
All Land	357	402	480	465	553	527	626	588	701	655	778	730	855	806	936	885	1019	967	1102	1050	1178

Table A.5 Low and High Estimates of the Area of Land Close to Sea Level in Maryland

	Meters above Spring High Water																			
	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high
County	0.5		1.0		1.5		2.0		2.5		3.0		3.5		4.0		4.5		5.0	
	----------------Cumulative (total) amount of Dry Land below a given elevation---------------																			
Anne Arundel	1.7	7.2	6.7	15	12	26	20	39	32	50	44	59	54	68	63	77	72	86	81	94
Baltimore County	2.3	6.6	7.3	13	14	20	21	27	28	36	37	46	47	56	57	65	66	73	75	81
Baltimore City	0.2	2.1	0.9	3.9	1.7	5.7	2.7	7.5	4.2	9.7	5.7	12	7.4	14	9.6	17	12	19	14	21
Calvert	0.4	3.9	1.7	5.8	3.1	7.6	4.6	10	6.1	14	7.6	17	10.0	21	14	26	17	31	21	36
Caroline	0.7	3.2	2.2	6.1	4.1	9.2	6.9	13	9.9	16	13	20	16	23	19	27	23	30*	26	33*
Cecil	0.2	2.5	1.0	5.2	1.8	7.9	3.7	12	5.7	16	7.8	20	11	25	16	29	20	34	24	38
Charles	0.7	12	4.8	21	9.0	30	15	40	22	53	30	67	40	77	53	85	66	93	77	99
Dorchester	30	120	150	215	231	269	282	313	322	348	358	386	396	416	423	439	445	457	462	474
Harford	0.7	17	7.6	25	15	33	22	40	28	49	34	57	42	64	50	69	59	74	65	78
Howard	0	0.01	0.01	0.03	0.01	0.05	0.02	0.07	0.04	0.1	0.05	0.14	0.07	0.2	0.1	0.2	0.1	0.3	0.2	0.3
Kent	0.2	8.4	4.8	16	10	23	16	33	23	45	29	56	37	68	48	80	59	93	71	105
Prince George's	0.2	2.2	0.9	3.9	1.6	5.6	2.9	7.2	4.3	8.9	5.6	11	7.1	13	8.9	16	11	19	13	21
Queen Anne's	0.6	4.1	5.3	12	14	22	24	35	37	50	52	68	69	88	89	107	107	126	125	143
Somerset	17	58	70	101	113	153	168	193	198	210	215	233	240	260	268	289	297	318	327	345
St. Mary's	2.4	16	8.0	28	14	41	24	58	35	79	46	101	62	118	83	129	104	139	120	148
Talbot	2.2	7.8	11	24	30	54	64	99	110	139	149	175	184	210	218	239	245	260	266	279
Wicomico	5.0	15	18	29	32	43	47	58	62	72	76	86	90	101	105	115	119	129	133	142
Worcester	4.4	21	25	48	53	83	88	119	124	153	158	183	187	209	213	235	239	261	265	288
Statewide	**69**	**307**	**326**	**570**	**560**	**832**	**812**	**1104**	**1053**	**1350**	**1267**	**1596**	**1500**	**1833**	**1737**	**2045**	**1960**	**2243***	**2165**	**2425***

*This value is probably too low because of a data limitation. See Section 1.3 of this report

Table A.5 Low and High Estimates of the Area of Land Close to Sea Level in Maryland (continued)

		low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high
County		**0.5**		**1.0**		**1.5**		**2.0**		**2.5**		**3.0**		**3.5**		**4.0**		**4.5**		**5.0**	
Wetlands	Tidal	---------Cumulative (total) amount of Nontidal Wetlands below a given elevation---------																			
Anne Arundel	12	0.2	0.7	0.6	1.6	1.1	4.8	3.1	8.1	6.3	11	9.5	12	12	14	13	15	14	16	15	17
Baltimore County	10	0.1	0.3	0.3	0.7	0.7	1.0	1.0	1.3	1.3	1.5	1.5	1.7	1.7	1.8	1.8	2.0	2.0	2.2	2.2	2.3
Baltimore City	0.2	<0.01	0.03	0.01	0.04	0.02	0.05	0.03	0.1	0.04	0.1	0.05	0.1	0.06	0.1	0.06	0.1	0.07	0.1	0.08	0.1
Calvert	15	0.1	0.9	0.4	1.3	0.7	1.7	1.1	2.2	1.4	3.0	1.7	3.8	2.2	4.7	3.0	5.7	3.8	6.6	4.7	7.5
Caroline	14	0.3	1.4	0.7	2.6	1.3	4.0	2.5	5.3	3.5	6.4	4.4	7.5	5.3	8.6	6.2	9.8	7.1	11*	8.0	12*
Cecil	13	0.01	0.2	0.04	0.7	0.1	1.2	0.4	1.7	0.8	2.3	1.2	2.8	1.7	3.5	2.2	4.2	2.8	4.9	3.5	5.5
Charles	24	0.1	3.8	1.5	6.5	2.9	9.2	4.8	12	7.0	14	9.3	16	12	18	14	20	16	21	18	23
Dorchester	425	15	46	53	70	76	90	94	104	107	112	114	121	124	129	131	136	137	139	140	143
Harford	29	0.2	2.5	1.2	3.8	2.3	5.0	3.3	6.2	4.3	7.6	5.2	9.0	6.4	10	7.8	11	9.1	11	10	12
Howard	0	0	0.03	0.01	0.04	0.02	0.04	0.03	0.05	0.04	0.06	0.04	0.06	0.05	0.07	0.06	0.08	0.06	0.09	0.07	0.10
Kent	18	0.1	1.1	0.9	2.6	2.0	4.1	3.3	5.4	4.3	6.8	5.2	7.9	6.1	9.3	7.2	11	8.3	13	9.7	14
Prince George's	14	0.1	0.8	0.3	1.4	0.6	2.0	1.0	2.5	1.5	3.2	2.0	3.8	2.5	4.7	3.2	5.6	3.8	6.5	4.6	7.2
Queen Anne's	21	0.2	1.1	1.5	3.0	3.2	4.8	4.9	6.5	6.5	8.1	7.9	9.6	9.5	12	11	14	13	16	15	18
Somerset	265	6.6	16	17	21	23	31	35	40	41	43	45	52	54	60	62	69	71	78	81	90
St. Mary's	19	0.5	2.8	1.7	5.3	2.8	7.8	4.6	11	6.7	15	8.8	19	12	22	16	25	20	28	23	31
Talbot	26	0.1	0.3	0.5	1.0	1.3	2.1	2.5	4.2	4.8	6.2	6.8	8.5	9.1	12	13	15	16	17	18	20
Wicomico	67	5.4	9.9	11	13	16	22	24	29	30	35	37	44	47	54	56	60	62	66	67	70
Worcester	142	0.7	5.2	6.0	10	11	16	17	22	23	29	30	36	37	42	43	48	49	54	54	58
Statewide	**1116**	**29**	**93**	**97**	**146**	**145**	**207**	**203**	**261**	**249**	**304**	**289**	**355**	**341**	**406**	**390**	**451**	**435**	**490***	**474**	**531***
		Cumulative (total) amount of land below a given elevation																			
Dry Land		69	307	326	570	560	832	812	1104	1053	1350	1267	1596	1500	1833	1737	2045	1960	2243*	2165	2425*
Nontidal Wetlands		29	93	97	146	145	207	203	261	249	304	289	355	341	406	390	451	435	490*	474	531*
All Land	1116	1214	1516	1539	1832	1820	2155	2130	2481	2418	2769	2672	3067	2957	3354	3243	3612	3510	3849*	3754	4071*

*This value is probably too low because of a data limitation. See Section 1.3 of this report

Table A.6 Low and High Estimates of the Area of Land Close to Sea Level in **Washington, D.C.**

		Meters above Spring High Water																			
		low	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**
		0.5		**1.0**		**1.5**		**2.0**		**2.5**		**3.0**		**3.5**		**4.0**		**4.5**		**5.0**	
		----------------Cumulative (total) amount of Dry Land below a given elevation---------------																			
Washington, D.C.		1.6	3.0	2.8	4.4	4.1	5.8	5.5	7.4	7.0	9.3	8.9	11	11	13	13	15	14	16	16	18
Wetlands	Tidal	---------Cumulative (total) amount of Nontidal Wetlands below a given elevation---------																			
Washington, D.C.	0.5	0.03	0.05	0.05	0.07	0.07	0.1	0.09	0.12	0.12	0.14	0.13	0.16	0.15	0.19	0.18	0.24	0.2	0.3	0.28	0.32
		Cumulative (total) amount of land below a given elevation																			
Dry Land		2	3	3	4	4	6	5	7	7	9	9	11	11	13	13	15	14	16	16	18
Nontidal Wetlands		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
All Land	0.5	2	3	3	5	5	6	6	8	8	10	9	12	11	14	13	15	15	17	17	19

Table A.7 Low and High Estimates of the Area of Land Close to Sea Level in Virginia

Jurisdiction	Meters above Spring High Water																			
	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high
	0.5		1.0		1.5		2.0		2.5		3.0		3.5		4.0		4.5		5.0	
	----------------Cumulative (total) amount of Dry Land below a given elevation---------------																			
Eastern Shore	**21**	**63**	**56**	**111**	**93**	**159**	**137**	**204**	**180**	**243**	**221**	**279**	**258**	**315**	**294**	**349**	**329**	**382**	**362**	**416**
Accomack	13	41	37	78	65	115	98	149	131	172	160	192	180	211	200	227	218	242	233	257
Northampton	7.4	22	20	33	29	44	39	55	49	71	61	87	78	104	94	122	111	140	129	159
Northern Virginia	**0**	**5.1**	**2.8**	**10**	**6.3**	**15**	**9.7**	**20**	**13**	**25**	**17**	**29**	**21**	**34**	**25**	**39**	**30**	**44**	**35**	**49**
Arlington	0	0.2	0.1	0.5	0.3	0.7	0.5	1.3	0.6	1.9	0.8	2.6	1.4	3.3	2.1	4	2.7	4.7	3.4	5
Alexandria	0	0.4	0.3	0.9	0.6	1.3	0.9	1.7	1.2	2.1	1.5	2.5	1.8	2.9	2.2	3.2	2.5	3.6	2.9	4
Fairfax	0	2	1.1	3.9	2.5	5.9	3.8	7.6	5.2	9.2	6.6	11	8	12	9.5	14	11	15	12	18
Prince William	0	1	0.5	2	1.2	3	1.9	3.9	2.6	4.7	3.3	5.5	4	6.3	4.8	7.2	5.6	8	6.4	8.8
Rappahannock Area	**0**	**3.3**	**1.8**	**6.5**	**4.1**	**9.9**	**6.4**	**14**	**8.7**	**20**	**11**	**26**	**15**	**31**	**20**	**37**	**26**	**43**	**32**	**49**
Stafford	0	1.4	0.8	2.7	1.7	4.2	2.7	5.4	3.6	6.8	4.6	8.1	5.7	9.4	6.9	11	8.2	12	9.5	14
Fredericksburg	0	0.1	0.04	0.1	0.1	0.2	0.1	0.2	0.2	0.3	0.2	0.3	0.3	0.4	0.3	0.4	0.3	0.5	0.4	0.5
King George	0	2.7	1.5	5.4	3.3	8.1	5.2	11	7.1	16.7	9	22	12	27	17	32	22	37	27	43
Spotsylvania	0	0.09	0.05	0.2	0.1	0.3	0.2	0.3	0.2	0.4	0.3	0.5	0.3	0.5	0.4	0.6	0.5	0.7	0.5	0.8
Caroline	0	0.4	0.3	0.9	0.6	1.3	0.9	1.8	1.2	2.3	1.5	2.8	1.9	3.3	2.4	3.8	2.9	4.4	3.4	5.2
Northern Neck	**0.1**	**22**	**11**	**43**	**27**	**66**	**42**	**92**	**58**	**141**	**74**	**190**	**100**	**239**	**147**	**287**	**193**	**336**	**240**	**378**
Westmoreland	0	4.7	2.4	9.3	5.7	14	9	21	12	37	16	53	24	69	39	84	54	100	69	112
Richmond	0	4.6	2.4	8.9	5.5	13	8.7	18	12	25	15	32	20	38	26	44	32	51	38	57
Northumberland	0	5.9	2.8	11	6.9	17	11	24	15	44	19	64	27	84	46	104	65	124	85	141
Lancaster	0.1	7	3.6	14	8.5	21	14	28	19	35	24	42	29	48	36	55	42	61	48	68
Middle Peninsula	**9.1**	**42**	**33**	**89**	**66**	**139**	**108**	**190**	**149**	**230**	**186**	**268**	**220**	**307**	**258**	**336**	**292**	**364**	**319**	**392**
Essex	0	3.8	2	7.3	4.6	11	7.1	15	9.7	22	12	28	17	34	22	40	28	46	34	53
King and Queen	0	2.9	1.7	5.7	3.7	8.6	5.5	12	7.5	15	9.6	19	13	22	16	26	19	30	23	33
King William	0	1.6	0.9	3.2	2	4.8	3.1	8.4	4.2	13	5.4	18	9.6	22	14	27	18	32	23	36
Middlesex	0.2	3.4	2	6.8	4.4	11	7	14	10	19	13	23	16	27	20	31	24	35	28	39
Gloucester	4.1	16	13	33	26	50	41	67	55	76	67	84	75	93	84	99	91	104	96	111

Table A.7 Low and High Estimates of the Area of Land Close to Sea Level in Virginia (continued)

	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high
	0.5		1.0		1.5		2.0		2.5		3.0		3.5		4.0		4.5		5.0	
Mathews	4.7	15	13	33	26	54	44	73	62	85	79	97	90	108	101	113	111	117	115	121
Hampton Roads	**24**	**91**	**78**	**200**	**154**	**333**	**264**	**469**	**381**	**650**	**519**	**848**	**711**	**1045**	**907**	**1192**	**1089**	**1307**	**1215**	**1424**
James City	0.1	3.8	2	7.2	4.7	11	7	14	9.4	18	12	22	15	26	19	30	23	34	27	39
York	1.4	6	5	13	9.9	21	16	28	23	33	28	37	33	42	38	45	42	48	44	51
Newport News	2.2	6.9	6	11	9.7	15	13	18	16	21	19	25	23	28	26	33	30	38	35	42
Poquoson	1.4	4.5	4	8.8	7.4	13	11	16	15	16	16	17	17	17	17	17	17	17	17	17
Hampton	1.9	5.9	5	18	13	32	25	45	38	60	51	74	65	88	80	93	90	98	95	102
Surry	0	1.4	1	2.7	1.7	4.1	2.7	5.3	3.6	6.2	4.6	7.1	5.5	8	6.4	9	7.2	9.9	8.1	11
Isle of Wight	0.2	3.4	2	6.2	4.2	9.1	6	12.8	8	17	10	22	14	26	18	31	22	35	27	42
Norfolk	1.9	5.8	5	17	13	30	24	42	35	67	52	91	77	115	101	120	118	124	122	128
Virginia Beach	9.3	33	30	69	55	117	94	163	138	219	185	273	241	327	295	368	347	393	378	418
Suffolk	0.7	4.3	3.1	7.1	5.4	10	7.5	15	10	23	13	31	21	39	28	50	37	60	47	73
Portsmouth	1.2	3.9	3.5	9.6	7.6	15	13	22	18	33	27	45	38	56	50	61	58	65	63	70
Chesapeake	3.5	12	11	31	22	57	45	87	69	137	100	205	162	272	229	337	298	385	353	430
Other Jurisdictions	**0**	**9.9**	**5.7**	**19**	**12**	**29**	**19**	**40**	**26**	**54**	**32**	**67**	**44**	**80**	**56**	**93**	**68**	**106**	**81**	**122**
Charles City	0	3.2	1.8	6.3	4	9.6	6.2	13	8.4	18	11	23	15	28	19	32	23	37	28	43
Chesterfield	0	1.3	0.8	2.6	1.7	3.9	2.5	4.8	3.4	5.5	4.3	6.2	5	7	5.7	7.7	6.3	8.4	7	8.9
Colonial Heights	0	0.04	0.02	0.1	0.05	0.1	0.07	0.12	0.09	0.14	0.12	0.15	0.1	0.2	0.1	0.2	0.15	0.19	0.16	0.24
Hanover	0	0.02	0.02	0.05	0.03	0.1	0.05	0.2	0.1	0.3	0.1	0.4	0.2	0.5	0.3	0.6	0.4	0.7	0.5	0.7
Henrico	0	0.8	0.5	1.5	1	2.3	1.5	2.8	2	3.2	2.5	3.7	2.9	4.1	3.3	4.6	3.8	5.1	4.2	6.3
Hopewell	0	0.4	0.2	0.8	0.5	1.1	0.7	1.3	1	1.4	1.2	1.6	1.4	1.7	1.5	1.8	1.6	1.9	1.7	2.2
New Kent	0	2.1	1.2	4.1	2.6	6.2	4	9.4	5.4	13	6.9	17	10	21	14	25	18	29	22	34
Petersburg	0	0	0	0	0	0	0	<0.01	0	0.01	<0.01	0.01	<0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.03
Prince George	0	1.9	1.1	3.8	2.4	5.7	3.7	8.1	5	11	6.3	14	8.8	17	12	20	15	23	17	26
Williamsburg	0	0.05	0.03	0.1	0.06	0.1	0.1	0.2	0.1	0.3	0.2	0.3	0.2	0.4	0.3	0.4	0.3	0.5	0.4	0.6
Statewide	**54**	**236**	**189**	**479**	**362**	**751**	**585**	**1029**	**816**	**1362**	**1060**	**1707**	**1368**	**2051**	**1708**	**2332**	**2028**	**2582**	**2283**	**2830**

Table A.7 Low and High Estimates of the Area of Land Close to Sea Level in Virginia (continued)

Jurisdiction		Meters above Spring High Water																			
		low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high
		0.5		1.0		1.5		2.0		2.5		3.0		3.5		4.0		4.5		5.0	
	Tidal	---------Cumulative (total) amount of Nontidal Wetlands below a given elevation---------																			
Eastern Shore	**946**	**7**	**22**	**20**	**48**	**39**	**76**	**63**	**101**	**87**	**114**	**107**	**126**	**119**	**137**	**131**	**146**	**141**	**153**	**149**	**161**
Accomack	484	7	21	19	45	36	70	58	92	80	104	98	114	108	124	119	132	128	138	134	145
Northampton	462	0.4	1.2	1	3.4	2.5	5.9	4.7	8.1	7	9.7	8.8	11	10	13	12	14	14	15	15	16
Northern Virginia	**17**	**0**	**1**	**0**	**2**	**1**	**3**	**2**	**3**	**2**	**4**	**3**	**4**	**3**	**5**	**4**	**5**	**4**	**6**	**5**	**6**
Stafford	6.8	0	0.5	0.3	1	0.6	1.5	1	1.9	1.3	2.3	1.7	2.6	2	2.9	2.3	3.3	2.6	3.6	3	3.9
Alexandria	0.2	0	0.03	0.02	0.07	0.04	0.1	0.06	0.11	0.09	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.12
Fairfax	4.9	0	0.2	0.1	0.4	0.2	0.6	0.4	0.7	0.5	0.8	0.6	0.9	0.7	1.1	0.9	1.2	1	1.3	1.1	1.4
Prince William	5.1	0	0.2	0.1	0.3	0.2	0.5	0.3	0.6	0.4	0.6	0.5	0.7	0.6	0.8	0.7	0.8	0.7	0.9	0.8	0.9
Rappahannock Area	**20**	**0**	**0.6**	**0.3**	**1.2**	**0.7**	**1.7**	**1.1**	**2.4**	**1.5**	**3**	**1.9**	**3.6**	**2.5**	**4.2**	**3.1**	**4.9**	**3.7**	**5.5**	**4.3**	**6.2**
Fredericksburg	0	0	<0.01	<0.01	0.01	<0.01	0.01	<0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
King George	13	0	0.5	0.3	1	0.6	1.5	1	2	1.3	2.4	1.7	2.8	2.1	3.3	2.5	3.7	2.9	4.1	3.3	4.6
Spotsylvania	0.1	0	0.02	0.01	0.03	0.02	0.05	0.03	0.06	0.04	0.06	0.05	0.07	0.06	0.08	0.06	0.08	0.07	0.09	0.08	0.12
Caroline	6.3	0	0.1	0.03	0.1	0.1	0.2	0.1	0.3	0.2	0.5	0.2	0.7	0.3	0.9	0.5	1.1	0.7	1.3	0.9	1.5
Northern Neck	**57**	**0**	**2.5**	**1.2**	**4.8**	**2.9**	**7.3**	**4.7**	**9.8**	**6.4**	**14**	**8.1**	**18**	**10**	**22**	**14**	**26**	**18**	**30**	**22**	**34**
Westmoreland	14	0	0.5	0.3	1	0.6	1.5	1	2.2	1.3	3.9	1.7	5.6	2.5	7.2	4.1	8.9	5.7	10.6	7.3	12
Richmond	22	0	0.9	0.4	1.7	1	2.5	1.6	3.3	2.2	3.9	2.8	4.5	3.4	5.1	4	5.7	4.5	6.3	5.1	6.9
Northumberland	11	0	0.5	0.3	1.1	0.6	1.6	1	2.2	1.4	3.7	1.8	5.1	2.4	6.6	3.8	8	5.2	9.6	6.6	11
Lancaster	9.8	<0.01	0.5	0.3	1.1	0.7	1.6	1.1	2.1	1.4	2.5	1.8	2.8	2.2	3.2	2.5	3.5	2.8	3.8	3.2	4.2
Middle Peninsula	**165**	**2.6**	**12**	**9.5**	**26**	**19**	**40**	**31**	**54**	**44**	**66**	**55**	**78**	**67**	**90**	**79**	**98**	**90**	**106**	**98**	**113**
Essex	28	0	0.8	0.4	1.5	0.9	2.3	1.5	2.9	2	3.4	2.5	3.9	3	4.4	3.5	4.8	3.9	5.3	4.4	5.9
King and Queen	22	0	0.9	0.5	1.7	1.1	2.5	1.6	3.1	2.2	3.5	2.8	4	3.2	4.4	3.6	4.8	4	5.3	4.4	5.8
King William	36	0	0.4	0.2	0.7	0.5	1.1	0.7	1.4	0.9	1.7	1.2	2	1.5	2.3	1.8	2.6	2	2.9	2.3	3.3
Middlesex	9.7	<0.01	0.7	0.4	1.4	0.8	2.1	1.4	2.8	1.9	3.1	2.4	3.5	2.8	3.8	3.2	4.1	3.5	4.5	3.8	4.8
Gloucester	44	1.4	5.5	4.5	12	9.1	19	15	25	20	28	25	31	27	34	30	36	33	37	34	38

Table A.7 Low and High Estimates of the Area of Land Close to Sea Level in Virginia (continued)

Jurisdiction		Meters above Spring High Water																			
		low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high
		0.5		1.0		1.5		2.0		2.5		3.0		3.5		4.0		4.5		5.0	
Mathews	27	1.2	3.8	3.5	8.6	6.7	14	11	19	16	26	22	34	29	41	37	46	44	51	48	55
Hampton Roads	**329**	**12**	**42**	**38**	**74**	**64**	**96**	**84**	**127**	**104**	**167**	**127**	**205**	**164**	**245**	**202**	**285**	**242**	**326**	**279**	**391**
James City	33	<0.01	0.8	0.4	1.5	0.9	2.2	1.4	2.8	1.9	3.3	2.5	3.7	2.9	4.2	3.3	4.6	3.8	5.1	4.2	5.6
York	17	0.19	0.9	0.7	2.7	1.9	4.9	3.7	6.7	5.6	7.4	6.9	8	7.6	8.7	8.2	9.1	8.8	9.5	9.2	9.9
Newport News	15	0.1	0.3	0.3	0.7	0.5	1	0.9	1.3	1.2	1.4	1.35	1.42	1.4	1.5	1.4	1.5	1.5	1.6	1.6	1.7
Poquoson	24	0.02	0.1	0.1	0.4	0.3	0.8	0.6	1.1	0.9	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Hampton	14	0.06	0.2	0.2	0.4	0.3	0.6	0.5	0.9	0.7	1.5	1.1	2.2	1.8	2.9	2.5	4	3.3	5.1	4.4	6.2
Surry	11	0	0.6	0.3	1.3	0.8	1.9	1.2	2.4	1.7	2.5	2.1	2.7	2.4	2.9	2.6	3	2.7	3.2	2.9	3.4
Isle of Wight	29	<0.01	0.3	0.2	0.6	0.4	0.9	0.6	1.4	0.8	2.2	1	3.1	1.5	4	2.4	4.8	3.2	5.7	4	7.3
Norfolk	4.7	0.1	0.3	0.2	0.5	0.4	0.8	0.7	1.1	0.9	1.3	1.1	1.5	1.3	1.7	1.5	1.7	1.7	1.7	1.7	1.7
Virginia Beach	112	4.2	14	13	25	22	33	29	41	37	46	43	50	48	53	51	56	54	57	56	59
Suffolk	26	0.03	0.2	0.1	0.3	0.2	0.4	0.3	0.8	0.4	1.3	0.5	1.8	1	2.3	1.4	3.1	2.1	6.8	2.9	33
Portsmouth	3.7	2.4	7.7	6.8	8.9	8.9	9.2	9.1	9.5	9.3	9.9	9.6	10	10	11	10	11	10.7	11	10.9	11
Chesapeake	40	4.5	17	15	32	28	40	36	58	44	89	56	120	86	152	116	186	149	217	180	251
Other Jurisdictions	**85**	**0**	**5.5**	**3.2**	**11**	**6.9**	**16**	**10**	**20**	**14**	**22**	**18**	**24**	**20**	**26**	**22**	**28**	**24**	**30**	**26**	**33**
Charles City	22	0	1.9	1.1	3.7	2.4	5.6	3.6	6.8	4.9	7.4	6.2	8	6.9	8.6	7.5	9.2	8.1	9.8	8.6	11
Chesterfield	11	0	0.4	0.2	0.7	0.4	1.1	0.7	1.2	0.9	1.2	1.1	1.2	1.17	1.24	1.2	1.3	1.2	1.3	1.2	1.3
Henrico	4.2	0	0.04	0.02	0.08	0.05	0.12	0.1	0.2	0.1	0.2	0.1	0.2	0.2	0.3	0.2	0.3	0.2	0.4	0.3	0.4
Hopewell	0.7	0	0.1	0.1	0.2	0.1	0.3	0.2	0.3	0.3	0.4	0.3	0.4	0.3	0.4	0.36	0.4	0.37	0.41	0.38	0.42
New Kent	34	0	2.3	1.3	4.5	2.9	6.8	4.4	8.1	6	8.7	7.6	9.3	8.2	9.8	8.8	10.4	9.3	11	9.9	12
Prince George	11	0	0.8	0.5	1.5	1	2.3	1.5	3.1	2	3.9	2.6	4.7	3.3	5.5	4	6.3	4.8	7.1	5.5	7.5
Williamsburg	0.4	0	0.02	0.01	0.03	0.02	0.05	0.03	0.06	0.04	0.07	0.05	0.08	0.06	0.1	0.07	0.11	0.09	0.12	0.1	0.14
Statewide	**1619**	**21**	**86**	**72**	**167**	**134**	**240**	**197**	**317**	**260**	**389**	**320**	**459**	**387**	**529**	**455**	**594**	**523**	**657**	**583**	**745**
	Cumulative (total) amount of land below a given elevation																				
Dry Land		54	236	189	479	362	751	585	1029	816	1362	1060	1707	1368	2051	1708	2332	2028	2582	2283	2830
Nontidal Wetlands		21	86	72	167	134	240	197	317	260	389	320	459	387	529	455	594	523	657	583	745
All Land	1619	1694	1941	1881	2265	2115	2611	2401	2965	2694	3370	2999	3785	3374	4199	3782	4545	4170	4858	4486	5193

Table A.8 Low and High Estimates of the Area of Land Close to Sea Level in North Carolina

County	Meters above Spring High Water																			
	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high
	0.5		1.0		1.5		2.0		2.5		3.0		3.5		4.0		4.5		5.0	
	---------------Cumulative (total) amount of dry land below a given elevation--------------																			
Beaufort	46	90	107	153	174	232	254	314	338	398	419	479	502	573	597	652	669	708	719	741
Bertie	1.8	3.4	4.7	6.8	8.2	10	12	15	17	20	22	26	28	32	35	40	44	51	56	65
Bladen	0	0	0	<0.01	<0.01	0.01	0.02	0.06	0.1	0.2	0.2	0.4	0.5	1.1	1.5	3	4	8.2	10	16
Brunswick	13	18	22	28	33	40	45	52	57	65	70	79	85	95	102	112	119	130	136	145
Camden	10	21	25	45	59	100	115	147	157	188	201	231	240	256	261	281	290	313	321	336
Carteret	52	89	120	172	212	279	318	371	393	412	419	428	434	444	451	462	468	477	481	487
Chowan	2.9	5.0	6.5	9.2	11	15	17	22	27	35	42	55	65	85	100	122	137	159	173	188
Columbus	<0.01	0.01	0.02	0.04	0.05	0.1	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.1	1.2	1.5	1.6	1.9
Craven	7.5	15	19	30	36	52	59	77	84	102	109	130	138	164	174	199	208	233	241	265
Currituck	20	34	46	67	83	115	140	174	197	231	248	269	282	297	303	309	312	316	318	322
Dare	43	60	66	80	84	96	100	111	115	124	127	134	136	140	141	144	145	147	147	148
Duplin	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	0.01	0.02	0.03	0.07	0.1	0.2	0.2	0.3	0.4	0.8	0.9	1.5
Edgecombe	0	0	0	0	0	0	0	0	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	0.01	0.02	0.03
Gates	5.3	11	11	16	17	22	22	27	28	35	36	50	52	69	72	85	87	103	107	130
Greene	0	0	0	0	0	0	0	0	0	0	0	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	0.01	0.01	0.02
Halifax	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	<0.01	<0.01	0.06
Hertford	3.7	6.9	7.4	11	12	17	17	21	22	26	26	31	31	36	37	42	43	49	50	55
Hyde	276	405	428	476	490	528	543	581	594	627	635	654	661	676	680	690	692	696	698	702
Jones	1.8	2.7	3.0	4.0	4.4	5.6	6.1	7.7	8.4	11	11	14	15	19	20	25	27	32	35	41
Lenoir	0	0	0	0	0	0	0	0.01	0.02	0.05	0.06	0.1	0.2	0.3	0.4	0.7	0.9	1.5	1.7	2.8
Martin	0.5	1.8	2.6	5.6	7.0	11	13	18	19	23	24	27	28	30	30	33	33	35	36	38
New Hanover	7.1	12	13	19	21	26	28	33	35	41	43	50	52	59	62	69	72	79	81	87
Northampton	0.05	0.1	0.2	0.3	0.3	0.4	0.4	0.8	0.9	1.5	1.6	2.6	2.8	3.8	4.0	5.1	5.3	6.5	6.7	8.0
Onslow	24	31	33	41	44	52	55	65	68	78	82	93	97	108	112	125	130	144	149	162
Pamlico	24	44	60	90	112	145	165	189	204	225	238	258	269	284	291	302	307	314	317	320
Pasquotank	11	26	40	65	83	112	131	161	178	202	221	259	290	350	382	418	432	449	457	460
Pender	5	9	11	16	18	24	27	35	39	50	54	68	73	88	93	109	115	130	135	147
Perquimans	5.0	8.8	12	18	24	39	52	79	97	124	145	189	227	296	335	381	402	420	427	432
Pitt	1.1	1.8	2.4	3.7	4.7	6.5	7.8	10	12	15	17	21	24	30	34	40	45	52	57	65
Sampson	0	0	0	0	0	0	0	0	0	0.02	0.03	0.06	0.07	0.1	0.15	0.2	0.3	0.5	0.6	0.9
Tyrrell	130	235	269	321	331	351	358	369	371	374	375	378	378	379	380	380	380	380	380	380
Washington	5.6	14	22	38	49	68	81	106	128	165	192	238	272	340	387	452	484	519	535	556
Statewide	**697**	**1144**	**1330**	**1717**	**1916**	**2346**	**2566**	**2986**	**3188**	**3571**	**3759**	**4164**	**4385**	**4854**	**5086**	**5484**	**5654**	**5956**	**6079**	**6304**

Table A.8 Low and High Estimates of the Area of Land Close to Sea Level in North Carolina (continued)

County		Meters above Spring High Water																			
		low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high
		0.5		1.0		1.5		2.0		2.5		3.0		3.5		4.0		4.5		5.0	
Wetlands	Tidal	---------Cumulative (total) amount of Nontidal Wetlands below a given elevation---------																			
Beaufort	35	65	95	105	131	139	162	171	202	215	244	252	272	278	290	294	306	310	320	323	330
Bertie	0.3	110	123	127	132	136	142	147	153	159	167	171	177	181	186	191	200	207	219	225	234
Bladen	0	<0.01	0.1	0.2	0.6	0.9	1.8	2.1	3.3	4.1	6.3	7.3	10	11	15	16	21	23	29	31	36
Brunswick	109	38	44	47	52	55	58	61	65	67	71	73	77	79	82	85	88	90	93	95	98
Camden	7.1	137	146	149	155	157	165	168	175	177	184	187	194	197	201	203	210	214	233	243	258
Carteret	334	34	67	87	117	136	164	180	202	216	231	237	243	247	254	258	267	273	281	286	293
Chowan	0	29	32	34	37	38	40	42	44	46	49	51	56	59	64	70	79	84	91	96	104
Columbus	0	0.2	0.5	0.8	1.3	1.9	2.7	3.2	3.9	4.4	5.1	5.5	6.1	6.4	6.7	7	7.3	7.5	8.0	8.9	11
Craven	12	59	74	80	94	100	115	121	137	142	154	159	170	173	184	188	198	202	213	217	227
Currituck	125	129	144	150	159	164	172	178	184	188	194	196	199	201	203	204	206	209	215	219	221
Dare	168	376	525	553	604	619	651	659	664	664	665	666	666	666	666	666	666	666	666	666	666
Duplin	0	0	0	0	0	0	0	0	0.01	0.03	0.1	0.2	0.5	0.7	1.4	1.8	2.9	3.4	4.7	5.3	6.7
Edgecombe	0	0	0	0	0	0	0	0	0	0	0	0	<0.01	<0.01	<0.01	<0.01	0.01	0.01	0.03	0.05	0.09
Gates	0	78	89	89	93	94	98	99	102	103	107	108	114	115	121	122	126	126	129	129	132

Table A.8 Low and High Estimates of the Area of Land Close to Sea Level in North Carolina (continued)

County		Meters above Spring High Water																			
		low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high
		0.5		1.0		1.5		2.0		2.5		3.0		3.5		4.0		4.5		5.0	
Greene	0	0	0	0	0	0	0	0	0	0	0	0	<0.01	<0.01	0.01	0.01	0.02	0.03	0.1	0.1	0.2
Halifax	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	<0.01	0.03	0.3	0.5	1.6
Hertford	0	45	53	54	58	58	61	62	65	66	69	69	71	71	74	74	77	78	79	80	81
Hyde	199	325	461	488	538	549	571	578	592	598	614	619	634	638	653	660	672	675	682	685	689
Jones	3.5	7.8	10	11	13	14	16	16	18	19	21	21	23	24	26	26	28	29	31	31	33
Lenoir	0	0	0	0	0.07	0.13	0.38	0.5	1.1	1.5	2.8	3.3	4.9	5.6	7.6	8.4	11	12	14	15	17
Martin	0	58	67	73	88	93	103	106	114	117	124	126	130	132	136	137	140	142	145	147	150
New Hanover	56	28	35	36	39	40	42	43	45	46	48	49	51	52	53	54	56	57	58	59	60
Northampton	0	0.9	1.9	2.0	2.6	2.7	3.5	3.7	5.9	6.0	7.3	7.6	9.6	9.9	11	11	12	12	13	13	14
Onslow	69	25	30	31	35	36	40	41	45	46	49	51	54	55	59	60	64	65	68	69	72
Pamlico	112	52	67	73	81	86	97	106	123	131	142	148	161	171	186	192	201	206	215	221	232
Pasquotank	0.3	50	58	62	68	71	75	79	84	88	93	96	102	106	113	116	119	121	122	124	124
Pender	38	83	107	113	128	132	145	150	161	165	175	179	189	192	202	206	216	219	229	232	239
Perquimans	0.04	38	44	47	52	55	61	66	74	79	86	90	98	103	113	124	137	144	158	167	180
Pitt	0	21	25	27	30	32	35	36	39	41	44	46	49	51	54	57	60	62	65	67	70
Sampson	0	0	0	0	0	0	0	0	<0.01	0.02	0.4	0.6	1.4	1.6	2.3	2.6	3.6	4.0	5.2	5.7	6.8
Tyrrell	3.8	422	502	523	554	559	569	571	579	582	591	593	601	606	614	616	620	621	622	622	623
Washington	0.3	70	78	86	92	96	101	106	112	118	128	134	145	152	162	168	175	180	188	192	197
Statewide	**1272**	**2280**	**2879**	**3048**	**3354**	**3465**	**3694**	**3794**	**3992**	**4087**	**4269**	**4347**	**4509**	**4583**	**4741**	**4818**	**4969**	**5041**	**5198**	**5273**	**5405**
		Cumulative (total) amount of land below a given elevation																			
Dry Land		697	1144	1330	1717	1916	2346	2566	2986	3188	3571	3759	4164	4385	4854	5086	5484	5654	5956	6079	6304
Nontidal Wetlands		2280	2879	3048	3354	3465	3694	3794	3992	4087	4269	4347	4509	4583	4741	4818	4969	5041	5198	5273	5405
All Land	1272	4249	5296	5650	6343	6653	7312	7633	8250	8547	9112	9378	9945	10240	10867	11176	11725	11967	12426	12624	12981

Appendix B

Low and High Estimates for the Area of Dry and Wet Land Close to Sea Level, by Subregion[a] (square kilometers)

[a] 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 and an assumed standard error of 30 cm in the estimation of spring high water. For details, see main text of this Section 1.3.

Table B.1 Low and High Estimates for the Area of Dry and Wet Land Close to Sea Level – Long Island Sound, New York

Locality		Elevations above spring high water									
		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										
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**
	Tidal	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

Table B.2 Low and High Estimates for the Area of Dry and Wet Land Close to Sea Level in New York Harbor

			Elevations above spring high water									
			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**									
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**
		Tidal	**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		**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

Table B.3 Low and High Estimates for the Area of Dry and Wet Land Close to Sea Level in New Jersey Shore

County		Elevations above spring high water:									
		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									
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**
	Tidal	**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

Table B.4 Low and High Estimates for the Area of Dry and Wet Land Close to Sea Level in Delaware Estuary

			Elevations above spring high water:									
			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[a]	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**
		Tidal	**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

[a] 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.

Table B.5 Low and High Estimates for the Area of Dry and Wet Land Close to Sea Level in DelMarVa Atlantic Coast

			Elevations above spring high water:									
			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**
		Tidal	**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**[a]	**3.7**	**14.1**	**13.4**	**28.7**	**39.2**	**55.4**	**62.7**	**74.1**	**91.9**	**98.1**
Dry and Nontidal wetland			31	102	96	179	244	335	388	474	642	721
All Land		923	954	1025	1019	1102	1167	1259	1311	1397	1565	1644

[a] Includes 375 square kilometers of tidal mudflats in Northampton and Accomack counties.

Table B.6 Low and High Estimates for the Area of Dry and Wet Land Close to Sea Level in Hampton Roads, Virginia

Locality		Elevations above spring high water									
		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										
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**
	Tidal	**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

Table B.7 Low and High Estimates for the Area of Dry and Wet Land Close to Sea Level in Middle Peninsula and Northern Neck Areas, Virginia

Locality		Elevations above spring high water									
		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										
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**
	Tidal	**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

Table B.8 Low and High Estimates for the Area of Dry and Wet Land Close to Sea Level in Potomac River

			Elevations above spring high water									
			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**
		Tidal	**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

Table B.9 Low and High Estimates for the Area of Dry and Wet Land Close to Sea Level – Maryland Western Shore

		Elevations above spring high water									
		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**
	Tidal	**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

Table B.10 Low and High Estimates for the Area of Dry and Wet Land Close to Sea Level – Chesapeake Bay Eastern Shore

			Elevations above spring high water									
			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**
		Tidal	**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

Appendix C

Low and High Estimates of the Area of Land Close to Sea Level, by Region: Mid-Atlantic[a] (square kilometers)

[a] 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 and an assumed standard error of 30 cm in the estimation of spring high water. For details, see main text of this Section 1.3.

Table C.1 Low and High Estimates of the Area of Land Close to Sea Level by Region

Jurisdiction	Meters above Spring High Water																			
	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high
	0.5		1.0		1.5		2.0		2.5		3.0		3.5		4.0		4.5		5.0	
	---------------Cumulative (total) amount of Dry Land below a given elevation---------------																			
L.I. Sound and Peconic	**6**	**31**	**22**	**59**	**42**	**86**	**63**	**111**	**85**	**135**	**106**	**158**	**127**	**181**	**149**	**200**	**170**	**216**	**190**	**229**
South Shore Long Island	**19**	**70**	**59**	**134**	**108**	**198**	**161**	**250**	**216**	**293**	**266**	**335**	**309**	**369**	**347**	**400**	**380**	**429**	**410**	**450**
NY Harbor/ Raritan Bay Total	**5**	**72**	**47**	**143**	**93**	**200**	**139**	**230**	**185**	**260**	**215**	**288**	**240**	**316**	**265**	**343**	**290**	**360**	**314**	**374**
New York	0	13	8	25	16	37	24	44	32	51	40	58	46	65	52	72	59	76	65	78
New Jersey	5	59	39	117	77	163	115	186	153	209	175	230	194	251	213	271	231	284	249	295
New Jersey Shore	**18**	**61**	**66**	**129**	**131**	**186**	**184**	**237**	**223**	**283**	**262**	**327**	**304**	**369**	**344**	**409**	**382**	**445**	**418**	**481**
Delaware Bay Total	**19**	**62**	**52**	**108**	**88**	**154**	**124**	**206**	**166**	**259**	**217**	**312**	**268**	**366**	**321**	**421**	**374**	**470**	**427**	**512**
New Jersey	3	19	15	36	27	53	39	73	52	94	70	114	90	134	109	154	127	170	146	182
Delaware	15	43	38	71	61	101	85	133	114	165	146	198	178	232	212	267	247	300	281	330
Delaware River Total	**17**	**80**	**56**	**146**	**103**	**210**	**152**	**262**	**201**	**315**	**249**	**368**	**296**	**417**	**342**	**467**	**386**	**512**	**430**	**549**
Delaware: fresh	2	6	5	10	8	14	11	19	15	24	19	28	24	32	28	36	32	39	35	42
Delaware: saline	5	13	12	20	17	27	23	33	29	40	35	47	41	54	49	62	56	70	64	77
New Jersey: fresh	0	18	7	35	17	52	28	67	39	83	52	98	65	114	77	130	90	144	102	154
New Jersey: saline	6	27	21	48	37	68	53	82	68	96	82	109	95	121	108	133	119	143	130	152
Pennsylvania	4	17	11	33	24	49	37	61	50	73	61	85	71	96	81	106	90	115	99	123
Atlantic Coast of Del-Mar-Va Total	**27**	**87**	**81**	**148**	**140**	**212**	**200**	**275**	**259**	**334**	**318**	**390**	**373**	**443**	**425**	**495**	**477**	**548**	**529**	**599**
Delaware	11	32	28	53	46	74	64	95	82	117	104	139	126	163	149	187	172	210	196	234
Maryland	3	17	20	40	44	69	74	97	101	123	126	145	148	163	165	180	182	196	199	211
Virginia	13	37	33	55	49	69	62	82	75	94	87	106	99	117	111	129	122	141	134	154
Chesapeake Bay Total	**102**	**466**	**441**	**906**	**791**	**1357**	**1193**	**1827**	**1587**	**2334**	**1973**	**2859**	**2448**	**3378**	**2962**	**3818**	**3446**	**4234**	**3865**	**4633**
Delaware	1	2	1	3	3	5	4	7	6	10	9	14	12	18	15	24	20	29	26	36
Maryland	66	290	306	530	515	763	738	1007	952	1227	1141	1451	1352	1670	1572	1865	1778	2047	1966	2213
fresh	9	35	33	70	63	115	106	167	152	212	192	263	243	325	307	394	377	466	449	533
vulnerable	49	187	234	344	379	477	515	605	633	704	731	804	830	892	911	958	974	1011	1024	1058
saline	8	68	39	117	74	171	118	235	167	311	218	385	280	454	354	513	427	570	492	623

Table C.1 Low and High Estimates of the Area of Land Close to Sea Level by Region (continued)

Jurisdiction		Meters above Spring High Water																			
		low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high
		0.5		1.0		1.5		2.0		2.5		3.0		3.5		4.0		4.5		5.0	
District of Columbia		2	3	3	4	4	6	5	7	7	9	9	11	11	13	13	15	14	16	16	18
Virginia		34	172	131	369	268	583	445	805	622	1088	815	1383	1073	1677	1362	1915	1634	2141	1857	2366
fresh		1	26	15	50	33	75	50	106	67	152	89	198	125	244	169	292	214	340	260	394
vulnerable		3	8	7	17	14	26	22	35	30	40	37	44	42	48	46	51	50	53	52	55
saline		30	138	108	302	222	482	373	665	525	896	689	1140	906	1385	1147	1573	1370	1748	1545	1916
Virginia Beach Atlantic Coast		**7**	**27**	**25**	**56**	**45**	**99**	**78**	**142**	**118**	**180**	**158**	**219**	**196**	**257**	**235**	**288**	**272**	**299**	**293**	**310**
Pamlico Albemarle Sounds		**602**	**1004**	**1160**	**1492**	**1657**	**2024**	**2211**	**2573**	**2746**	**3080**	**3246**	**3601**	**3798**	**4215**	**4421**	**4760**	**4903**	**5144**	**5241**	**5412**
Atlantic Coast of NC		**94**	**140**	**170**	**225**	**259**	**322**	**355**	**413**	**442**	**491**	**514**	**563**	**586**	**639**	**666**	**724**	**751**	**812**	**838**	**892**
Total NY to NC		**918**	**2101**	**2181**	**3545**	**3457**	**5047**	**4860**	**6526**	**6228**	**7964**	**7523**	**9418**	**8946**	**10949**	**10475**	**12325**	**11831**	**13470**	**12956**	**14441**
Wetlands	Tidal	---------Cumulative (total) amount of Nontidal Wetlands below a given elevation---------																			
L.I. Sound and Peconic	**36**	**1**	**2**	**2**	**4**	**3**	**6**	**4**	**7**	**6**	**8**	**7**	**9**	**8**	**10**	**9**	**11**	**10**	**12**	**11**	**13**
South Shore Long Island	**104**	**1**	**4**	**4**	**7**	**6**	**9**	**8**	**10**	**9**	**11**	**11**	**12**	**11**	**13**	**12**	**13**	**13**	**14**	**14**	**15**
NY Harbor/ Raritan Bay Total	**68**	**0**	**3**	**2**	**6**	**4**	**8**	**6**	**9**	**7**	**10**	**9**	**11**	**9**	**12**	**10**	**13**	**11**	**14**	**12**	**16**
New York	9	0	1	0	1	1	1	1	2	1	2	2	2	2	2	2	2	2	2	2	2
New Jersey	59	0	2	2	5	3	7	5	7	6	8	7	9	8	10	9	11	9	12	10	13
New Jersey Shore	**524**	**11**	**52**	**42**	**92**	**72**	**129**	**101**	**157**	**128**	**181**	**152**	**205**	**174**	**227**	**196**	**249**	**216**	**269**	**237**	**286**
Delaware Bay Total	**497**	**16**	**54**	**45**	**90**	**72**	**121**	**98**	**139**	**121**	**156**	**140**	**173**	**157**	**188**	**172**	**202**	**186**	**214**	**199**	**224**
New Jersey	261	9	38	30	67	51	92	72	106	91	119	105	132	118	142	129	153	139	161	148	167
Delaware	236	7	16	15	23	20	29	26	33	31	37	35	41	39	46	43	49	47	53	51	57
Delaware River Total	**216**	**12**	**41**	**33**	**64**	**49**	**85**	**65**	**93**	**80**	**101**	**90**	**108**	**97**	**115**	**103**	**122**	**109**	**127**	**116**	**133**
Delaware: fresh	5	0	1	1	1	1	2	2	2	2	2	2	3	2	3	3	3	3	3	3	3
Delaware: saline	69	1	3	3	3	3	4	4	5	4	5	5	6	5	6	6	7	6	7	7	8
New Jersey: fresh	29	0	10	6	20	12	29	19	31	25	34	29	37	32	40	34	43	37	46	39	48
New Jersey: saline	108	10	25	22	35	30	44	37	47	44	50	47	52	50	55	52	57	54	59	56	62
Pennsylvania	6	1	2	1	4	3	6	4	8	6	9	7	10	8	11	9	12	9	12	10	12
Atlantic Coast of Del-Mar-Va Total	**757**	**3**	**13**	**13**	**26**	**24**	**38**	**36**	**49**	**47**	**57**	**55**	**64**	**62**	**70**	**68**	**74**	**73**	**78**	**77**	**82**

Table C.1 Low and High Estimates of the Area of Land Close to Sea Level by Region (continued)

Jurisdiction		Meters above Spring High Water																			
		low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high
		0.5		1.0		1.5		2.0		2.5		3.0		3.5		4.0		4.5		5.0	
Delaware	41	2	5	4	7	7	10	9	12	11	14	13	16	15	17	16	18	18	20	19	21
Maryland	105	0	4	5	8	9	13	14	17	18	22	22	26	26	28	29	31	31	33	33	34
Virginia	611	1	5	4	10	9	16	13	19	18	21	20	23	22	24	23	25	24	26	25	27
Chesapeake Bay Total	**1903**	**44**	**151**	**143**	**259**	**231**	**375**	**334**	**489**	**425**	**590**	**510**	**699**	**618**	**809**	**724**	**911**	**827**	**1008**	**920**	**1132**
Delaware	7	1	2	2	3	2	4	3	4	4	5	5	6	6	8	7	9	8	11	10	13
Maryland	1011	29	88	92	137	136	194	189	244	231	282	267	329	315	377	361	420	404	458	441	497
fresh	161	2	9	7	18	14	28	23	38	32	48	42	62	57	79	74	99	94	119	114	142
vulnerable	741	26	69	79	101	110	137	147	166	170	182	188	206	213	228	232	242	245	251	253	259
saline	109	1	10	6	18	12	29	19	40	28	51	36	61	45	70	55	79	64	87	73	95
District of Columbia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Virginia	884	14	60	49	119	92	178	141	240	190	302	239	363	296	424	356	481	415	539	469	622
fresh	168	1	12	8	21	14	30	21	37	27	44	34	52	40	59	47	70	56	83	66	118
vulnerable	88	2	5	4	11	9	18	15	25	21	28	26	31	30	35	33	38	36	41	39	45
saline	628	12	43	37	87	69	129	106	178	142	230	179	280	227	330	276	373	324	415	364	458
Virginia Beach Atlantic Coast	**124**	**6**	**21**	**20**	**37**	**33**	**47**	**42**	**57**	**52**	**66**	**61**	**73**	**69**	**81**	**76**	**88**	**84**	**92**	**89**	**96**
Pamlico Albemarle Sounds	**829**	**2083**	**2625**	**2772**	**3039**	**3130**	**3320**	**3401**	**3562**	**3640**	**3789**	**3852**	**3984**	**4045**	**4173**	**4235**	**4352**	**4409**	**4532**	**4592**	**4695**
Atlantic Coast of North Carolina	**443**	**197**	**255**	**275**	**315**	**335**	**374**	**393**	**429**	**448**	**481**	**495**	**525**	**538**	**568**	**583**	**616**	**632**	**666**	**680**	**710**
Total NY to NC	**5500**	**2374**	**3221**	**3351**	**3940**	**3959**	**4512**	**4487**	**5001**	**4963**	**5449**	**5381**	**5864**	**5788**	**6266**	**6189**	**6652**	**6571**	**7026**	**6948**	**7401**
		Cumulative (total) amount of land below a given elevation																			
Dry Land		918	2101	2181	3545	3457	5047	4860	6526	6228	7964	7523	9418	8946	10949	10475	12325	11831	13470	12956	14441
Nontidal Wetlands		2374	3221	3351	3940	3959	4512	4487	5001	4963	5449	5381	5864	5788	6266	6189	6652	6571	7026	6948	7401
All Land	5500	8792	10822	11032	12985	12915	15059	14847	17027	16690	18913	18404	20782	20234	22715	22163	24476	23902	25996	25403	27342

CHAPTER 2. SITE-SPECIFIC SCENARIOS FOR WETLANDS ACCRETION IN THE MID-ATLANTIC

2.1. Site-Specific Scenarios for Wetlands Accretion as Sea Level Rises in the Mid-Atlantic Region

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2.1.1 Introduction

One of the key questions to be addressed by the U.S. Climate Change Science Program's (CCSP) sea level rise synthesis and assessment is "To what extent can wetlands vertically accrete and thus keep pace with rising sea level; that is, will sea level rise cause the area of wetlands to increase or decrease?" Although predictive models for wetland soil response to sea level rise have been available for some years (e.g., Krone, 1987) and have been amplified to encompass biotic as well as mineral contributions to vertical soil building (e.g., Morris et al., 2002; Rybzyck and Cahoon, 2002), applying these models over wetland landscapes requires detailed information on wetland biogeomorphic processes. Many site-specific field studies can provide this information for local areas, but available models cannot, at present, predict coastal wetland response to sea level rise over large areas.

To support the CCSP efforts and provide spatially explicit landscape scale predictions of coastal wetland response to future sea level rise, an expert panel approach was used. EPA's Climate Change Division (CCD), which has the lead on the sea level rise synthesis and assessment product for CCSP, determined that the focus would be on the Mid-Atlantic (defined here as the Atlantic shore of Long Island to Virginia). They also provided three sea level rise scenarios for the panel to consider:

- Current rates: rates and the regions to which the rates apply were to be determined by the panel;
- An increase of 2 mm per year above the current rates (termed here midrange sea level rise);
- An increase of 7 mm per year above the current rates (termed here high-range sea level rise).

The panel's task was to assess for the Mid-Atlantic region how coastal wetlands would respond to changes associated with these sea level rise scenarios. To support this effort, a literature review of published, and in some cases unpublished, reports of recent and historical accretion rates for the Mid-Atlantic was conducted.

Expert Panel Approach

The panel consisted of a group of experts with first-hand knowledge of the coastal wetland geomorphic processes in the Mid-Atlantic. They convened in a 2-day workshop in February 2006 at the Patuxent Wildlife Research Center in Maryland. Their deliberations were designed to ensure that conclusions were based on an understanding of the processes driving marsh survival in the face of sea level rise and how the magnitude and nature of these processes might change in the future owing to the effects of climate change and other factors.

To ensure a systematic approach across regions within the Mid-Atlantic and throughout the workshop, the following procedures were used:

- A series of geomorphic settings, and in some cases subsettings, was identified to assist in distinguishing between the different process regimes controlling coastal wetland accretion.[1] The settings were chosen to encompass the vast majority of coastal wetlands found on the Mid-Atlantic.

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[1] The term accretion is used in this report to describe net change in the relative elevation of the marsh surface in the tidal frame. Individual studies have distinguished between specific measures of elevation change (documented against a fixed datum) or surface accretion where methods focus on accumulation of material on or near the marsh surface.

- A suite of processes potentially contributing to marsh accretion in the Mid-Atlantic was established and described in general terms. In addition, likely future changes in current process regimes due to climate change were outlined.
- The Mid-Atlantic was divided into a series of regions based on similarity of process regime and current sea level rise rates. The current rate of sea level rise and the source of the tide gauge data supporting that rate were identified for each region. This rate defined the first of the sea level rise scenarios and provided the baseline for the mid-range and high-range rates.
- Within each region, geomorphic settings were delineated by drawing polygons onto 1:250,000 scale USGS topographic paper maps, and the fate of the wetlands within these settings under the three sea level rise scenarios was agreed upon. The fate of the wetlands was allocated to the categories described in Table 2.1.1 based on the following potential outcomes:
    - 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 might mean frequent inputs of sediments from storms or floods, or the maintenance of hydrologic conditions conducive to plant productivity. Given the complexity and inherent variability of factors (climatic and otherwise) influencing wetland accretion, the fate of these wetlands cannot be predicted by the panel. However, under the best of circumstances they are expected to survive.
    - Loss—wetlands will be subject to increased hydroperiod beyond that normally tolerated by the vegetative communities, leading to deterioration and conversion to open water.
- The paper maps were delivered to the EPA project officer, who defined a procedure for converting the polygons into a GIS data base, designed thematic map categories and map legends, and contracted with Stratus Consulting to prepare the maps that appear in this report. For further details of how the maps were created and the GIS output associated with this report, see Titus et al. (Section 2.2).

Report Content

This report summarizes the background information provided to the panel, and describes the geomorphic settings and accretionary processes identified by the panel for the Mid-Atlantic. The purpose of this report is not to provide a complete synthesis of the data assembled to inform the group or to reiterate the extensive literature of coastal wetland accretionary processes. The main focus of the report is to provide narrative discussion of the rationale behind the categories of wetland response to sea level scenarios depicted in the maps. This is provided by the regions defined by the panel, and includes a rationale for the selected current rate of sea level rise, the assignment of geomorphic settings and associated accretionary processes, and a summary of the spatial distribution of the response categories assigned within each region by the panel.

Table 2.1.1. Categories of Wetland Response to Sea Level Scenarios

Category	Summary Outcomes			Description
	Current	Midrange	High-Range	
Loss under current rates	L			These wetlands are not sustainable under current circumstances and they are not expected to be reestablished by natural processes in the future.
Marginal under current rates, loss under midrange scenario	M	L		These wetlands are marginal now and will be lost if sea level rise rates increase by 2 mm/yr.
Marginal under current rates, marginal or loss under midrange scenario	M	M–L		These wetlands are marginal now and will be able to keep pace only under the best of circumstances if sea level rise rates increase by 2 mm/yr.
Keeping pace under current rates, marginal under midrange, loss under high- range scenario	K	M	L	These wetlands are currently keeping pace and will continue to do so only under the best of circumstances if sea level rise rates increase by 2 mm/yr. They will be lost if sea level rise rates increase by 7 mm/yr.
Keeping pace under current and midrange rates, loss under high-range scenario	K	K	L	These wetlands are currently keeping pace and will continue to do so if sea level rise rates increase by 2 mm/yr. They will be lost if sea level rise rates increase by 7 mm/yr.
Keeping pace under current and midrange rates, marginal or loss under high-range scenario	K	K	M-L	These wetlands are currently keeping pace and will continue to do so if sea level rise rates increase by 2 mm/yr. They will keep pace only under the best of circumstances or in local areas if sea level rise rates increase by 7 mm/yr.
Keeping pace under current and midrange rates, marginal under high-range scenario	K	K	M	These wetlands are currently keeping pace and will continue to do so if sea level rise rates increase by 2 mm/yr. They will keep pace under the best of circumstances if sea level rise rates increase by 7 mm/yr
Keeping pace under all sea level rise scenarios	K	K	K	These wetlands are currently keeping pace and will continue to do so if sea level rise rates increase by 2 mm/yr or 7 mm/yr.

L – Loss, M – Marginal, K – Keeping Pace (see text for definitions).

2.1.2 Recent and Historical Rates

Site-specific field studies of coastal wetland response to sea level rise have been conducted across the Mid-Atlantic. Several types of techniques are used in these studies:

- Historical rates of material accumulation within the wetland soil. These studies use defined depth horizons within cores. The horizons are dated based on radiometric dating with the decay rate of the radionuclide (e.g., ^{137}Cs, ^{210}Pb, ^{14}C) determining the period over which the rates are calculated (e.g., Lynch et al., 1989; Rooth et al., 2003).
- Surficial accretion of material. Vertical increments of material are measured relative to the surface over study-defined periods, usually months to several years. A marker is placed on the marsh surface at the beginning of the study and buried over time (e.g., Cahoon and Turner, 1989).
- Net change in marsh elevation relative to a fixed datum. These techniques, such as the Sediment Erosion Tables (SETs) (Boumans and Day, 1993) or Rod Surface Elevation Tables (Cahoon et al., 2002), measure the net result of processes both increasing (e.g., surface sediment deposition, soil peat accumulation) and decreasing (e.g., compaction, decomposition) elevation. The datum is established at the start of the study and measurements are made periodically, usually at least annually, relative to this baseline.

Reed and Cahoon (1993) provide a more detailed account of the techniques and their assumptions concerning rates of change within marshes.

Table 2.1.2 lists the studies of wetland accretion in the Mid-Atlantic identified for this study and includes information on the methodology used as well as some basic descriptive terms for the studied marshes (derived from the source publications). Note that the term "accretion" is used in Table 2.1.2 generally, as in the rest of the report, to embrace rates of vertical change no matter which technique is used. In some studies multiple methods are used to derive several accretion rates at the same location. The results, presented here state by state, were intended to provide contextual information to the expert panel rather than define areas of geomorphic or accretionary commonality.

For coastal wetlands in New York, most of the identified studies used ^{210}Pb dating to derive accretion rates. None of the studies for which primary sources were found included accretion rates above 5 mm/yr, with most rates between 2 and 4 mm/yr. Interestingly, a number of separate papers on Flax Pond marshes, examining accretion in different marsh types and settings, show rates varying within the Flax Pond system from 1.6 to 6.3 mm/yr. The very few studies found for marshes in New Jersey showed great variation in rates from 3.8 mm/yr to more than 13 mm/yr.

For Delaware, rates of 2–7 mm/yr are common, with some higher rates found at Indian River Bay, Little Lagoon Marsh and Port Mahon (Kraft et al., 1992). Other studies in Delaware have measured accretion rates > 10 mm/yr but these are largely restored marshes building quickly toward an equilibrium tidal elevation (R.A. Orson, Orson Environmental Consultants, unpublished information). Although previous work (e.g., Pethick, 1981; Krone, 1987) suggests that marshes low in the tidal frame are likely to experience higher accretion rates, using these restored marsh rates to assess future response to sea level rise in established marshes would require an assumption about marsh elevation in the tidal frame that could not be supported by data. Most of the rates documented from primary sources for Delaware are based on radiometric dating. This technique incorporates any compaction of soil layers above the dated horizon and as such can be considered a more conservative measure of accretion than accumulation over a surficial marker horizon. Radiometric dating also averages rates of accretion over several decades or more, reducing the influence of episodic events on the measured rates.

For Maryland, more of the data shown in Table 2.1.2 are derived from short-term measurements, some for periods as short as 6 months. Rates range from very high, e.g., >15 mm/yr of accretion at fresh marshes in Jug Bay (Boumans et al., 2002), to highly negative, e.g., a loss of more than 15 mm in *Spartina patens* marshes on the Patuxent estuary (Childers et al., 1993). Longer term rates based on pollen or radiometric dating show positive accretion (negative rates can only be derived from elevation change measures such as SET or RSET) of between 1 and 10 mm/yr with great variation from site to site.

Both back barrier lagoon and riverine marshes have been studied in Virginia using marker horizons, SETs, and ^{210}Pb dating. The study by Darke and Megonigal (2003) on Walkerton Marsh shows a rate of accretion over a marker horizon of only 0.12 mm/yr. This is a fresh riverine system, and it is possible that surface elevation may be more driven by below-ground processes and not reflected in the surficial accumulation measured above the marker.

Table 2.1.2. Summary of published sources of accretion rates, by state, identified as part of this study.

Location	Accretion Rate (mm/yr)	Method	Marsh Type low/ high	Marsh Type fresh/ brackish/ salt	Dominate Plant Community	Geomorphic Setting	Source
DELAWARE							
Assawoman Bay lagoon marsh	3.5-8.2	Lead 210 & Cesium 137	low		*Spartina alterniflora*	lagoon	Kraft et al., 1992
Boat house cove	4.00			salt		estuarine	Carey, 1996 (in Nikitina et al., 2000)
Delaware Bay	3.0-5	Lead 210		salt		bay	Church et al., 1987
Delaware Bay	4-5					bay	Kraft et al., 1989 (in Fletcher et al., 1990)
Delaware Wildlands	3.40			salt			Carey, 1996 (in Nikitina et al., 2000)
Duck Creek	1.30	radiocarbon dating				estuarine	Pizzuto and Rogers, 1992
Duck Creek	3.2-3.4	Lead 210 & Cesium 137	low		*Spartina alterniflora*	estuarine	Kraft et al., 1992
Great Marsh	2.9-8.2	Lead 210 & Cesium 137	low		*Spartina alterniflora*		Kraft et al., 1992
Indian River Bay	2.3-10.7	Lead 210 & Cesium 137	low		*Spartina alterniflora*	bay	Kraft et al., 1992
Indian River Bay lagoon	5.0-6.9	Lead 210 & Cesium 137	low		*Spartina alterniflora*	lagoon	Kraft et al., 1992
Leipsic River	2.90	Lead 210	low	salt	*Spartina alterniflora*	estuarine	Nikitina et al., 2000
Lewes	>10	Cesium 137				estuarine	Brickman, 1978 (in Stevenson et al., 1986)
Lewes	3.30			salt		estuarine	Carey, 1996 (in Nikitina et al., 2000)
Lewes	4.70	Lead 210		salt		estuarine	Church et al., 1981
Lewes	5.00	marker horizon (<1 year)				estuarine	Stumpf, 1983
Lewes	2.0-3.6	Lead 210 & Cesium 137	low		*Spartina alterniflora*	estuarine	Kraft et al., 1992
Little Lagoon marsh	2.8-10	Lead 210 & Cesium 137	low		*Spartina alterniflora*	lagoon	Kraft et al., 1992
Mispillion River marsh	3.6-5.3	Lead 210 & Cesium 137	low		*Spartina alterniflora*	estuarine	Kraft et al., 1992
No specific location	5.1-6.3	marker horizon					Stearns & MacCreary, 1957
No specific location	5.00	Lead 210	low	salt			Lord, 1980 (in Armentano et al., 1988)
Port Mahon	0.04		high			estuarine	Khalequzzaman, 1989 (in Fletcher et al., 1993)

Location	Accretion Rate (mm/yr)	Method	Marsh Type low/ high	fresh/ brackish/ salt	Dominate Plant Community	Geomorphic Setting	Source
Port Mahon	2-19.1	Lead 210 & Cesium 137	low		*Spartina alterniflora*	estuarine	Kraft et al., 1992
Pot Nets North	3.90			salt			Carey, 1996 (in Nikitina et al., 2000)
Rehoboth Bay	3.3-7.6	Lead 210 & Cesium 137	low		*Spartina alterniflora*	bay	Kraft et al., 1992
Rehoboth Bay	2.60	Lead 210				lagoon	Chrzastowski, 1986 (in Schwimmer and Pizzuto, 2000)
Rehoboth Bay lagoon	2.3-5.9	Lead 210 & Cesium 137	low		*Spartina alterniflora*	lagoon	Kraft et al., 1992
South Bowers Marsh	1.8-7.8	Lead 210 & Cesium 137	low		*Spartina alterniflora*	estuarine	Kraft et al., 1992
Wolfe Glade	0.3-3.0	radiocarbon dating				estuarine	Fletcher et al., 1993
Wolfe Runne	3.70			salt			Carey, 1996 (in Nikitina et al., 2000)
Woodland Beach	2.1-6.8	Lead 210 & Cesium 137	low		*Spartina alterniflora*	estuarine	Kraft et al., 1992
MARYLAND							
Blackwater	1.7-3.6	Lead 210				estuarine	Stevenson et al., 1985
Chincoteague Bay	1.50					back barrier bay	Bartberger, 1976 (in Orson et al., 1985)
Deal Island Management Area	4.0- SET 6.4- marker	SET & marker horizon (6 mo)		salt	*Spartina alterniflora*	estuarine	Rooth and Stevenson, 2000
Jug Bay	11.19-SET 16.59-marker	SET & marker horizon (2 years)	mid	fresh	*Typha angustifolia & Typha latifolia*	estuarine	Boumans et al., 2002
Jug Bay	5.39- SET 9.39- marker	SET & marker horizon (2 years)	low	fresh	*Nuphar advena*	estuarine	Boumans et al., 2002
Jug Bay	-11.1- SET 1.2-marker	SET & marker horizon (2 years)	high	fresh	*Alnus serrulata*	estuarine	Boumans et al., 2002
Jug Bay	4.30	carbon 14 & pollen analysis	high	fresh	*Typha angustifolia & Typha latifolia*	estuarine	Khan and Brush, 1994
Jug Bay	4.20	carbon 14 & pollen analysis	low	fresh	*Nuphar advena*	estuarine	Khan and Brush, 1994
Kenilworth Marsh	1.75	SET (2 years)				riverine	Hammerschlag (personal communication, USGS)
Kingman Marsh	-5.00	SET (2 years)				riverine	Hammerschlag (personal communication, USGS)
Kings Creek Preserve	4.0-9.5	Lead 210		salt	*Phragmites australis*	estuarine	Rooth et al., 2003
Lower Pocomoke River	1.50	pollen dating				estuarine	Douglas, 1985 (in Stevenson and Kearney, 1996)

Location	Accretion Rate (mm/yr)	Method	Marsh Type: low/ high	Marsh Type: fresh/ brackish/ salt	Dominate Plant Community	Geomorphic Setting	Source
Monie Bay	1.5-6.3	pollen dating		brackish	*Sp. patens, Spartina cynosuroides & Scirpus olneyi*	estuarine	Ward et al., 1998
Monie Bay	7.2-7.8	Lead 210, Cesium 137 & pollen dating		brackish	*Sp. patens, Spartina cynosuroides & Scirpus olneyi*	estuarine	Kearney & Stevenson, 1991
Muddy Creek	3.33	SET (2 years)	high	brackish	*Scirpus olneyi*	estuarine	Childers et al., 1993
Nanticoke River Estuary	1.8-7.4	pollen dating	high-low	brackish	*Phragmites australis & Spartina cynosuroides*	estuarine	Kearney and Ward, 1986
Patuxent River	-1.40	SET (2 years)		fresh		estuarine	Childers et al., 1993
Patuxent River	4.40	SET (2 years)			*Spartina patens*	estuarine	Childers et al., 1993
Patuxent River	24.00	SET (2 years)			*Spartina patens*	estuarine	Childers et al., 1993
Patuxent River	20.70	SET (2 years)			*Phragmites*	estuarine	Childers et al., 1993
Patuxent River	-16.20	SET (2 years)			*Spartina patens*	estuarine	Childers et al., 1993
Patuxent River	-14.50	SET (2 years)				mudflat	Childers et al., 1993
Patuxent River	52.00	SET (2 years)				mudflat	Childers et al., 1993
Potomac River	1.7-15.5					estuarine	Brush et al., 1982 (in Orson et al., 1990)
NEW JERSEY							
Great Egg Harbor	6.0-10	Cesium 137				lagoon	Psuty (personal communication, Rutgers University)
Little Beach	3.80 (no specifics of SET or marker)	SET & marker horizon (3 years)	high		*Spartina alterniflora*	back barrier lagoon	Erwin et al., 2006
Princeton/ Jefferson marsh	12-13.2	Cesium 137, Lead 210 & pollen/historical		fresh		estuarine	Orson et al., 1990
NEW YORK							
Alley Pond	3.50	Lead 210	high	salt	*Spartina patens*	estuarine	Cochran et al., 1998
Carmans River	2.7-3.3	Lead 210				back barrier marsh	Kolker, 2005
Caumsett Park	4.10	Lead 210	high	salt	*Spartina patens*	estuarine	Cochran et al., 1998
Flax Pond	4.7-6.3	Lead 210	low	salt	*Spartina alterniflora*	estuarine	Armentano and Woodwell, 1975
Flax Pond	2.10	Lead 210	high	salt	*Spartina patens*	estuarine	Cochran et al., 1998
Flax Pond	2.5-4.7	historical record		brackish	*Spartina alterniflora*	estuarine	Flessa et al., 1977
Flax Pond	1.60	Lead 210				estuarine	Kolker, 2005

Location	Accretion Rate (mm/yr)	Method	Marsh Type low/ high	Marsh Type fresh/ brackish/ salt	Dominate Plant Community	Geomorphic Setting	Source
Flax Pond	4.00	Lead 210				estuarine	Muzyka, 1976 (in Richard, 1978)
Flax Pond	2-4.25	marker horizon (1.5 years)				estuarine	Richard, 1978
Fresh Pond	4.30	Lead 210				estuarine	Clark and Patterson, 1985
Goose Creek	2.40	Lead 210	high	salt	*Spartina patens*	estuarine	Cochran et al., 1998
Hempstead Bay	1.4-5	Lead 210				estuarine	Kolker, 2005
Hubbard County Park	2.3-3	Lead 210				back barrier marsh	Kolker, 2005
Hunter Island	1.10	Lead 210	high	salt	*Spartina patens*	estuarine	Cochran et al., 1998
Jamaica Bay	2.8-4.4	Lead 210				lagoon	Kolker, 2005
Jamaica Bay	5.0-8		high			lagoon	Zeppie, 1977 (in Hartig et al., 2002)
Nissequogue River	3.5-4	Lead 210				estuarine	Kolker, 2005
Shelter Island	3.00	Lead 210	high	salt	*Spartina patens*	estuarine	Cochran et al., 1998
Stony Brook Harbor	2.4-2.8	Lead 210	high-low			estuarine	Cademartori, 2000 (in Hartig et al., 2002)
Youngs Island	4.6-4.8	Lead 210				estuarine	Cademartori, 2000 (in Kolker, 2005)
Youngs Island	3.5-4.8	Lead 210				estuarine	Cochran et al., 1998 (in Kolker, 2005)
VIRGINIA							
Gleason Marsh	0.27	marker horizon (19 months)		fresh	*Sp. cynosuroides & Eliocharis quadrangulata*	riverine	Darke and Megonigal, 2003
Mockhorn	12.70 (no specifics on SET or marker)	SET & marker horizon (4 years)	high		*Spartina alterniflora*	back barrier lagoon	Erwin et al., 2006
Oyster	1-2.2	Lead 210		salt	*Spartina alterniflora*	back barrier marsh	Oertel et al., 1989
Wachapreague	2.3- SET 8.5- marker	SET & marker horizon (4 years)	high		*Spartina alterniflora*	back barrier lagoon	Erwin et al., 2006
Walkerton Marsh	0.12	marker horizon (19 months)		fresh	*Pontedaria cordata & Acorus calamus*	riverine	Darke and Megonigal, 2003

2.1.3. Settings and Processes

The fate of coastal wetlands in the Mid-Atlantic will be determined in large part by the way in which the accretionary processes change with climate drivers. These processes vary by geomorphic setting. The expert panel identified five primary geomorphic settings with several subsettings for the coastal wetlands of the Mid-Atlantic:

- 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)

This classification is similar to global scale assessments of others (e.g., Woodroffe, 2002; Cahoon et al., 2006) but is more detailed in its consideration of subsettings to reflect the finer scale of expert panel assessment.

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, and 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.

Accretionary processes vary among settings. The panel identified nine basic processes that influence the ability of wetlands in these settings to keep pace with sea level rise:

- **Storm sedimentation**. Storm-driven sedimentation typically occurs on time scales of years to decades, resulting in inputs of sediments into marshes and forest greater than those that occur under more common process regimes. The source can be sediment-laden floodwaters associated with high precipitation in adjacent watersheds (e.g., Pasternack and Brush, 1998), local resuspension within coastal bays (e.g., Reed, 1989), or overwash of barrier beaches to bordering marshes (e.g., Donnelly et al., 2001). The latter effect is more important to back barrier marshes than to flood tide deltas. Within ES marshes, storm flooding can lead to both the import and export of material.

- **Tidal Fluxes of Sediment.** Although tidal exchange is limited at the heads of estuaries, many FF and FM marshes in the Mid-Atlantic are potentially exposed to tidal sediment input. Ebb dominance can lead to export of sediment from the system through subtidal channels and the deepening of these channels, especially in BB and SF marshes (Aubrey and Weishar, 1998). This reduces sediment availability within the lagoons for resuspension and transport to marshes during storms. Within ES marshes, tidal exports have been shown to result in a substantial loss of sediment in severely stressed marshes

(Stevenson et al., 1988). It is possible that as the sea level rises, wetland systems could become flood dominated. The role of tidal flux in influencing accretion would then be modulated by the available sediment supply to the system (e.g., fluvial and oceanic sources, described separately).

- **Peat Accumulation.** In freshwater systems where productivity is high, the accumulation of organic material in the wetland soil is a key driver of accretion. However, both microbial degradation of marsh peat and plant die-offs can lead to a drop in marsh surface elevation (e.g. Nyman et al., 1993; DeLaune et al., 1994). This process is most important in FM, and can also be impacted by changes in salinity increasing the potential for organic matter decomposition by sulfate-reducing bacteria. However, the *Spartina patens* marshes common in ES are also characterized by organic soils. BB and SF marshes are dominated by *Spartina alterniflora*. Peat accumulation may not be a primary driver of accretion in these systems, but organic-rich soils still occur.

- **Ice Rafting.** Ice accumulation and movement during the winter months strip remnant vegetation from the marsh surface, exposing the marsh surface. When marsh soil is rafted with moving ice floes, it can contribute sediment to the area where the ice floe melts, sometimes on the marsh surface (Wood et al., 1989). The effect of this process on accretion is localized and can be both erosive and accretionary.

- **Nutrient Supply.** Most wetlands in the Mid-Atlantic are not nutrient limited, so changes in the supply of nutrients do not have a substantial effect on accretion. However, in sandy substrates where soil organic matter is limited, e.g., BB and some SF marshes, it can increase plant productivity (Bertness, 1999). It has less of a role in FF, FM, and ES soils that are dominated by fine sediments and are more organic in nature.

- **Groundwater.** Groundwater can supply freshwater and nutrients to inshore bays and tidal wetlands (e.g., Bokuniewicz, 1980). Reduction in salt stress and increased nutrition can increase the productivity of some marshes, but this effect is very localized.

- **Fluvial sediment supply.** The role of fluvial sediment delivery to tidal wetlands during nonstorm conditions varies across the estuarine gradient. In FF and FM, these inputs can occur several times per year and thus provide a recurring source of sediment (Pasternack and Brush, 1998). Within the estuary, ES marshes in the vicinity of an estuarine turbidity maximum are most likely to benefit as the fluvial sediment is trapped within a zone of the estuary and is more available to marshes in that area. Local streams can also supply individual ES marshes with sediment. Toward the coast in BB and SF systems, fluvial input of sediment is generally minimal, but it could be locally important where streams discharge directly into coastal lagoons. In many systems, fluvial sediment supplies are strongly affected by dams and local land use practices. In these systems, future fluvial sediment supplies will be affected by jurisdictional responses to climate change.

- **Herbivory.** Although the effects of herbivory on tidal marshes can be dramatic (Ford and Grace, 1998) and their role in limiting regeneration of wetland forests is of concern, the effects of herbivory on accretionary processes are indirect and most likely important only locally. Some recent work has suggested that grazing by snails can be an important control on above-ground productivity in salt marshes (Silliman and Zieman, 2001); the effect on accretion has not been documented.

- **Oceanic Sediment Inputs.** The import of sediment from the ocean by tides and during storms can be of importance in SF and BB systems, especially flood tide deltas.

2.1.4. Wetland Responses to Sea Level Scenarios

Table 2.1.1 describes the potential wetland responses associated with the three sea level scenarios. The regions delineated by the expert panel have been described according to geomorphic setting and wetland response. In all cases the panel's assessment of wetland response assumes that human activities that influence marsh accretionary processes (e.g., dredged channels that act as sediment sinks and limit the supply of sediment for accretion) do not change in the future. The exception to this is where climate change is considered to influence the activity (e.g., land use) and thus the accretionary processes. Each section includes the panel's rationale and narrative supporting the current sea level rise rate, the character and distribution of geomorphologic settings, and wetland response to future sea level rise scenarios.

New York – Long Island

This region encompasses the tidal marshes on the Atlantic shore of Long Island. The most appropriate tide gauge to document current sea level rise trends is New York City. The current rate of sea level rise for the area was determined to be 3 mm/yr, making the two future rates considered 5 mm/yr and 10 mm/yr. The geomorphic setting for these marshes is either BB or SF (Figure 2.1.1).

The dominant accretionary processes are storm sedimentation and peat accumulation. Future climate change will result in an increase in the magnitude of coastal storms, due to increasing sea-surface temperatures, and their frequency will be at least as common as at present (Webster et al., 2005). Thus, there is likely to be a net increase in storm sedimentation in marshes in this region. Although sea level rise may drive an increase in peat accumulation, local anthropogenic impacts to sediment geochemistry may currently be leading to peat deterioration. The response of marshes in this region to climate change depends in large part on their ability to cope with the nontrivial anthropogenic impacts caused from the New York City Metropolitan Region (e.g., Kolker, 2005). Any increase in vertical accretion driven by peat accumulation will occur only up to a threshold level. This threshold is currently unknown for this region and has not been assessed for such impacted marshes as those on Long Island. It has been identified as ~10 mm/yr for Rhode Island marshes (Bricker-Urso et al., 1989) and >12 mm/yr for marshes in the southeastern United States (Morris et al., 2002).

In addition, other accretionary processes are also expected to change (Scavia et al., 2002):

- Tidal fluxes may shift to more ebb dominance as the tidal prism increases, exporting more sediment.
- Ice effects will diminish in importance as climate warms, reducing both destructive and constructive influences.
- Nutrient delivery from coastal watersheds is likely to increase, because both climatic effects and land use changes result in greater runoff, though it is highly dependent on local land use practices. This increase could stimulate productivity in local marsh areas.
- Fluvial sediment inputs will be equal to or greater than present inputs and may positively influence marsh accretion locally, but are also dependent on local land use practices.

Figure 2.1.2 illustrates that the only marshes in this region that are expected to survive the highest rate of future sea level rise are BB lagoonal fill marshes near Gilgo and Cedar islands, and those immediately behind Long

Beach. These are areas where marshes are currently expanding, indicating adequate sediment supply from overwash and tidal inlets. BB lagoonal fill marshes in east and west Jamaica Bay, and SF marshes fringing Jamaica Bay, Middle Bay, and East Bay, will be able to keep pace with midrange sea level rise but are likely to be lost if sea level increases to 10 mm/yr. These marshes are supplied with sediment from storm reworking but also require peat accumulation to retain their elevation. Marshes in the western part of Jamaica Bay mostly comprise dredge fill and are subject to loss factors other than insufficient vertical accretion. A rate of 10 mm/yr is most likely too great for them to survive. The BB flood tide delta marshes adjacent to Jones Inlet will be marginal at the higher rate of rise and may be lost, but are likely to survive midrange predictions. Extensive areas of marsh, both BB and SF, surrounding Great South Bay, Moriches Bay, and Shinnecock Bay, as well as those east of Southampton, are keeping pace with current rates of sea level rise but will be marginal if rates increase to 5 mm/yr. Most of these are salt marshes, and episodic supply of sediment from storms and organic accumulation may not be enough to compensate for even an increase of 2 mm/yr over current trends. Loss rates are already high in the marshes of central Jamaica Bay (38–78 percent; Hartig et al., 2002). There is no expectation that these marshes will become more viable in the future. Many of the marshes in this region are highly susceptible to human activities both directly and indirectly, and their survival, especially under marginal conditions, will largely depend on how development pressures and other land use changes influence patterns of sediment supply and dispersal within this region.

Raritan Bay/New York Bay

This region encompasses the tidal marshes of Raritan Bay and New York Bay and extends north to the Hackensack Meadows. The most appropriate tide gauge to document current sea level rise trends is Sandy Hook, New Jersey. The current rate of sea level rise for the area was determined to be 4 mm/yr, making the two future rates considered 6 mm/yr and 11 mm/yr. The geomorphic setting for these marshes includes small areas of FM along the South River and Raritan River, with most of the area being ES and SF marshes (Figure 2.1.3).

The dominant accretionary processes are peat accumulation and fluvial sediment inputs. Vertical accretion driven by peat accumulation is also expected to increase in the future in response to increased sea level. However, in most of these marshes, this increase will occur only up to a threshold level. The exception is the FM area where peat accumulation should allow marshes to accrete and even expand in the face of high-range sea level rise. The threshold level for ES and SF marshes is currently unknown for this region, although lower salinity ES marshes will be less subject to the threshold and more similar to FM. Fluvial sediment inputs are expected to increase in this area as climate changes cause precipitation events to be more intense and periodic, resulting in flashy runoff (National Research Council, 2004). Other accretionary processes are also expected to change:

- Future climate change will result in an increase in the magnitude of coastal storms, and their frequency will be at least as common as at present, resulting in a net increase in storm sedimentation in marshes in this region.
- Tidal fluxes may alter, but the effect is minimal in this region and the nature of the effect on accretion is variable.
- Ice effects will diminish in importance as climate warms.
- Nutrient delivery from coastal watersheds is likely to increase as both climatic effects and land use changes result in greater runoff.
- Oceanic sediment inputs to SF may increase because of an increase in storms.

In this region, human activities could have a greater direct effect on the viability of the wetlands than climatic effects on accretionary processes. Development pressures and land use changes alter hydrology and nutrient delivery and facilitate invasions, e.g., Phragmites. This can alter plant community structure, which in turn influences peat accumulation and accretion.

Figure 2.1.4 shows that FM along the tidal sections of the South River and Raritan River will survive 11 mm/yr of sea level rise and could even expand because of their high productivity and potential for peat accumulation. All the remaining ES and SF marshes will become marginal if sea level rise accelerates to 6 mm/yr and will be lost under the high-range estimate of 11 mm/yr. For the ES marshes to survive the high-range estimate, sediment input would need to increase dramatically or plant communities would need to change to those with greater potential for peat accumulation. As noted above, human influence may result in such shifts whether or not high-range sea level rise estimates hold true. For the SF marshes to survive 11 mm/yr of sea level rise, a massive increase in sediment inputs would be required. This is not foreseen at this time.

New Jersey Shore

This region encompasses the Atlantic shore of New Jersey from Sandy Hook to Cape May. Two tide gauges, Sandy Hook and Cape May, can be used to document current sea level rise trends for this shoreline. The current rate of sea level rise for the area was determined to be 4 mm/yr, making the two future rates considered 6 mm/yr and 11 mm/yr. The geomorphic setting varies along the shore (Figure 2.1.5). At the northern end, the marshes are mostly ES with some SF, while farther south along the barrier island shoreline BB marshes, both back barrier and lagoonal fill, and SF marshes are dominant. There are ES and even FM within the tidal portions of watersheds draining into the back barrier lagoons.

The dominant accretionary processes are storm sedimentation and peat accumulation. Future climate change will result in an increase in the magnitude of coastal storms due to increasing sea-surface temperatures, and their frequency will be at least as common as at present. Thus, there will be a net increase in storm sedimentation in marshes in this region. Vertical accretion driven by peat accumulation is also expected to increase in the future in response to increased sea level. However, this increase will occur only up to a threshold level. This threshold is currently unknown for this region and there are few published measurements of accretion in this area (Table 2.1.1). Other accretionary processes are also expected to change:

Tidal fluxes may shift to more ebb dominance as tidal prism increases.

- Ice effects, although marginal now, will diminish in importance as climate warms.
- Nutrient delivery from coastal watersheds is likely to increase as both climatic effects and land use changes result in greater runoff.

Fluvial sediment inputs will be equal to or greater than present inputs and may influence marsh accretion locally, especially in the lower sections of the shore. Coastal wetlands along the New Jersey shore are keeping pace with current rates of sea level rise (Figure 2.1.6). However, under midrange estimates they are all considered marginal in terms of survival. The marshes close to the Great Egg River and the Mullica River may be more likely to survive because they have localized sources of sediment from the rivers. Similarly, under the high-range estimates for sea level rise, most of the coastal marshes on the Jersey shore are likely to be lost, except those close to these localized sediment sources.

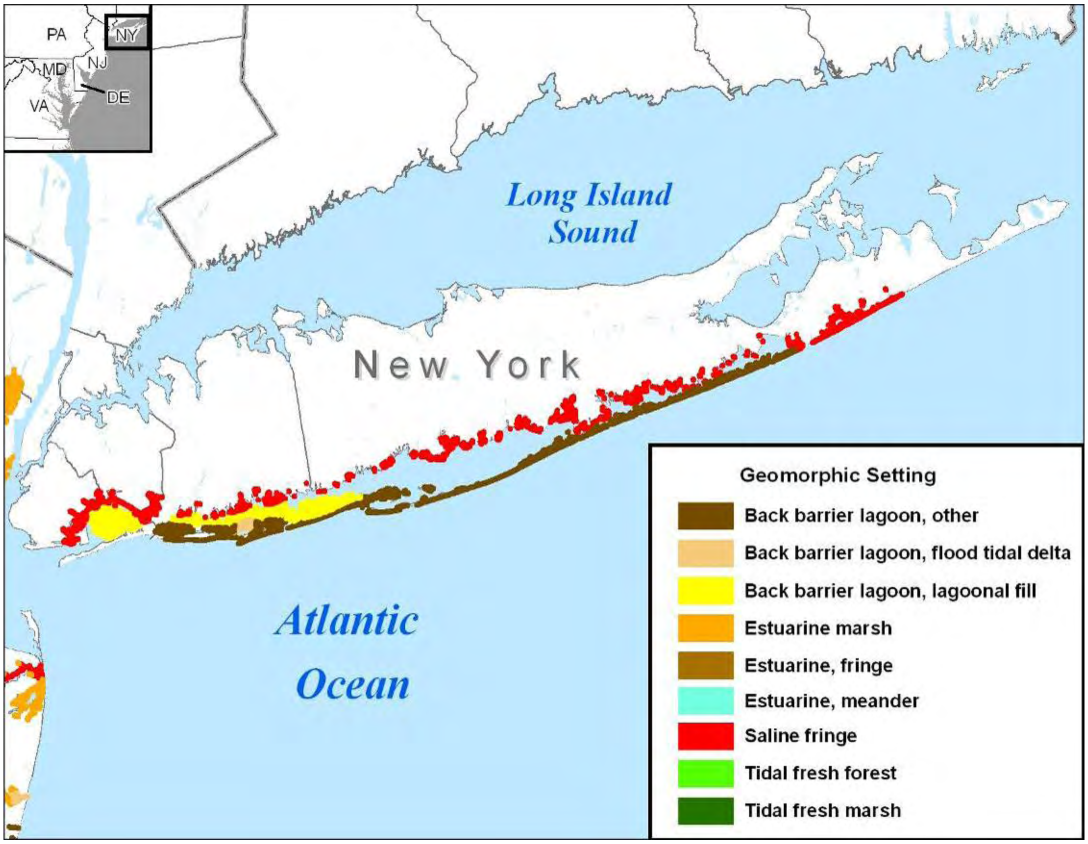

Figure 2.1.1. Geomorphic Settings for the New York – Long Island Region. Source: Titus et al. (Section 2.2).

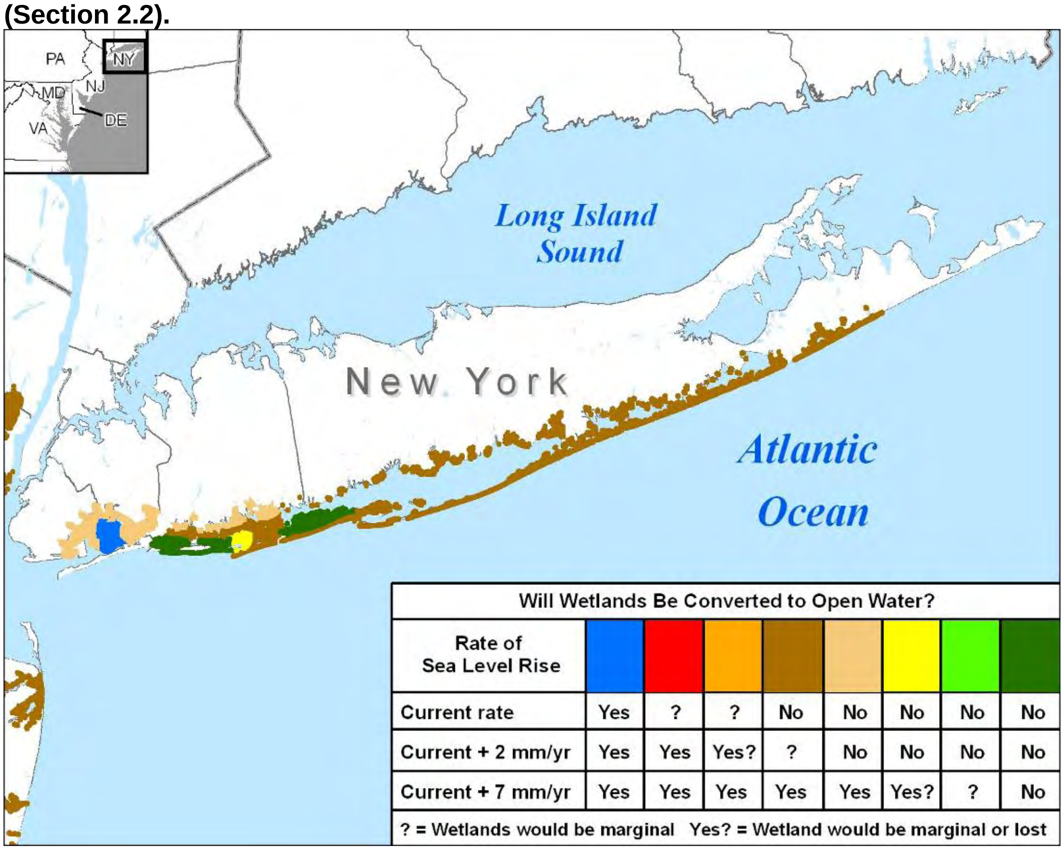

Figure 2.1.2. Wetland Response Map for New York - Long Island Region. Source: Titus et al. (Section 2.2).

Figure 2.1.3. Geomorphic Settings for the New York – Long Island Region. Source: Titus et al. (Section 2.2).

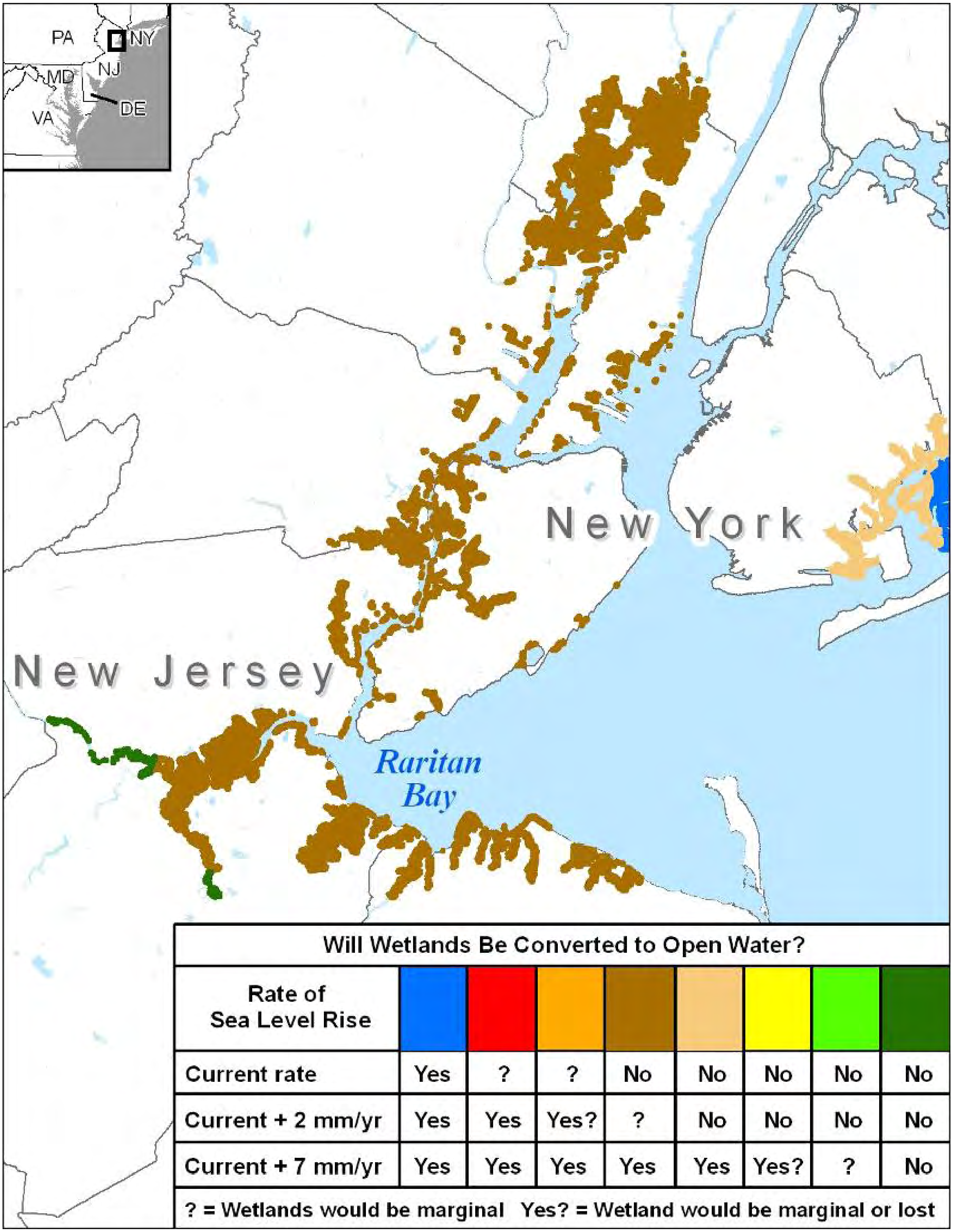

Figure 2.1.4. Wetland Response Map for Raritan Bay – New York Bay region. Source: Titus et al. (Section 2.2).

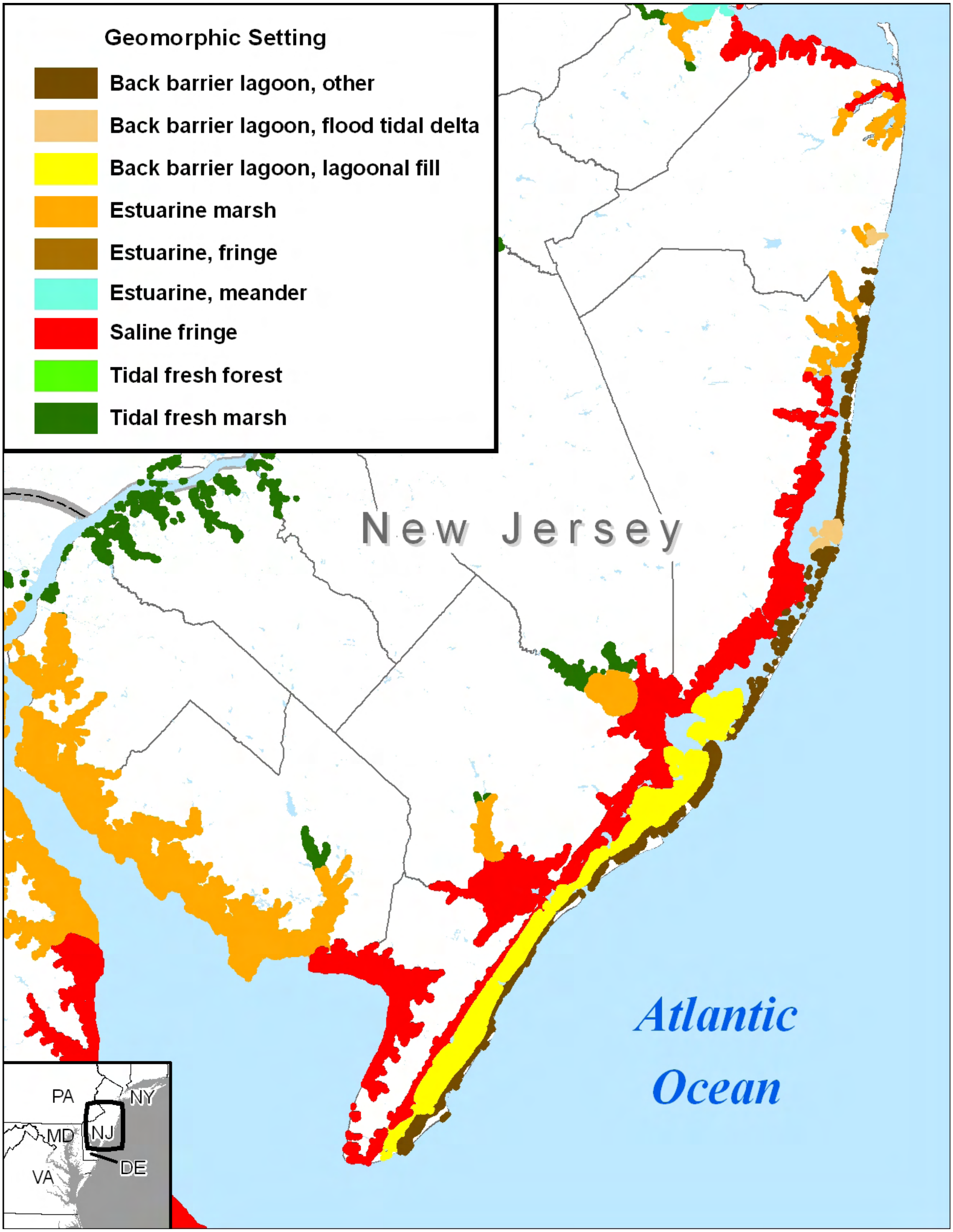

Figure 2.1.5. Geomorphic Settings for the New Jersey Shore Region. Source: Titus et al. (Section 2.2).

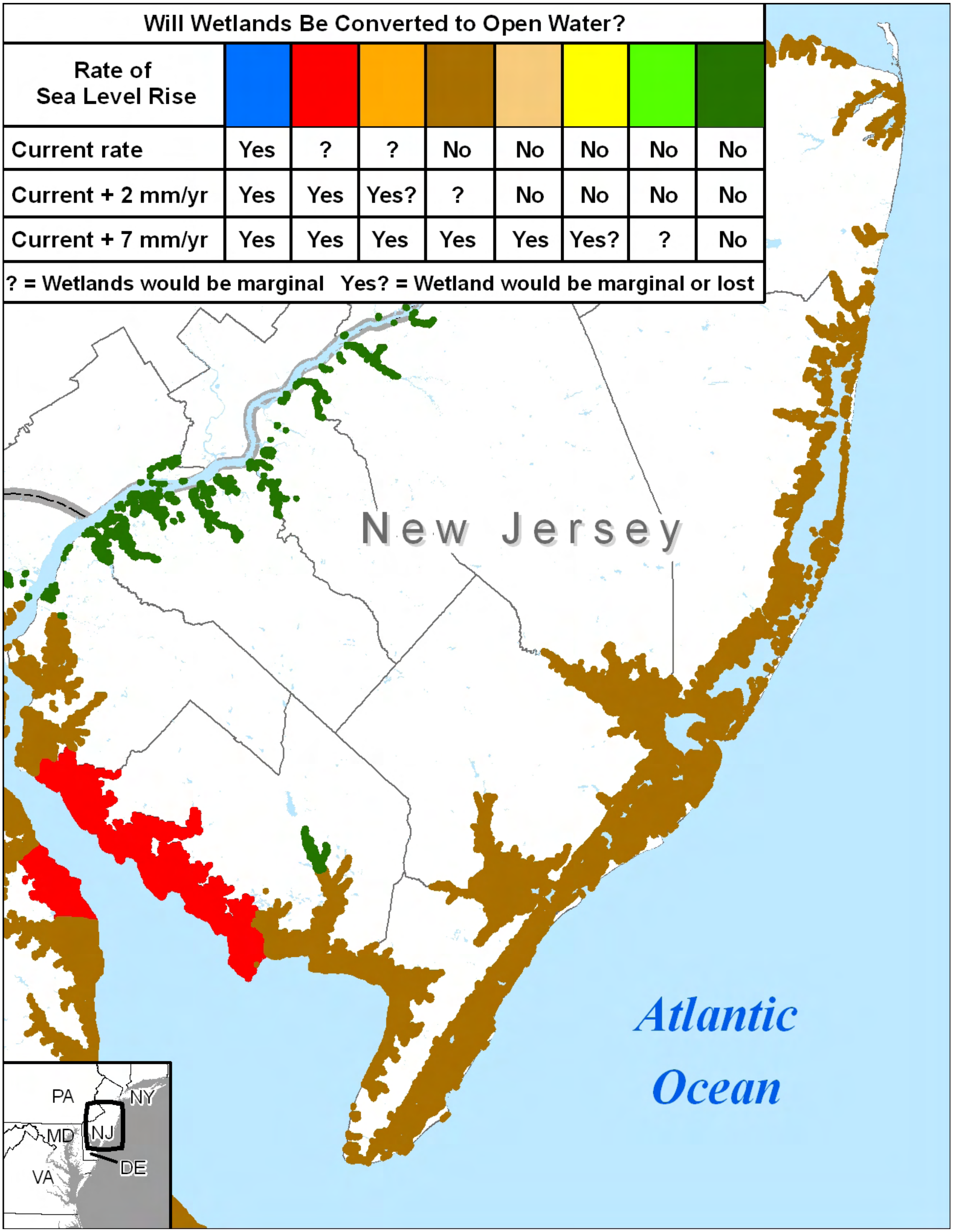

Figure 2.1.6. Wetland Response Map for the New Jersey Shore Region. Source: Titus et al. (Section 2.2).

Delaware Bay

This region encompasses the shores of Delaware Bay and the tidal portions of rivers flowing into the bay. Two tide gauges, Philadelphia and Lewes, can be used to document current sea level rise trends for this shoreline. The current rate of sea level rise for the area was determined to be 3 mm/yr, making the two future rates considered 5 mm/yr and 10 mm/yr. The geomorphic setting varies along the estuarine gradient (Figure 2.1.7). FM exists along tributaries of the Delaware River and in the upper tidal reaches of the Maurice River draining into the bay. Upper parts of Delaware Bay are bordered by ES marshes, with SF marshes toward the ocean.

The dominant accretionary processes vary according to geomorphic setting. Peat accumulation is important to all wetlands in this area. Vertical accretion driven by peat accumulation is expected to increase in the future in response to increased sea level. However, in most of these marshes this increase will occur only up to a threshold level. The exception is the FM area where, as long as marshes stay fresh, peat accumulation should allow marshes to accrete and even expand in the face of high range sea level rise. However, if these salinities increase with sea level rise, SO_4^{2-} reduction will increase, and that could lead to increased rates of decomposition and offset the rise due to peat accumulation. The threshold level for ES and SF marshes is currently unknown for this region, although lower salinity ES marshes will be less subject to the threshold and more similar to FM. Fluvial sediment inputs are important to FM and are expected to increase in this area as climate changes cause precipitation events to be more intense and periodic, resulting in flashy runoff. Future climate change will result in an increase in the magnitude of coastal storms due to increasing sea-surface temperatures, and their frequency will be at least as common as at present. Storm sedimentation is important to ES marshes in this region and is expected to increase in the future. The SF marshes in the lower bay, because of the high fetch and their exposure to oceanic influence, also receive sediment from the Atlantic. Greater storminess will increase the availability of these sediments, benefiting the SF marshes. Other accretionary processes are also expected to change:

- Tidal fluxes may alter, but the effect is minimal in this region.
- Ice effects are of minimal importance here and will diminish in importance as climate warms.
- Nutrient delivery from coastal watersheds is likely to increase as both climatic effects and land use changes result in greater runoff.

Figure 2.1.8 shows that all coastal wetlands in the Delaware Bay region are keeping pace with current rates of sea level rise. The FM marshes along the Delaware and Maurice rivers will survive 10 mm/yr of sea level rise, the high-range estimate, and could even expand because of their high productivity and potential for peat accumulation. However, under midrange estimates (5 mm/yr for this region), ES and SF marshes are all considered marginal in terms of survival and are expected to be lost under the high-range estimate of sea level rise. Sustainability of these marshes in the future will require either a substantial increase in sediment inputs or a change in plant community type to one with a greater potential for peat accumulation. Any such change in plant communities might also change the habitat value of these extensive Delaware Bay marshes. The role of storm sedimentation in future marsh accretion will be dependent to some extent on aspect. Marshes in the New Jersey shore receive less storm-related mineral sediment because nor'easters generally blow water out of the marshes in winter (toward the Delaware shore). These marshes may also be more remote from sediments introduced by period ocean waves from the southeast in summer.

Maryland/Virginia Shore

This region encompasses the Atlantic shore of Maryland and Virginia from Cape Henlopen to Cape Charles. The current rate of sea level rise for this area is best assessed using an average of regional gauges rather than data from a single location. The current rate of sea level rise for the area was determined to be 3 mm/yr, making the two future rates considered 5 mm/yr and 10 mm/yr. The geomorphic setting varies from north to south along this shore (Figure 2.1.9). Along the Delaware shoreline, BB marshes front small lagoons such as Rehoboth Bay and Indian River Bay, with SF on the upland margin. BB lagoonal fill becomes more important toward the southern end of Assateague Island. Farther south, BB flood tide delta marshes are interspersed with BB marshes along the barrier shoreline, with extensive BB lagoonal fill in Hog Island Bay and South Bay, and SF marshes along the upland margin.

The dominant accretionary processes are storm sedimentation and overwash from barrier beaches. Future climate change will result in an increase in the magnitude of coastal storms due to increasing sea-surface temperatures, and their frequency will be at least as common as at present. Thus, there will be a net increase in storm sedimentation in marshes in this region. Vertical accretion driven by peat accumulation is not as important in this area as in other marshes. Many of the marshes occur on pre-existing topographic highs that have been gradually flooding by rising seas. Tidal fluxes are also of minimal importance, except on the flood tide deltas, with local resuspension being the main source of sediment. Other accretionary processes are also expected to change:

- Nutrient delivery from coastal watersheds is likely to increase as both climatic effects and land use changes result in greater runoff.
- Fluvial sediment inputs will be equal to or greater than present inputs and may increase marsh accretion locally. However, watersheds draining into this region are generally small.

Figure 2.1.10 shows the accretion scenarios for this region. All marshes are keeping pace with current rates of sea level rise. However, should sea level rise rates increase to 5 mm/yr, the midrange estimate, they are considered to be marginal. Their survival is likely to depend on the frequency of storm impacts to supply sediments. Under the high range estimate of 10 mm/yr, these marshes will be lost because they will not be able to maintain their elevation.

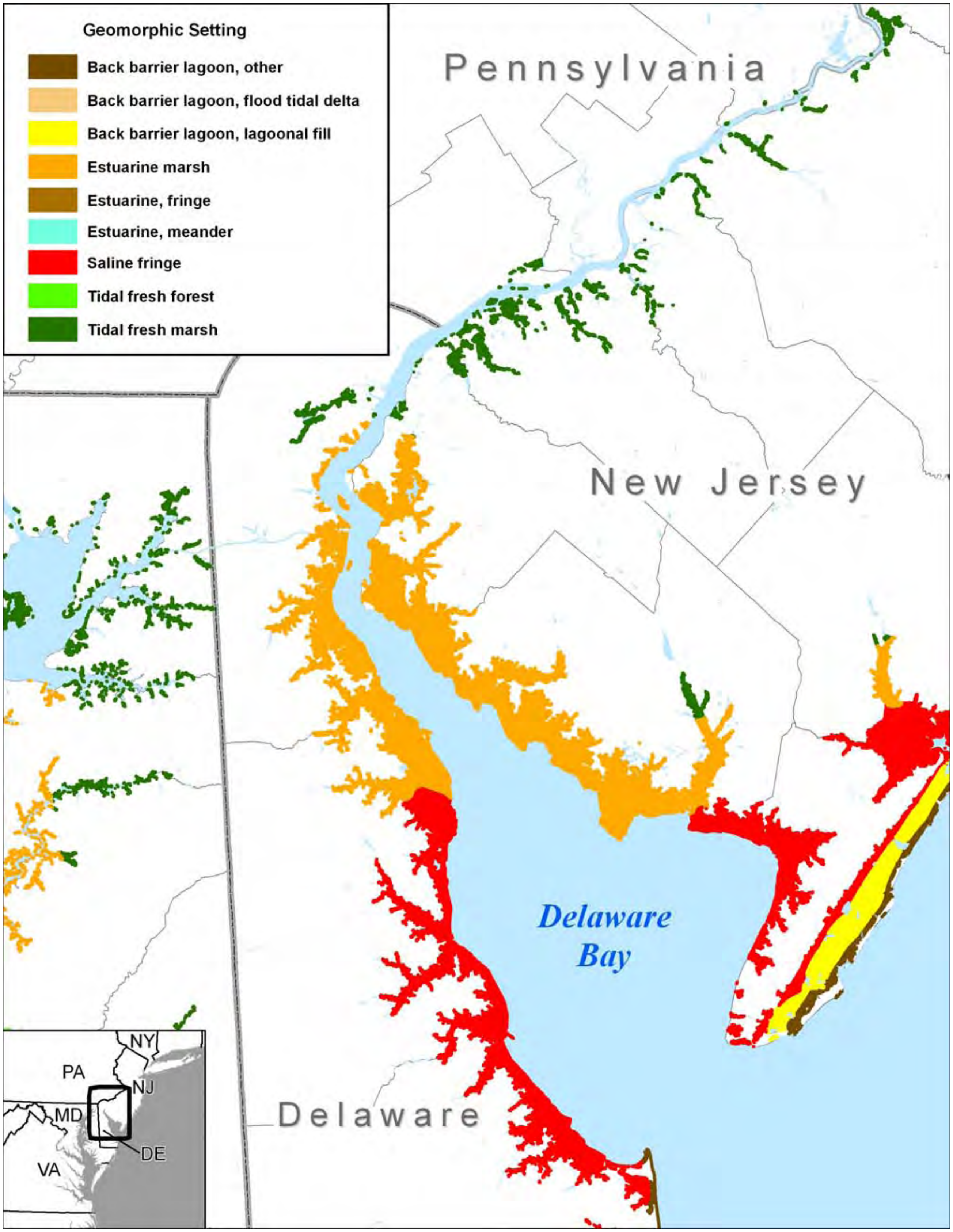

Figure 2.1.7. Geomorphic Settings for the Delaware Bay Region. Source: Titus et al. (Section 2.2).

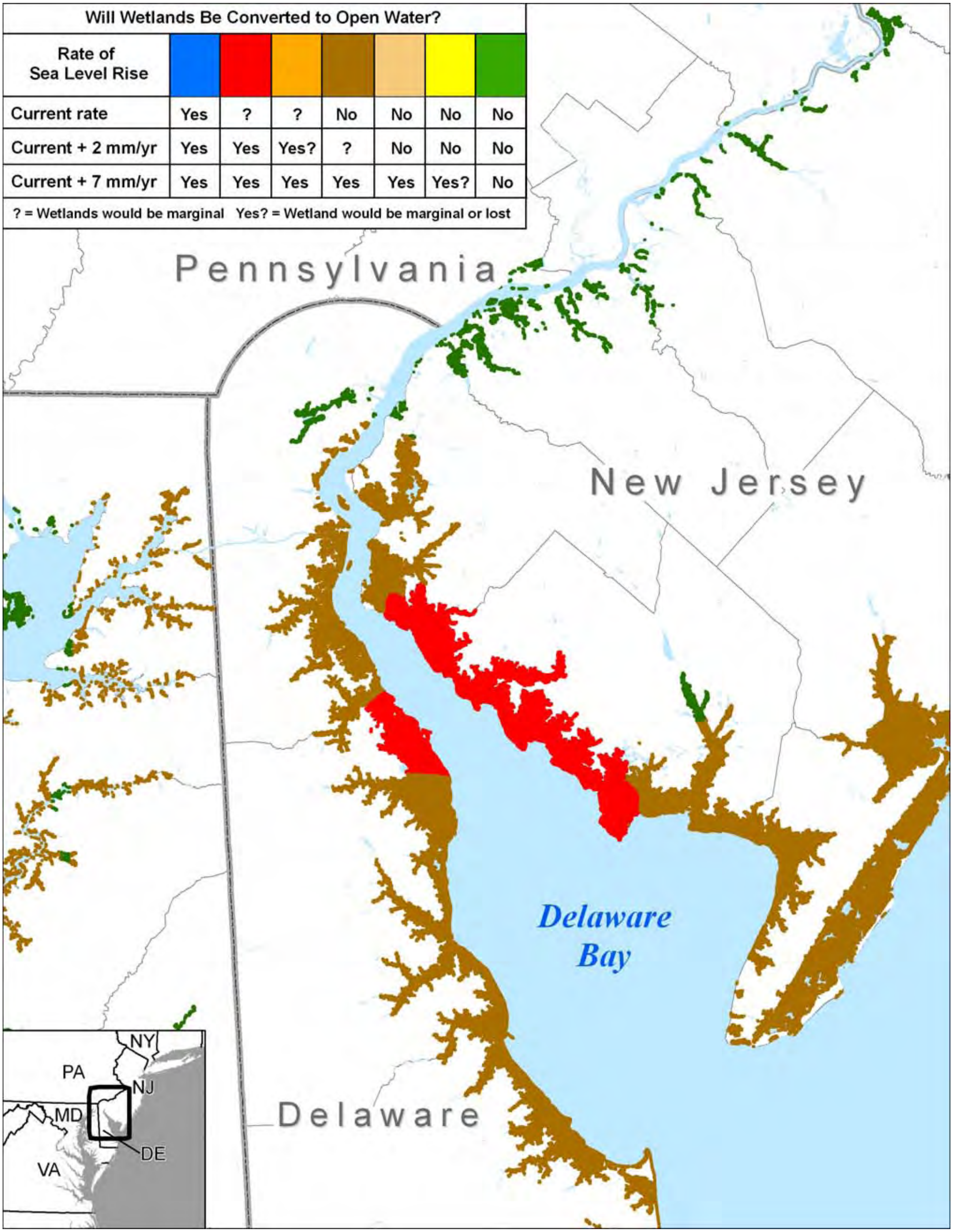

Figure 2.1.8. Wetland Response Map for the Delaware Bay Region. Source: Titus et al. (Section 2.2).

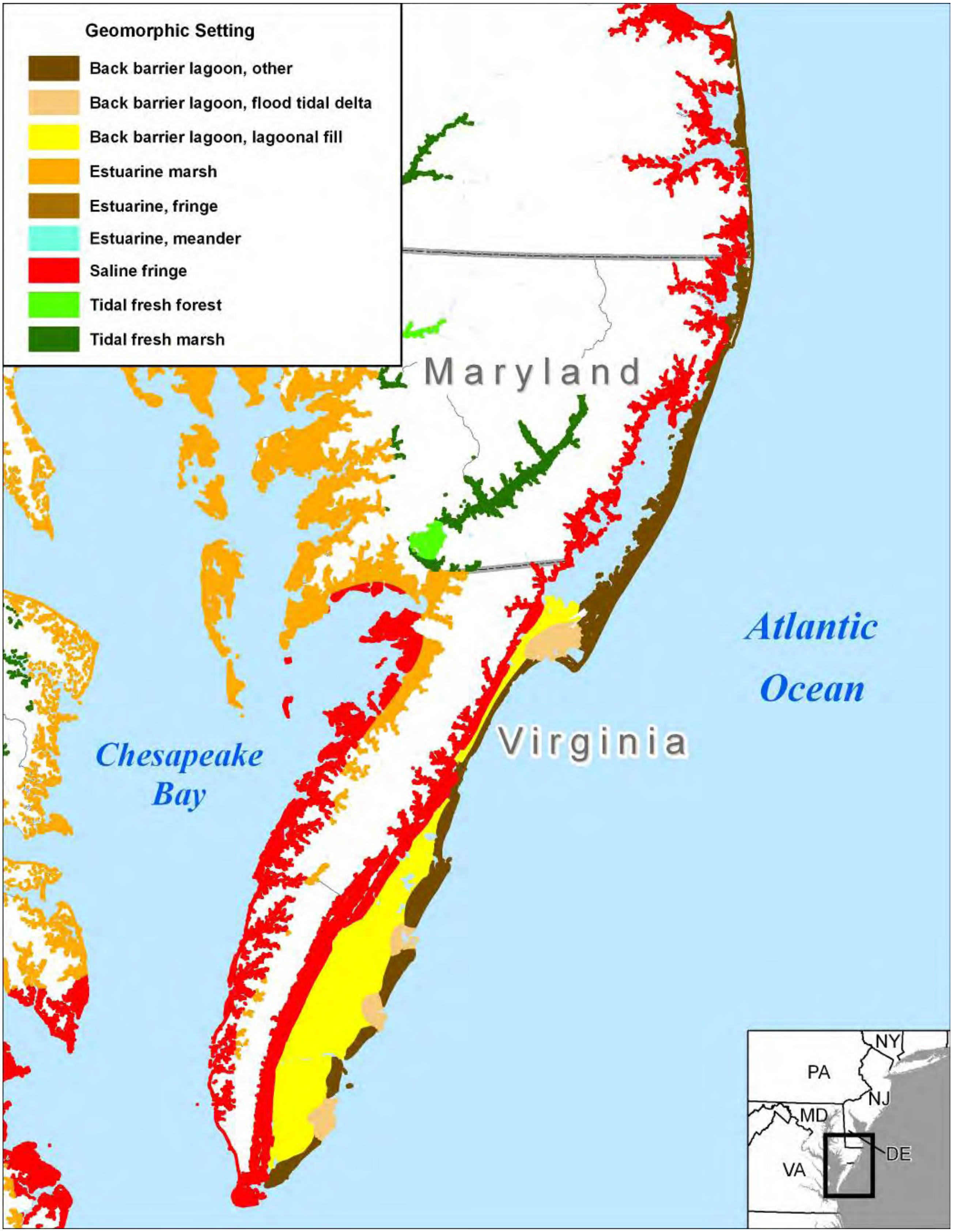

Figure 2.1.9. Geomorphic Settings for the Maryland-Virginia Shore Region. Source: Titus et al. (Section 2.2).

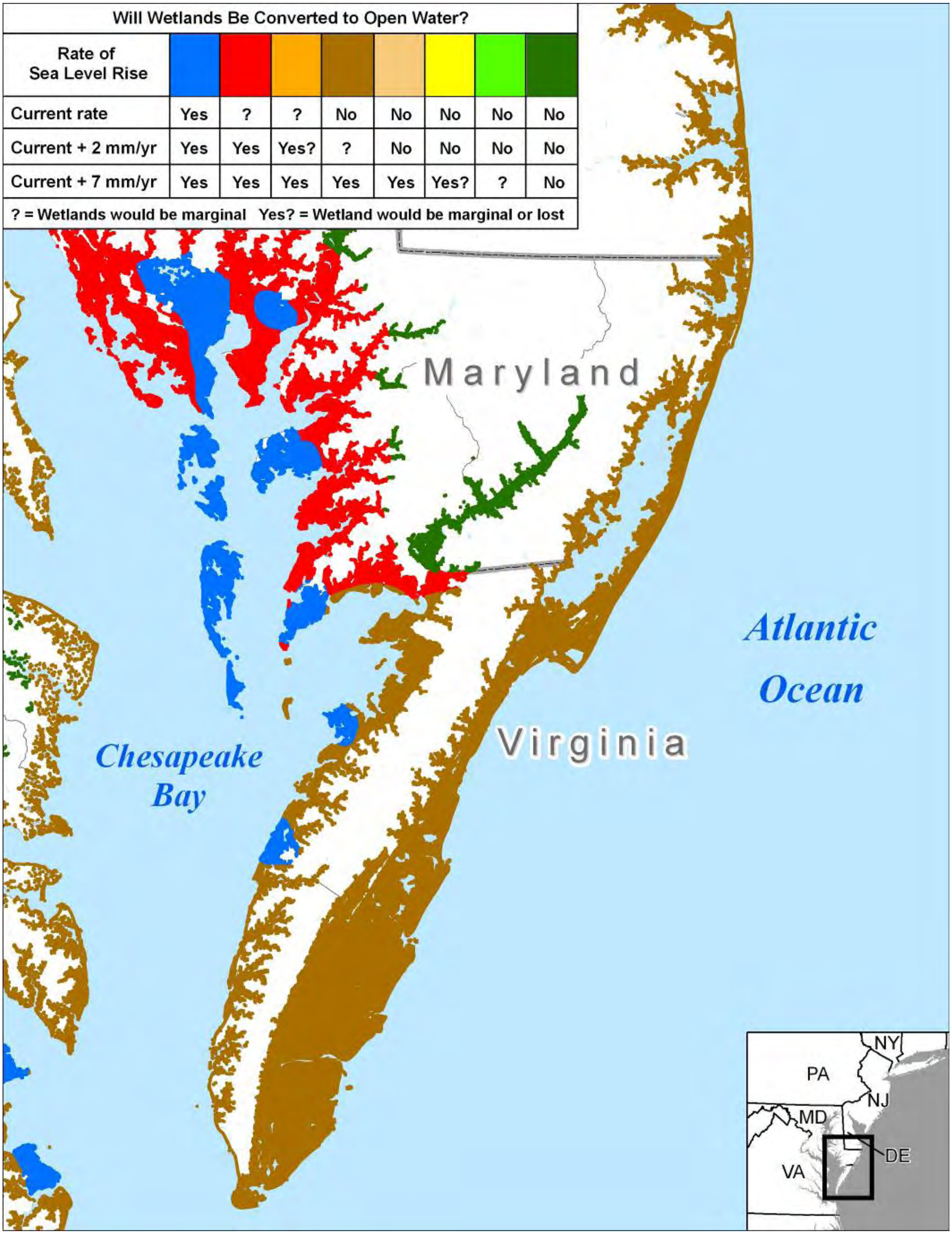

Figure 2.1.10. Wetland Response Map for the Maryland/Virginia Shore Region. Source: Titus et al. (Section 2.2).

Chesapeake Bay

This region encompasses the entire Chesapeake Bay, including the tidal portions of rivers draining into the Bay, with the exception of the Lower Maryland Eastern Shore region. Because of the great area involved, current sea level rise rates should be determined for the upper part of the Bay using the Baltimore gauge. The current rate of sea level rise in this area was determined to be 3 mm/yr, making the two future rates considered 5 mm/yr and 10 mm/yr. For the area south of the Potomac, local knowledge indicates that these rates should be higher: 4 mm/yr for current, 6 mm/yr for midrange, and 11mm/yr for high-range estimates.

Chesapeake Bay coastal wetlands occur in a variety of geomorphic settings (Figure 2.1.11). There is some FF within this region, most notably near Adelina on the Patuxent estuary. Throughout the Maryland portion of the Chesapeake Bay region, FM occurs in the tidal rivers, with ES marshes bordering the open bay. On the eastern shore of Virginia from Pocomoke Sound south, SF marshes occur, in some areas grading into ES toward the upland. On the western shore of Virginia, the lower reaches of the Rappahannock, the York and the James rivers are bordered by ES fringe marshes with FM farther from the Bay itself. SF marshes also occur on the margins of the Bay south of the Rappahannock River.

The dominant accretionary processes vary according to geomorphic setting. Peat accumulation is important to all wetlands in this area. Vertical accretion driven by peat accumulation is expected to increase in the future in response to increased sea level. However, in most of these marshes, this increase will occur only up to a threshold level. The exception is the FM area, where peat accumulation should allow marshes to accrete and even expand in the face of high-range sea level rise. The threshold level for ES and SF marshes is currently unknown for this region, although it is expected that the ES marshes may not even reach the threshold here. Fluvial sediment inputs are important to FM and are expected to increase in this area as climate changes cause precipitation events to be more intense and periodic, resulting in flashy runoff. Storm-driven sedimentation is important for ES marshes in this region. Future climate change will result in an increase in the magnitude of coastal storms due to increasing sea-surface temperatures, and their frequency will be at least as common as at present. Storm sedimentation is therefore expected to increase in the future. The SF marshes in the lower Bay may receive increased sediment in the future from the ocean. Greater storminess will increase the availability of these sediments. Other accretionary processes are also expected to change:

- Tidal fluxes may alter, but the effect is minimal in this region. In ES an increase in tidal prism may result in more export from already stressed marshes.
- Ice effects are of minimal importance here and will diminish in importance as climate warms.
- Nutrient delivery from coastal watersheds are likely to increase as both climatic effects and land use changes result in greater runoff.
- Herbivory, which is locally important here, is expected to decrease or remain the same because of management actions.

Figure 2.1.12 shows the accretion scenarios for the Chesapeake Bay region (note that the Lower Maryland Eastern Shore region is discussed separately below). FF and FM marshes are keeping pace with current rates of sea level rise, largely through peat accumulation, and will continue to accrete at rates at least sufficient to survive the high-range estimates for Chesapeake Bay region. There are some coastal wetlands, however, that cannot keep pace with current rates and are being lost. Specific areas are at Hog Island and Plum Tree Island National Wildlife Refuge on the western shore, and the Tobacco islands and Hacksneck areas on the eastern shore. These SF marshes are not sustainable and will certainly be lost under even midrange estimates of future sea level rise. The ES marshes bordering the bay and its tributaries are all considered to be keeping pace with current sea level rise rates (3–4 mm/yr in the region) but are marginal under midrange estimates.

Consequently, they will be lost if high-range estimates of future sea level rise are realized.

Lower Maryland Eastern Shore

This region encompasses the tidal wetlands on the eastern shore of Maryland and Virginia between the Chester River and the Pocomoke River. Most of this region lies in the upper part of Chesapeake Bay, and thus the Baltimore tide gauge is most appropriate. The current rate of sea level rise for the area was determined to be 3 mm/yr, making the two future rates considered 5 mm/yr and 10 mm/yr. The very southern part of this region lies south of the Potomac, and thus, as for the Chesapeake Bay region, local knowledge indicates that rates for the southern portion should be higher: 4 mm/yr for current, 6 mm/yr for midrange, and 11 mm/yr for high range estimates.

Coastal wetlands on the Lower Maryland Eastern Shore occur in a variety of geomorphic settings (Figure 2.1.13). There is some FF in the vicinity of Salisbury and Wellington where some cypress occurs within FM areas, and near Wye Mills farther north. FM occurs in the tidal rivers of the eastern shore, including the Choptank, Naticoke, and Pocomoke, with ES marshes bordering the open bay and on islands within the Bay. Some SF marshes occur on the north side of Pocomoke Bay.

The dominant accretionary processes are similar to those found in similar geomorphic settings in other parts of Chesapeake Bay. Peat accumulation is important to all wetlands in this area and is expected to increase in the future. In most of these marshes this increase will occur only up to a threshold level. The exception is the FM area, where peat accumulation should allow marshes to accrete and even expand in the face of high-range sea level rise. Fluvial sediment inputs are important to FM and are expected to increase in this area as climate changes cause precipitation events to be more intense and periodic, resulting in flashy runoff. Storm-driven sedimentation is important for ES marshes in this region and is expected to increase in the future. The SF marshes in this region are distant from direct oceanic inputs and will be unlikely to receive additional sediments in the future from this source. Changes in tidal flux may be important in exporting material from already stressed marshes. Herbivory, which is locally important here, is expected to decrease or remain the same because of management actions.

Figure 2.1.14 shows the accretion scenarios for this region. One of the reasons this area has been singled out from the other coastal wetlands in Chesapeake Bay is the extreme rate of wetland loss already being experienced in the area. Large areas of the ES marshes are apparently not currently keeping pace with sea level rise and are expected to be lost even without acceleration in sea level rise. These include the Blackwater National Wildlife Refuge marshes, Bloodsworth Island and South Marsh Island, as well as Deal Island and the Grays Island Marsh area east of Fishing Bay. The remainder of the ES marshes in the region are considered marginal even under current sea level rise conditions and they are expected to be lost if even the midrange estimate of future rise is realized. Accretion scenarios are most optimistic for the FM areas of the tidal rivers, where organic accumulation processes should allow marshes to keep pace with even high-range estimates of sea level rise.

Virginia Beach/Currituck Sound

This region encompasses the Virginia tidal marshes of Back Bay, including Back Bay National Wildlife Refuge and Northwest and North Landing rivers. These embayments and estuaries are the northernmost extent of Currituck Sound as it extends into Virginia. There are few tide gauges that reflect the setting of this area directly. The most appropriate tide gauges are Sewells' Point in Virginia and Beaufort, North Carolina. The current rate of sea level rise for the area based on these gauges was determined to be 4 mm/yr, making the two future rates considered 6 mm/yr and 11 mm/yr. The geomorphic setting for these marshes includes FF and FM mix along the Northwest and North Landing rivers, with ES and in Back Bay and BB marshes immediately behind the barrier shoreline (Figure 2.1.15).

The dominant accretionary processes are peat accumulation within FF and FM, and storm sedimentation inputs for the marshes surrounding Back Bay. Vertical accretion driven by peat accumulation is expected to increase in the future in response to increased sea level, and should be adequate to allow FF and FM wetlands to accrete and even expand in the face of high-range sea level rise. Storm-driven sedimentation is important for ES and BB marshes in this region. Future climate change will result in an increase in the magnitude of coastal storms due to increasing sea-surface temperatures, and their frequency will be at least as common as at present. Storm sedimentation is therefore expected to increase in the future. Other accretionary processes are also expected to change:

- Tidal fluxes may alter, but the effect is minimal in this region and the nature of the effect on accretion is negligible.
- Nutrient delivery from coastal watersheds is likely to increase as both climatic effects and land use changes result in greater runoff.

Figure 2.1.16 shows that none of the wetlands in the area will survive 11 mm/yr of sea level rise. Although the FF and FM marshes in other areas have been considered more resilient, in this area tidal fluctuations are so small that an increase of 2 mm/yr in sea level threatens to introduce both salinity and a changed hydroperiod to the fresh parts of the estuary. These wetlands are considered marginal today because they are stressed by existing sea level rise conditions. All the remaining ES and BB marshes will become marginal if sea level rise accelerates to 6 mm/yr and will be lost under the high-range estimate of 11 mm/yr. For the ES and BB marshes to survive, the midrange estimate sediment input from storms would need to increase, which is very dependent on actual storm impacts, frequency, and tracks.

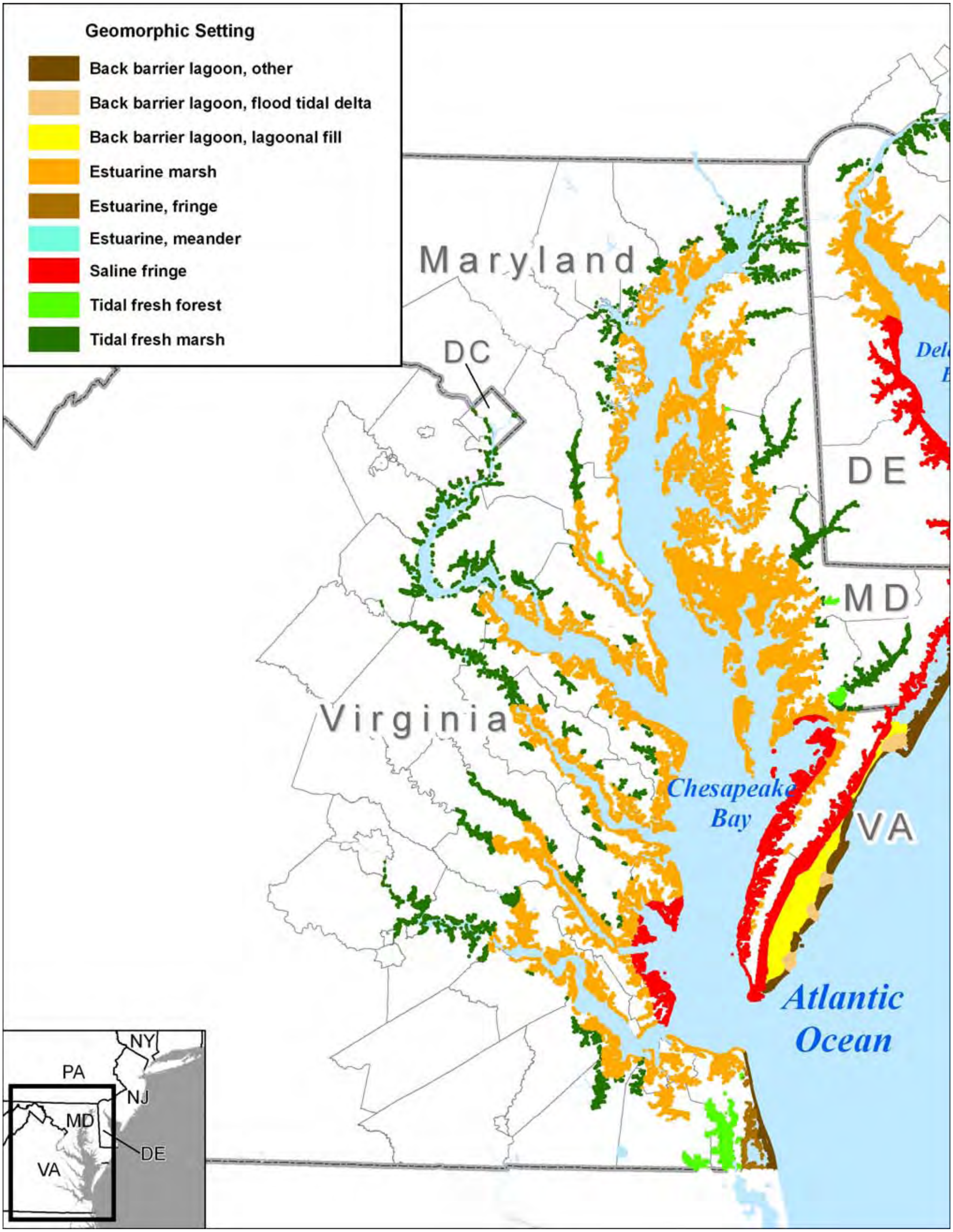

Figure 2.1.11. Geomorphic Settings for the Chesapeake Bay Region. Source: Titus et al. (Section 2.2).

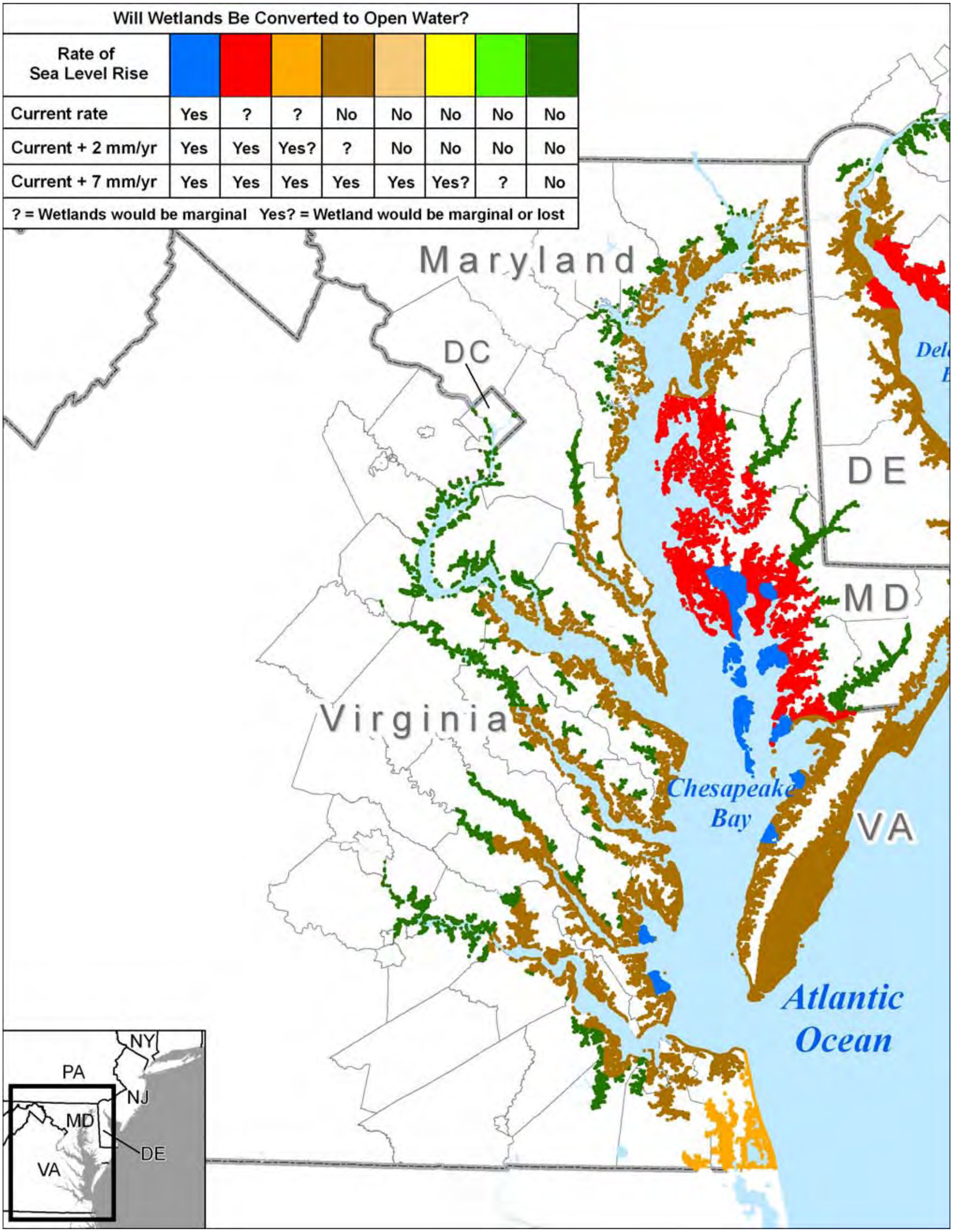

Figure 2.1.12. Wetland Response Map for the Chesapeake Bay Region. Note that the Lower Maryland Eastern Shore Region is considered separately. Source: Titus et al. (Section 2.2).

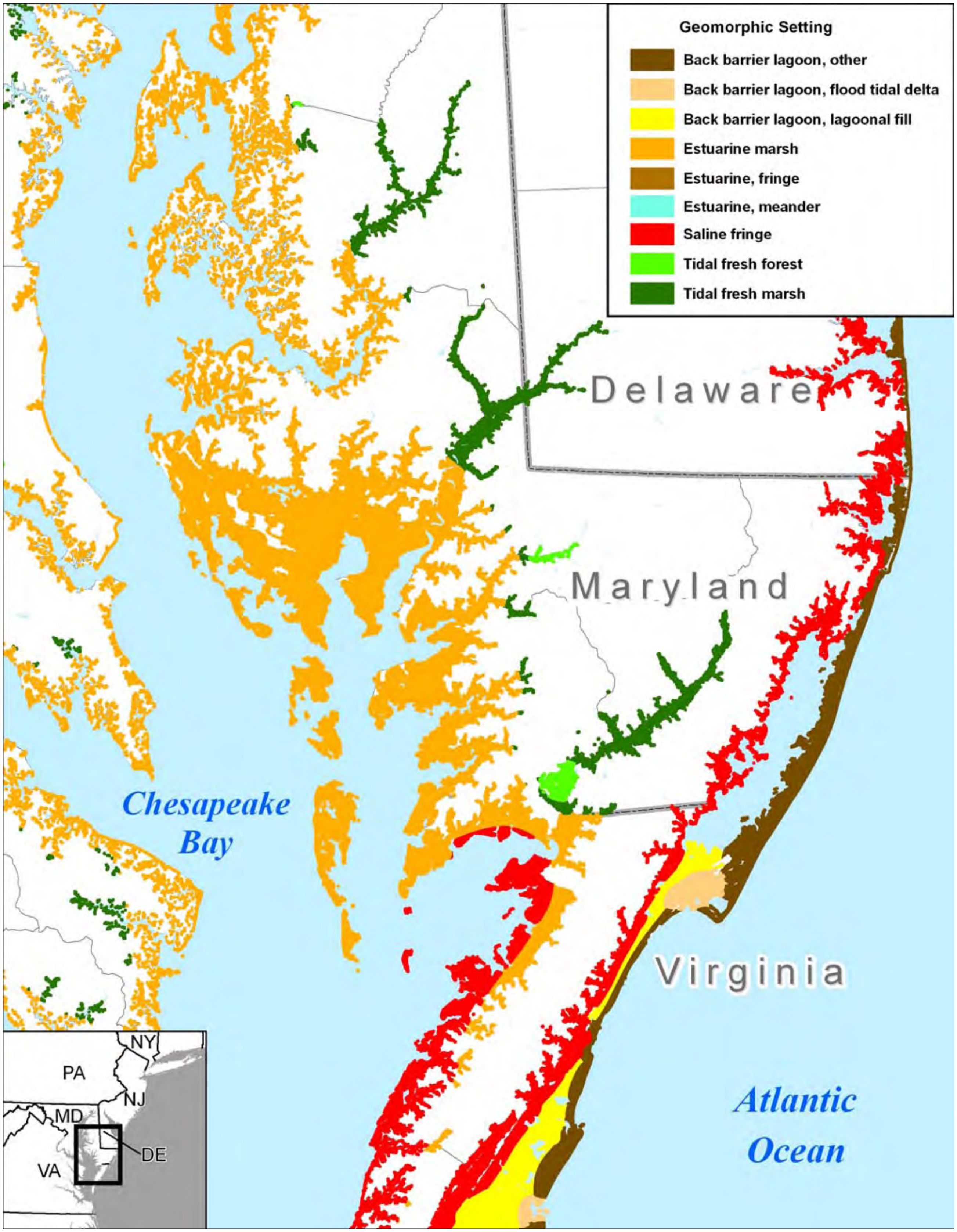

Figure 2.1.13. Geomorphic Settings for the Lower Maryland Eastern Shore Region. Source: Titus et al. (Section 2.2).

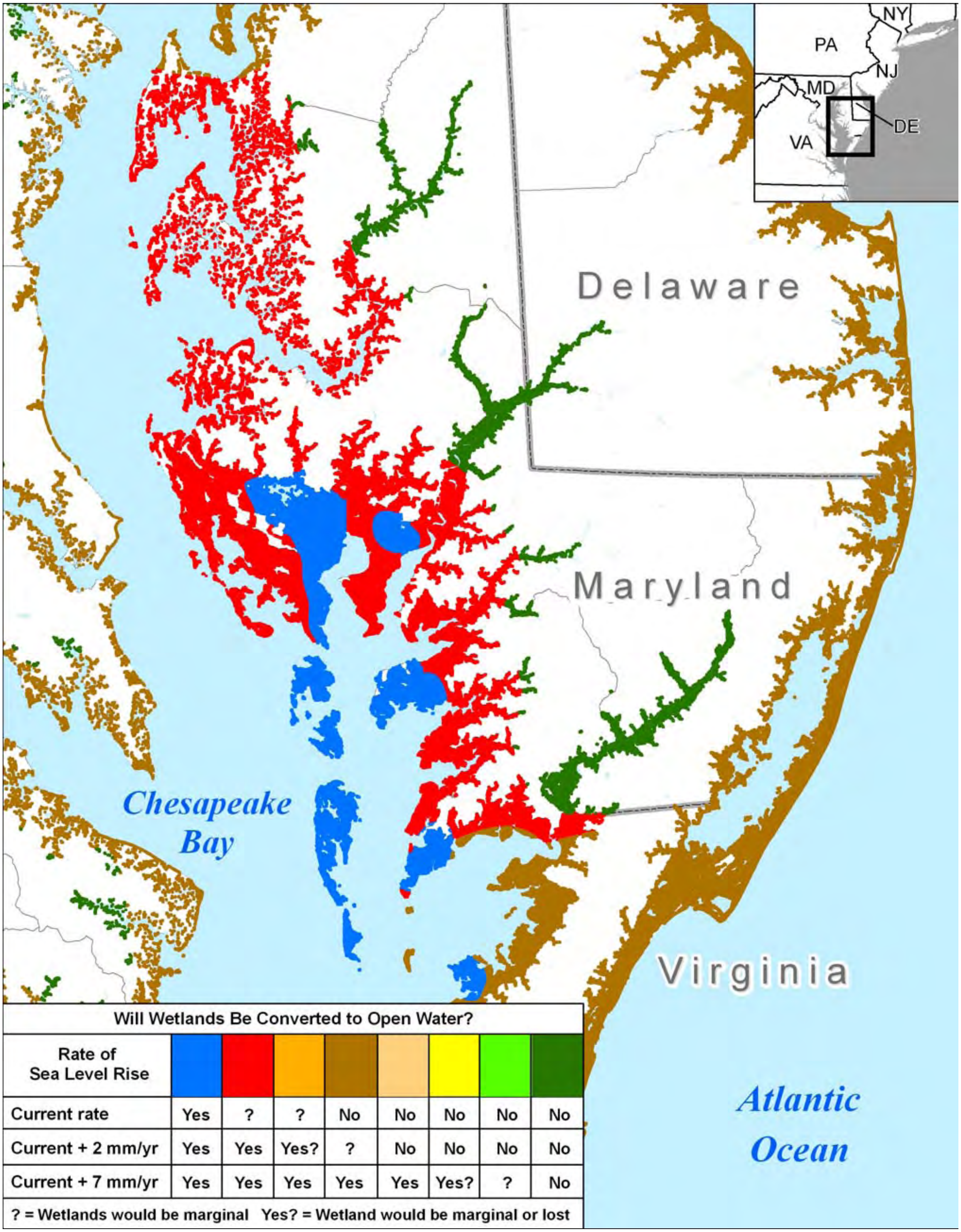

Figure 2.1.14. Wetland Response Map for the Lower Maryland Eastern Shore. Source: Titus et al. (Section 2.2).

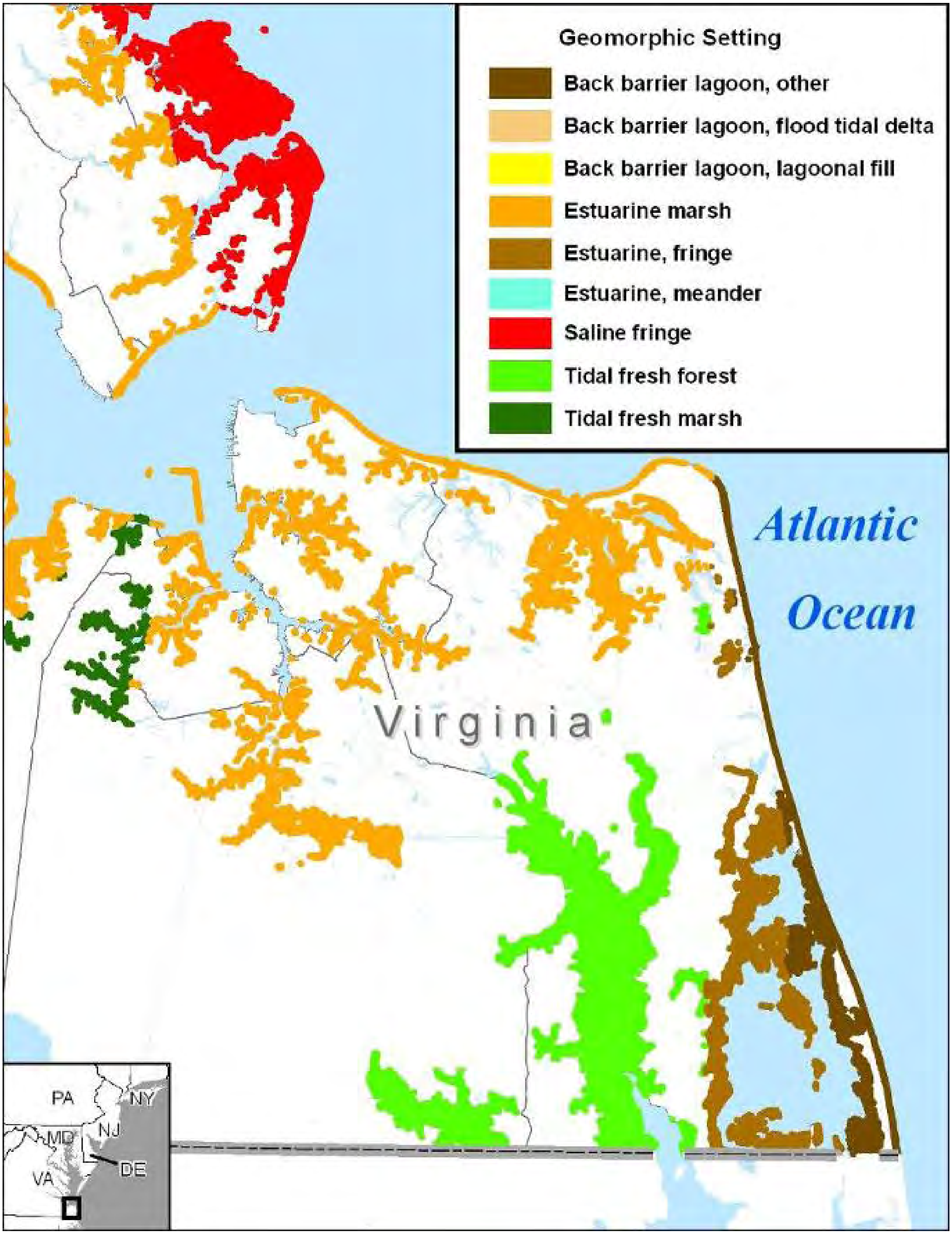

Figure 2.1.15. Geomorphic Settings for the Virginia Beach/Currituck Sound Region. Source: Titus et al. (Section 2.2).

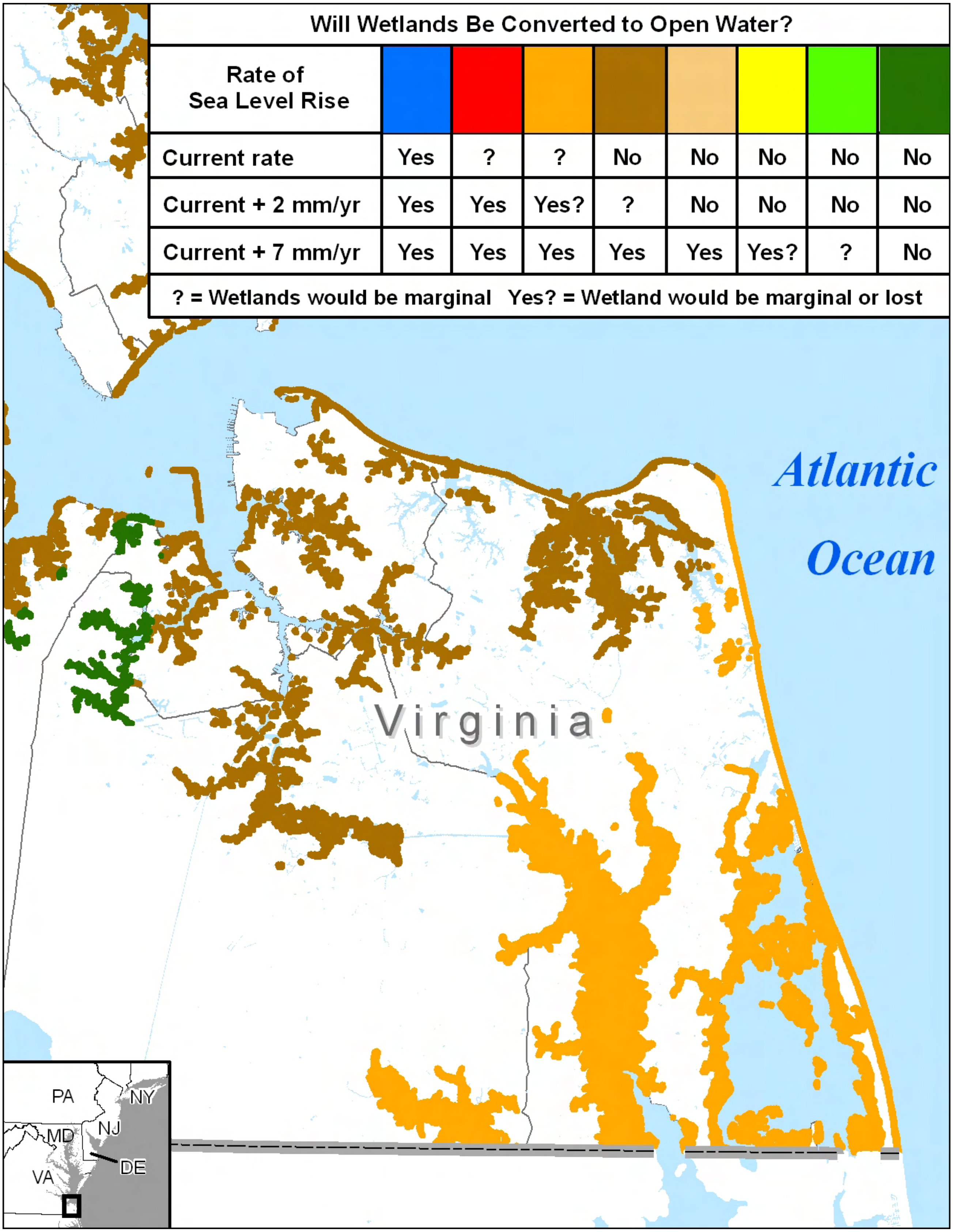

Figure 2.1.16. Wetland Response Map for the Virginia Beach/Currituck Sound Region. Source: Titus et al. (Section 2.2).

2.1.5. Summary and Conclusions

This study has shown that the prognosis for the coastal wetlands of the Mid-Atlantic under current sea level rise is for the most part good and that as rates accelerate toward midrange estimates, a 2 mm/yr increase, their survival depends on optimal hydrology and sediment supply conditions. There are exceptions to this assessment at both local and regional scales and some variation with geomorphic setting.

For the entire area, tidal fresh forests and marshes are considered the most sustainable. As long as salinities do not increase, these systems build vertically, primarily through organic accumulation, and are less dependent on mineral sediment supply. This bodes well for migration of tidal wetlands upstream along tidal rivers as sea level rises.

Those marshes that are currently being lost either locally within Jamaica Bay or at a larger scale on the Lower Maryland Eastern Shore are unlikely to be rebuilt or replaced by natural processes as sea level continues to rise. The Chesapeake wetlands are for the most part transgressive—formed as sea level flooded former uplands. Along the shores of the open Bay, such migration is limited by physical barriers or land use preferences, and any areal increase in fresh marshes along the tidal rivers as sea level rises will be limited. In back-barrier island marshes, transgression is impossible, and as such, island marshes may fare poorly. In Jamaica Bay, the marshes are built on lagoonal fill and relict flood tide delta deposits, but development of Rockaway Beach and dredging of the inlet have essentially halted these sedimentary processes; these marshes also are unlikely to be replaced by natural processes (Gornitz et al., 2001).

Perhaps of more concern are marshes considered marginal under current conditions, which are not expected to survive an acceleration of sea level rise. These marshes are concentrated in the Lower Maryland Eastern Shore region, and it is possible that restoration measures could be taken to improve their vigor or increase their elevation at least locally. Should they be lost, as predicted here, natural processes are not in place to rebuild them, and they could be replaced only by allowing major conversion of adjacent uplands to tidal wetlands. Even then, given the highly altered nature of this system, active restoration of hydrology and sediment supply pathways would be necessary to ensure their survival under even midrange estimates of sea level rise.

Very few brackish or salt marshes in the area can survive sea level rise rates in excess of 10 mm/yr. Where sediment supply from inlets, overwash, or rivers is substantial, local areas of marsh on Long Island could survive. This may be the case in some other back barrier marshes, but it will be very dependent on local storm-driven sediment supply.

This report has evaluated the fate of coastal wetlands according to three sea level rise estimates. The large difference, 5 mm/yr, between the midrange estimate and the high-range estimate means the study considered how marshes would respond to rates of 6 mm/yr and 11 mm/yr but not rates in between. Few studies specifically address the maximum rates at which marsh vertical accretion can occur. Morris et al. (2002) used modeling and field data to estimate that under high sediment supply conditions, *Spartina alterniflora* marshes in the Southeast could survive sea level rise rates as high as 12.5 mm/yr, and Bricker-Urso et al. (1989) posited a maximum rate of 14–16 mm/yr for salt marshes in Rhode Island. However, no studies have addressed the thresholds for organic accumulation in the marshes considered here. Determining the fate of coastal wetlands at rates of sea level rise between the mid and high estimates used here requires further elucidation of variations in this maximum rate regionally and among vegetative communities.

Acknowledgments

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2.2. Maps that Depict Site-Specific Scenarios for Wetland Accretion as Sea Level Rises along the Mid-Atlantic Coast

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Abstract

This paper develops maps and a data set depicting a set of site-specific assumptions for wetland vertical accretion developed by a panel of wetland scientists. The panel had drawn polygons on USGS 1:250,000 scale topographic maps. For each polygon, for each of three sea level rise scenarios, the panel indicated whether tidal wetlands within the polygon would be lost, keep pace, or be marginal. This paper describes how we converted the hard-copy polygons into a GIS database and created a set of maps to concisely depict the panel's findings.

2.2.1. Background

In Section 2.1, Reed et al.[1] explain the basis for an expert panel assessment of the ability of coastal wetlands to keep pace with rising sea level along the mid-Atlantic Coast from the south shore of Long Island to the Virginia/North Carolina border. That assessment was a part of EPA's effort to assess the possible vulnerability of tidal wetlands to rising sea level, which also depends on coastal topography[2] and coastal development.

This paper describes our efforts to create a GIS data layer and maps to depict the panel's assessment. The panel produced a set of marked-up hard copy USGS 1:250,000 scale maps and a set of spreadsheets. We used the hard copy maps to define our polygon boundaries and the spreadsheets to provide descriptions about those polygons (i.e., attributes).[4]

The panel drew polygons on the hard copy maps to approximately identify the areas associated with five primary geomorphic settings, with several subsettings. The USGS 1:250,000 scale topographic maps show roughly where wetlands exist; but they do not delineate the actual wetlands. Therefore, we construed each polygon as representing the panel's intent to identify an area within which all tidal wetlands could be associated with one of the following geomorphic settings or subsettings:

1. Tidal Fresh Forests
2. Tidal Fresh Marsh
3. Estuarine/Brackish Channelized Marshes
   a. Meander
   b. Fringing
   c. Island
4. Back Barrier Lagoon Marsh
   a. Back barrier/Other
   b. Active flood tide delta
   c. Lagoonal fill
5. Saline Marsh Fringe

Each polygon on the maps had an index number. The associated spreadsheets provided:

- Polygon index number
- Region (as described in the panel report)
- Two columns for geomorphic setting and subsetting,
- Three columns for the panel's prognosis for wetland accretion under three alternative sea level rise scenarios
- Place name (optional)
- Special explanation (if appropriate).

The three sea level rise scenarios were current rate, current rate + 2 mm/yr, and current rate + 7 mm/yr. For each of these three scenarios the spreadsheet provided a prognosis for wetland accretion for each polygon. In most cases, the prognosis was one of three possibilities: keeping

[1]Reed, D.J., D.A. Bishara, D.R. Cahoon, J. Donnelly, M. Kearney, Alex Kolker, L.L. Leonard, R. Orson, and J.C. Stevenson. 2008. Site-Specific Scenarios for Wetlands Accretion as Sea Level Rises in the Mid-Atlantic Region. Supporting Document for CCSP 4.1, Question 3. New Orleans, LA: Department of Earth and Environmental Sciences University of New Orleans.

[2]In Chapter 1, Titus and Wang develop a data set and maps expressing coastal elevations relative to spring high water, which is approximately the upper boundary of tidal wetlands. See Titus and Wang, 2008, Maps of Lands Close to Sea Level along the Middle Atlantic Coast of the United States: An Elevation Data Set to Use While Waiting for LIDAR, in *Background Documents Supporting Climate Change Science Program Synthesis and Assessment Product 4.1: Coastal Elevations and Sensitivity to Sea Level Rise*, EPA 430R07004, Washington, DC: U.S. EPA.

[4]In a GIS polygon layer, an attribute table associates information with each polygon.

pace, marginal, and loss (see Section 2.1, Reed et al. for description). In a few cases, however, the panel's original assessment was "marginal/loss" for a particular sea level rise scenario.[5]

2.2.2. Conversion of the Panel's Output to a GIS Dataset

Our final data set provides two layers:

- "Raw" consists of the polygons created by the panel (and the associated attributes), which identify the geomorphic setting.
- "Wetlands" is a coastal wetlands data set, with attributes that identify the geomorphic settings and wetland accretion potential as defined by the panel.

The Raw Data

Our objective was to convert the hand renderings into a digital data set suitable for use in a GIS. The polygons provided by the panel included tidal wetlands, nontidal wetlands, dry land, and open water; but the information developed by the panel applies only to the tidal wetlands within the polygon. We also inspected the results of our digitizing to identify and remedy those cases where a literal digital conversion of what the panel drew was inconsistent with the panel's intent. For example, the polygon boundaries did not include all of the tidal wetlands in some areas, because the USGS 1:250,000 scale topographic maps do not show all wetlands or indicate the head-of-tide (above which wetlands are nontidal).

The first step toward creating a data set was to create a tracing of the polygons according to a procedure developed by Russ Jones. The key aspects were to faithfully trace the panel polygons and the registration marks from the USGS maps. Dana Bishara of the University of New Orleans overlayed Mylar sheets on top of the 1:250,000 USGS maps and manually traced the polygons and registration marks, and sent them to Jones.

The second step was to digitize the polygons. Jones provided the Mylars to Digital Data Services, Inc. (Lakewood, Colorado), who scanned them to a digital format in color at 300 dots per inch in Tagged Image File Format (tif). Richard Streeter digitized the polygons into a GIS using raster-to-vector conversion software.[6] See Figure 2.2.1.

The third step was to overlay the polygons with a wetlands data set. Jones and Streeter created quad-specific maps in a GIS by overlaying the polygons on top of the EPA coastal wetlands data set (Chapter 1, Titus and Wang, see note 2). Figure 2.2.2 shows the initial "raw" product from this overlay, for the Salisbury (Maryland) quadrangle.

[5]These cases were all either along the South Shore of Long Island or in the Virginia Beach/Chesapeake area.

[6]ESRI, 2005, ArcScan software, v. 9.1, Redlands, CA: Environmental Systems Research Institute.

Figure 2.2.1. Polygons Created by Wetland Accretion Panel Assessment: Salisbury Quadrangle. The wetland accretion panel drew polygons on 1:250,000 USGS quads. Panel staff then traced the polygons onto Mylar. The black lines define subregions; the other colored lines define polygons representing wetlands of a given geomorphic setting.

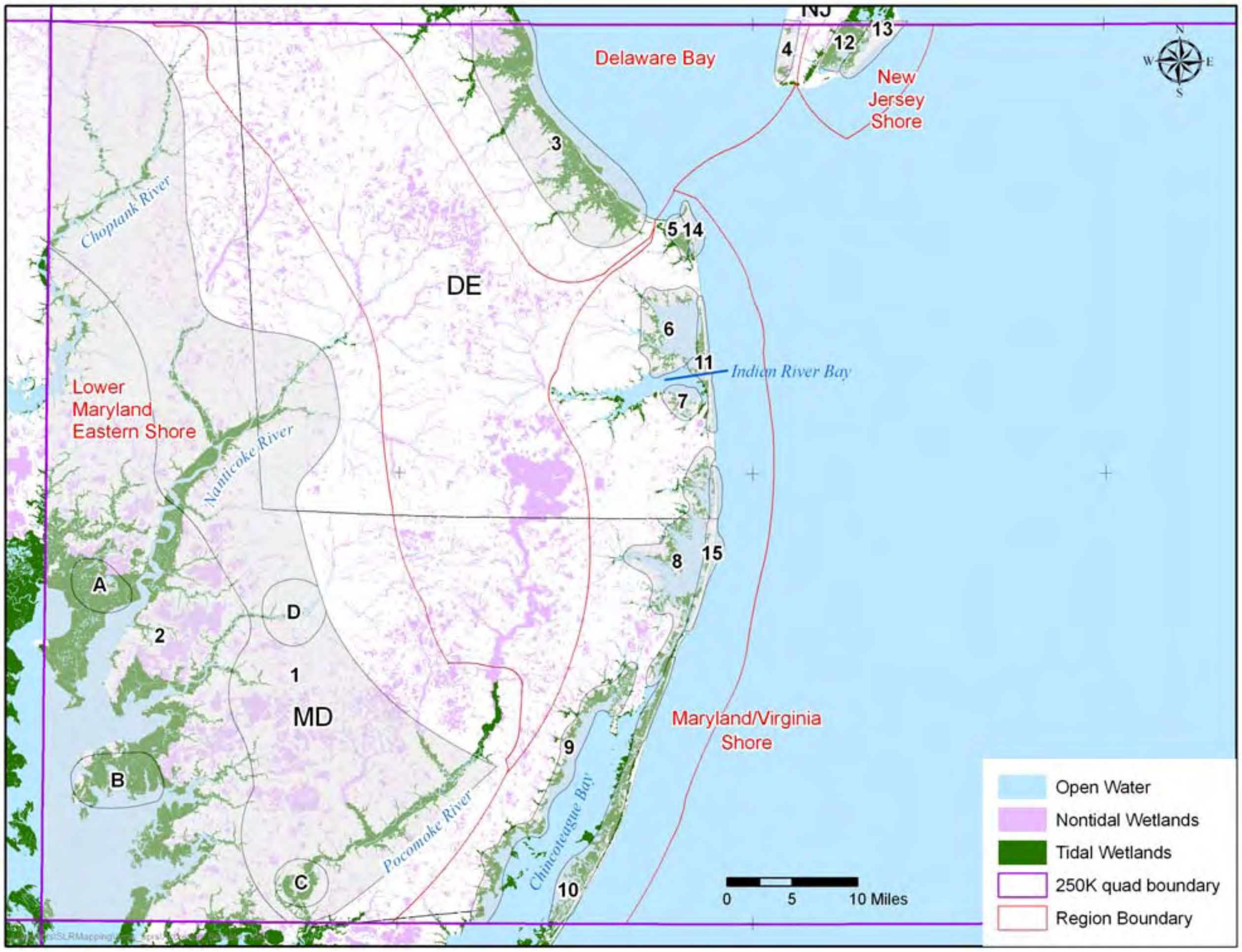


Figure 2.2.2. Overlay of the Polygons from Wetland Accretion Panel with a Wetlands Data Set: Salisbury Quadrangle. Each of the shaded polygons has an index number or letter; wetlands outside the shaded polygons were unassigned and had to be corrected. The light red lines that are not the boundary of a shaded polygon delineate the subregional boundaries. Note that that the shaded polygons do not include all of the tidal wetlands along Chincoteague and Indian River bays, nor the upper portions of the Choptank, Nanticoke, and Pocomoke rivers.

The fourth step was quality control of the polygons created by the panel. Figure 2.2.2 shows some of the issues that we addressed in this step. In many cases, tidal wetlands[7] lie outside of the geomorphic regions defined by the polygons, and assignments of geomorphic regions did not match local conditions (e.g., active flood tide deltas were not adjacent to inlets). In some cases, the tidal wetlands extended farther inland than the polygons. See, for example, the tidal wetlands that are not included in a shaded polygon to the west (inland) of polygon #3 along Delaware Bay; the extensive tidal wetlands along Rehoboth Bay (i.e., the bay between polygons #6 and #7), and the tidal wetlands along the upper Pocomoke River (i.e., the river that runs through polygon #C). In other cases, wetlands extend farther into the coastal lagoons than the polygons drawn by the panel indicated (e.g., the wetlands along polygons #9 and #10). In some cases, the original polygons omitted wetland areas, particularly in the upper reaches of estuaries; so we had no information on geomorphic setting or wetland accretion potential for wetlands in those areas (see Figures 2.2.2 and 2.2.3).

In general, the panel's polygon boundaries needed correction for several reasons:

[7]Titus and Wang (see note 2) generated a wetlands data set from a combination of National Wetlands Inventory wetlands and state wetlands data sets.

(a) Maps using a coarse 1:250,000 scale routinely show “scale mismatch” when overlaid with data created at a finer resolution.
(b) The panel’s polygon boundaries often omitted large areas of wetlands, because the USGS 1:250,000 maps do not show all wetlands.
(c) In some cases, the polygon boundaries did not track the landforms originally intended (e.g., the polygon around an inlet on the 1:250,000 scale map covering open water and missing the wetlands). This occurred primarily because the polygons that the panel had drawn were in many cases drawn to be “indicative” rather than precise; e.g., on the 1:250,000 map, the polygons boundaries as drawn sometimes differed from the actual boundary by approximately 1 cm.
(d) The panel did not have a watershed map, and in some cases the boundaries that they drew unintentionally crossed watershed boundaries or split a boundary. Many of these errors were apparent with the wetlands overlay.

We brought these cases to the attention of Reed and Bishara, who used our overlay to hand-edit the polygon boundaries to more closely follow the landforms and thus reflect the original intent of the panel. Streeter digitized the changes into the GIS. We then examined the maps a final time and made a small number of additional corrections. For example, in Figure 2.2.3, some tidal wetlands were not part of any “polygon” in the original panel output. The hand-edits assigned all of those wetlands to the same categories as the adjacent estuarine wetlands. Along the Christina River, this left us with estuarine wetlands upstream from freshwater wetlands; so we readjusted polygon 5 to include the upper portion of the tidal river. The net effect of these changes was to ensure that all tidal wetlands would be included in one of the shaded polygons, and associated with the correct landform and assigned region.

Wetlands Data Set

Our fifth step was to convert the raw data into a wetlands data set. This step involved both data processing and some cartography. Our data processing step involved importing the spreadsheets of attributes provided by Reed into the GIS and joining to the polygon layer via the index number that was common to both files. Finally, we transferred the attributes in the panel polygons to the EPA coastal wetlands data generated by Titus and Wang via a simple overlay function within the GIS. The final output of this fifth step is a polygon wetland data set with attributed defining geomorphic setting, accretion potential, and subregion. Figure 2.2.4 is an example of the resulting map.

2.2.3 Creating Maps from the Data

The cartographic step involved devising a reasonable way to portray the results of the panel assessment. The three main issues we considered were readability of small polygons, map colors, and the map legend.

Readability of Small Polygons

The purpose of the map is to show *where* wetlands are likely (or unlikely) to keep pace with sea level rise. We decided early on to use wetlands data rather than regional boundaries, because the area and location of wetlands is an important consideration. In places where the wetlands are a narrow fringe or widely dispersed islands, they are likely to be too small to be seen on a statewide map drawn to scale—not to mention a map of the entire mid-Atlantic. We looked at test maps drawn to scale, and the freshwater tidal wetlands along the Potomac and Delaware rivers were particularly hard to see.

Therefore, in printing these maps, we set the line widths to be scale-independent, to accentuate small areas. The net effect is that every tidal wetland polygon displays on our maps (unless overlaid with another wetland polygon).

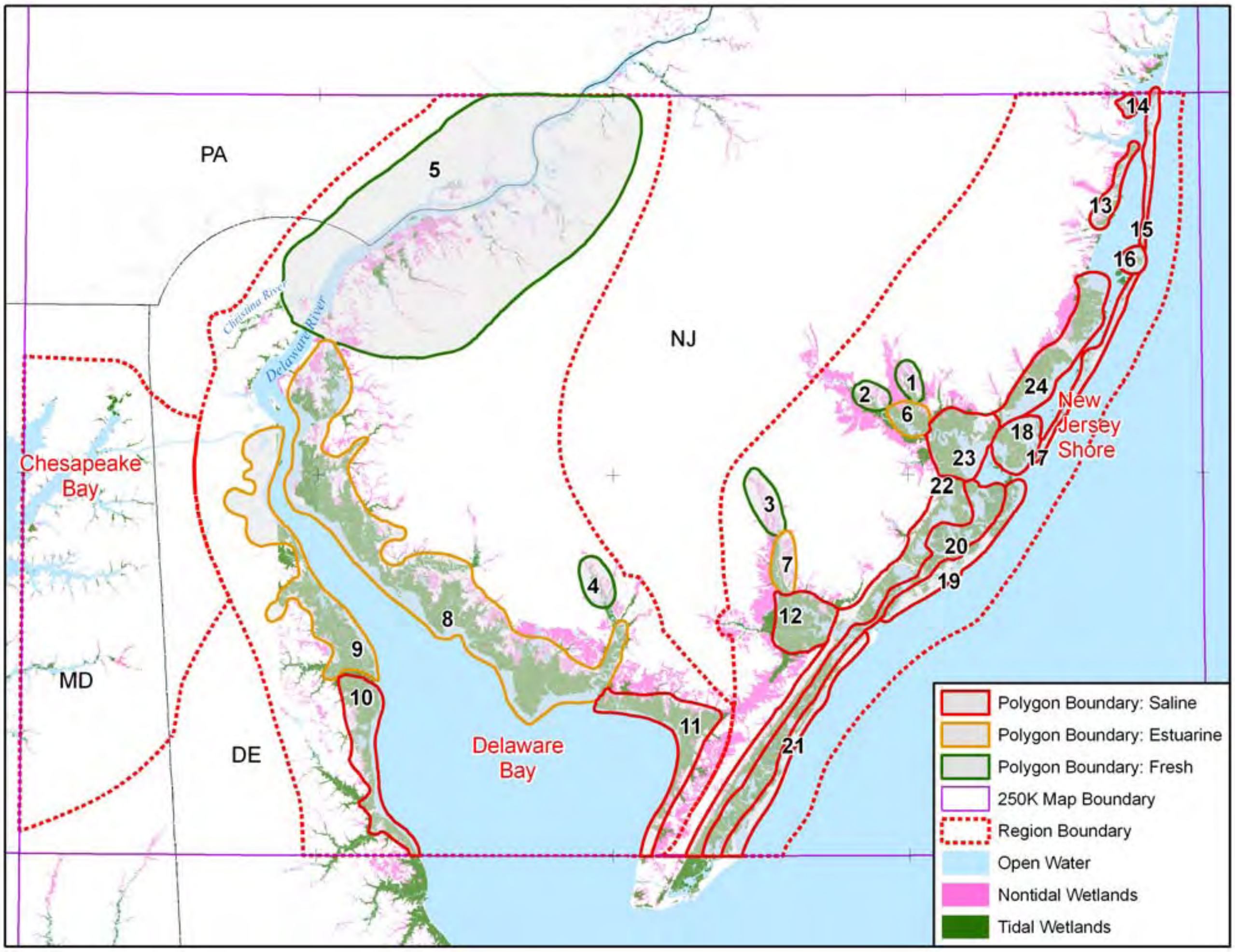


Figure 2.2.3. Overlay of the Polygons from Wetland Accretion Panel and Wetlands Data Set: Wilmington Quadrangle. The fresh/saline interface in the Delaware River is generally viewed as located near the Delaware/Pennsylvania border. But freshwater wetlands extend farther downstream, according to the panel. Polygon 5 represents the freshwater tidal marshes of the Delaware River watershed; the panel viewed the rest of the wetlands in the Delaware River watershed as estuarine marsh. Although the mouth of the Christina River into the Delaware River (southwest end of polygon 5) is in the freshwater marsh, the upstream portions of the river are shown as being estuarine marsh. We treated this as unintentional and altered the boundaries to show this entire river as freshwater marsh. Note also that that polygons denoting wetland zonation do not include all of the tidal wetlands on the Delaware side of the Delaware River and Bay.

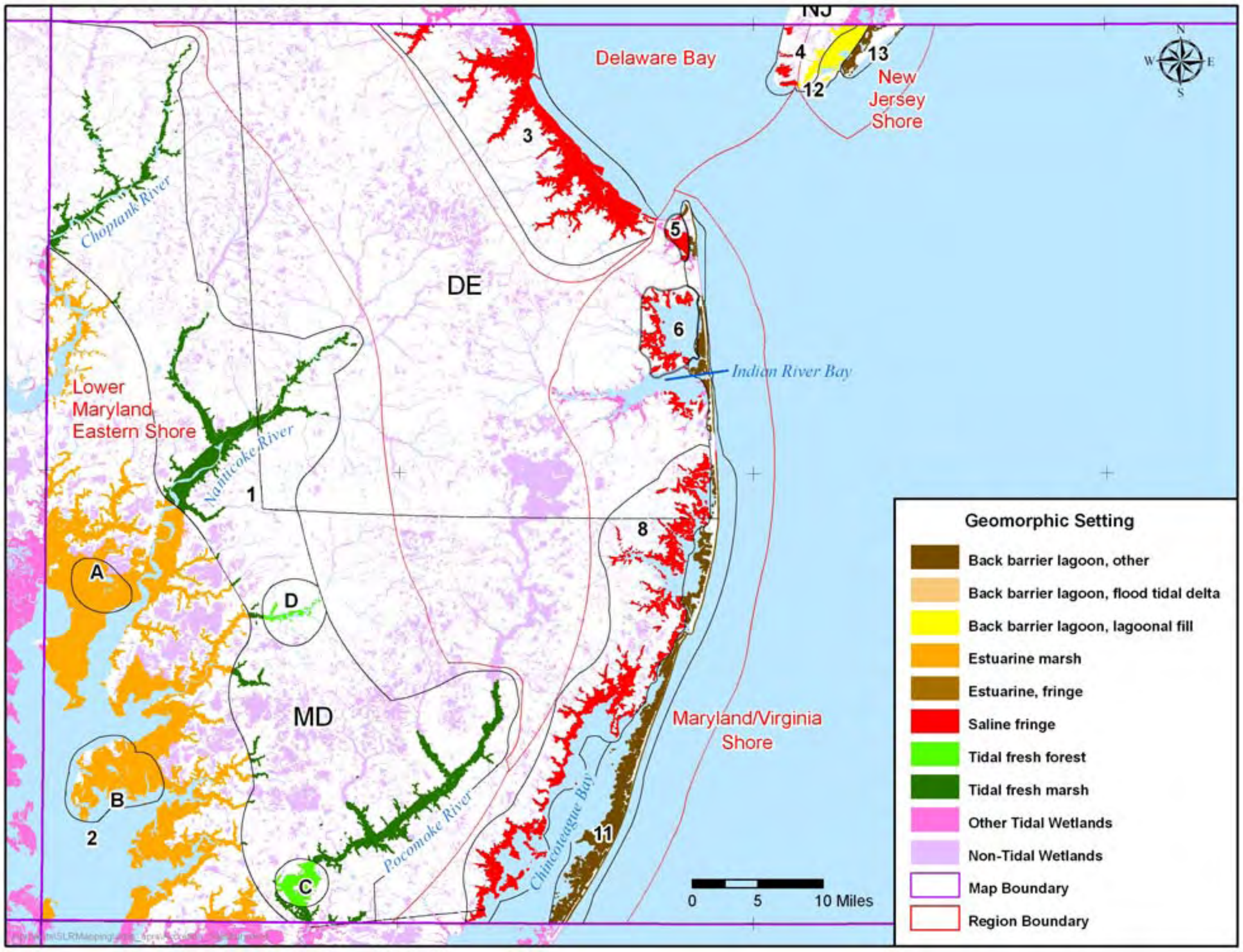


Figure 2.2.4. Wetland data displayed based on attributes provided by the panel for geomorphic setting. By this point, polygon boundaries had been revised to include most tidal wetlands. Compare with Figure 2.2.2. A few revisions were still needed, such as along Indian River Bay, where some tidal wetlands were still outside the polygon boundaries.

Expectation	Color	Reason for Color
Loss even at current rates:	Blue	Because it is becoming water anyway
Marginal today, loss at +2 m/yr:	Red	The standard color for a warning
Keeping pace today, marginal at 2 mm/yr, loss at 7 m/yr	Brown	A common color for environmental risk
Keep pace +2 mm/yr, loss at +7 mm/yr	Yellow Brown	A compromise between brown and green
Keeping with +2 mm/yr, marginal at +7 mm/yr	Light green	Wetlands likely to survive, stay green
Keeping pace at +7 mm/yr	Bold green	Wetlands very likely to survive (remain green)

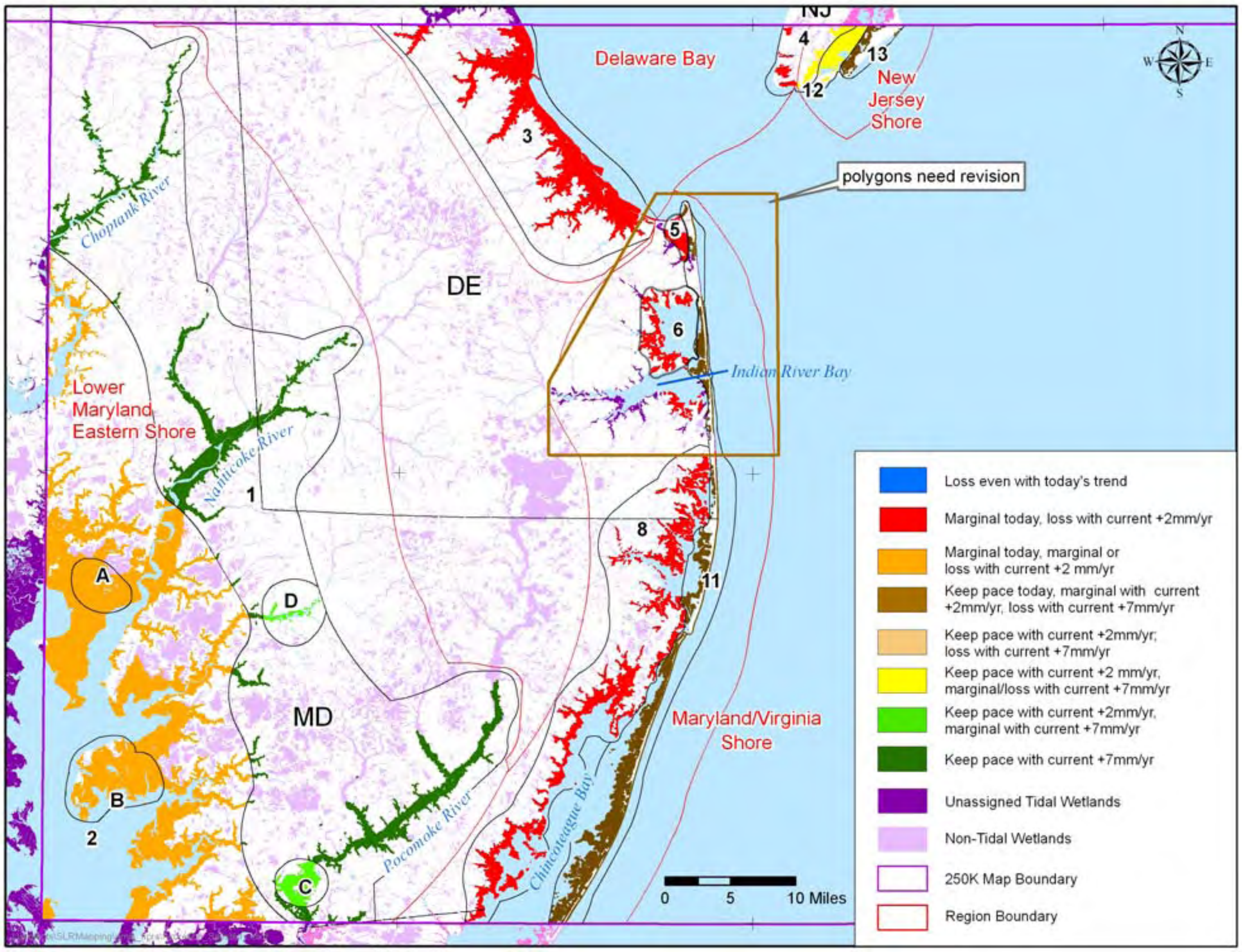


Figure 2.2.5. Wetland Accretion potential for polygons in the Salisbury quad. At this point, the polygons still needed revision around Indian River Bay.

Map Colors

The panel provided one of five accretion possibilities (keep pace, marginal/keep pace, marginal, marginal/loss, loss) for each of three sea level rise scenarios. That specification seemed to suggest a map for each sea level rise scenario—which could lead us to an unwieldy proliferation of maps. Putting all the information on a single map seemed more desirable. Fortunately, only 8 of the possible 15 combinations (5 accretion sensitivities by 3 sea level scenarios) occurred, a manageable number of colors.[8] Ignoring the areas of uncertainty (e.g., marginal/loss) actually leaves us with only 6 sensitivities, for which we defined the following colors.

We then defined intermediate colors for two other, more intermediate specifications: marginal today, marginal/loss at current +2 mm/yr, loss at current + 7 mm/yr (orange) and keep pace with current + 2 mm/yr and marginal/loss at current + 7 mm/yr (yellow). Figure 2.2.5 shows the resulting map for wetland accretion. The zipped file with which this data is distributed includes jpg's for the quads and the regions, as well as an overview map, following that color scheme. The reader may notice that the polygon boundaries and map colors in Figures 2.2.4 and 2.2.5 have been assigned to most of the tidal wetlands that had been omitted from the polygons in Figure 2.2.2. However, some of the wetlands around Rehoboth Bay were still unassigned. Similarly,

[8] During an initial review, the total number of combinations was reduced to 7, because the only polygon where wetlands were marginal at +7 mm/yr had been erroneously denoted as such. We've left that combination within the legend bar because it is an obvious possibility that may emerge during subsequent review or in other study areas.

assigning the map colors allowed us to notice a number of errors. We queried the data to identify all wetlands that had not been assigned a geomorphic setting, and looked for other cases where the geomorphic setting had a clear map boundary error.[9] We corrected the polygons based on our understanding of the panel's intent as documented by Reed et al. (see note 1).

Legend

One problematic aspect with maps following the format of Figure 2.2.5 is that the keys take a lot of words to repeat the same concepts. A single color bar would be preferable; but the panel did not characterize the wetlands with a single condition. We experimented with a pair of color bars, but people found that approach too confusing. The simplest alternative to a lot of words appears to be a table, with a color bar. (See Figure 2.2.6.)

Maps 2.2.1 and 2.2.2 provide the regional summary maps that we created based on the aforementioned considerations. Because the panel wanted to include subregional maps in the panel report, we also provided subregional maps. We do not reproduce those maps here but they are available with the data product EPA is distributing.[10] The consensus of panel members was that the accretion map is not valid at large scales. Therefore, the subregion-specific maps should not be reproduced without both a warning and an explanation about why the maps are being reproduced at this scale.[11]

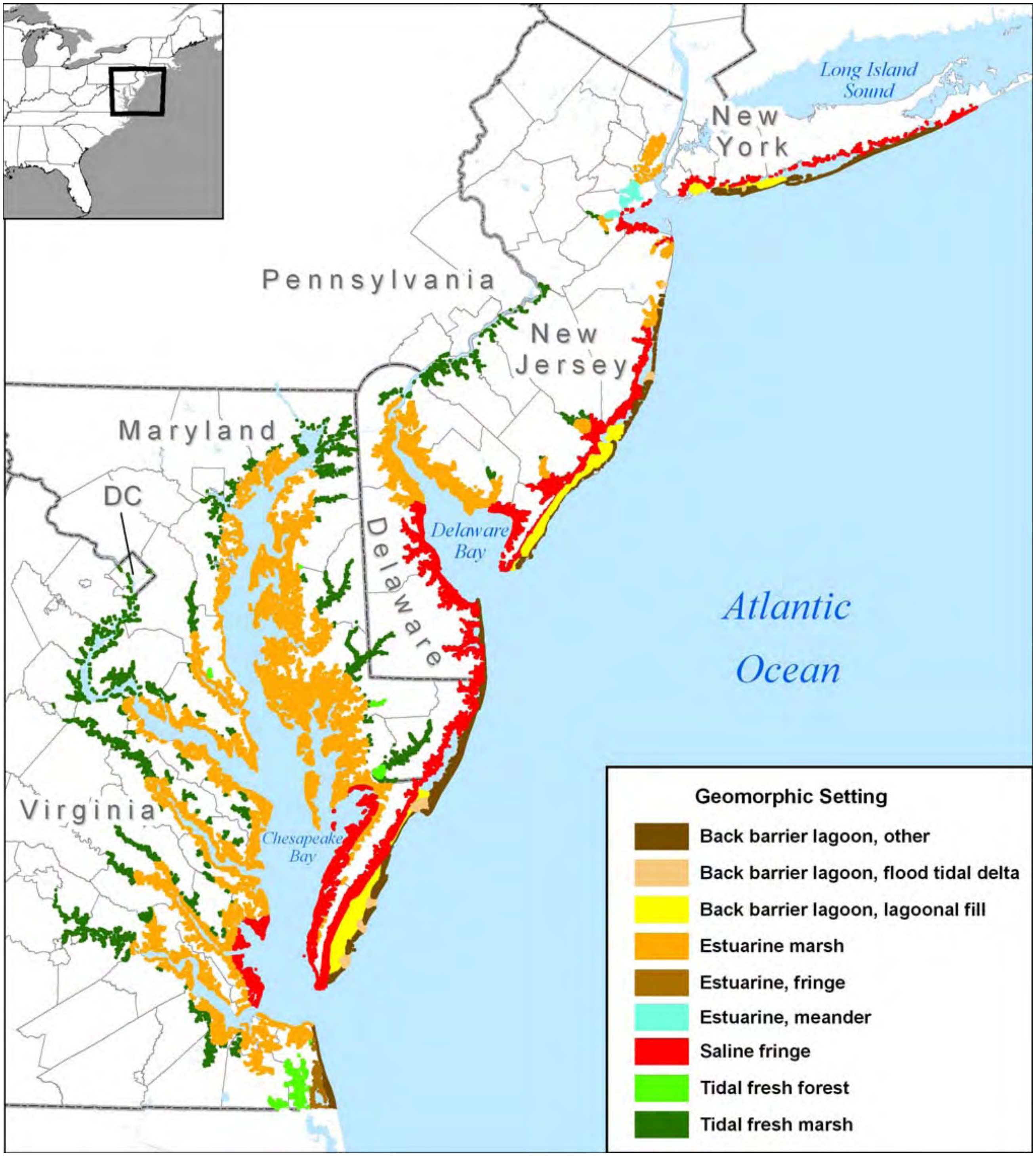
Will Wetlands Be Converted to Open Water?								
Rate of Sea Level Rise								
Current rate	Yes	?	?	No	No	No	No	No
Current + 2 mm/yr	Yes	Yes	Yes?	?	No	No	No	No
Current + 7 mm/yr	Yes	Yes	Yes	Yes	Yes	Yes?	?	No
? = Wetlands would be marginal Yes? = Wetland would be marginal or lost								

Figure 2.2.6. Legend for wetland accretion map.

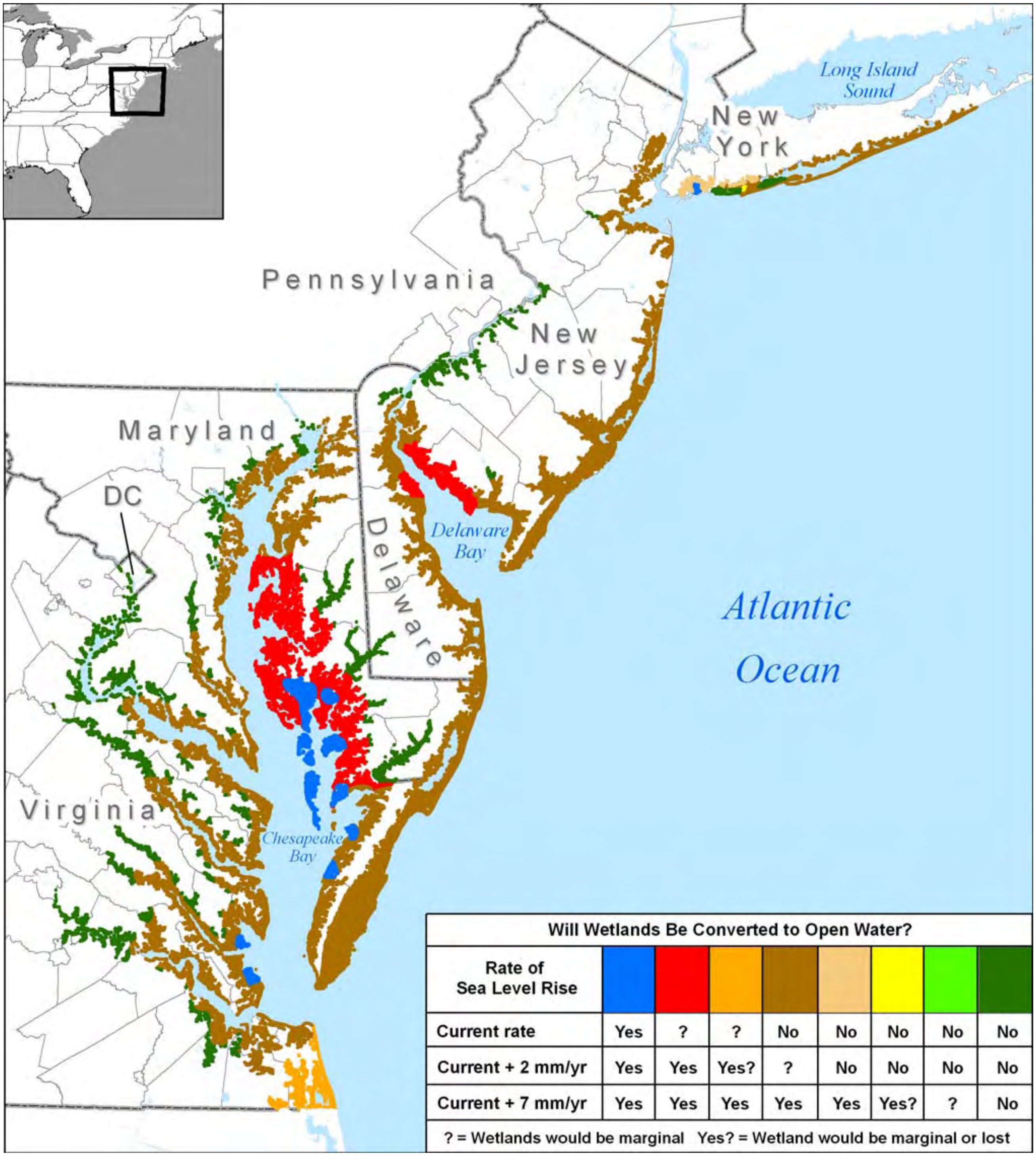
[9]For example, the polygon boundaries did not match—or the geomorphic setting was different—at a quadrangle boundary.

[10]Upon release of this report, EPA will make the data set described in this paper available to all researchers.

[11]Given the 1 cm errors in the hand renderings, National Map Accuracy standards would suggest a 1:5,000,000 scale.



Map 2.2.1. Geomorphic Setting of Tidal Wetlands: Montauk Point to Virginia Beach



Map 2.2.2 Potential for Tidal Wetland Accretion in the Mid-Atlantic: Montauk Point to Virginia Beach.

3. MID-ATLANTIC COASTAL HABITATS AND ENVIRONMENTAL IMPLICATIONS OF SEA LEVEL RISE

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3.1 Overview

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This overview considers the species and habitats of the mid-Atlantic from Virginia to New York that are at risk from sea level rise. For different habitats in this region, the ecological implications of sea level rise vary in extent and certainty. Vegetation type, soil type, sediment inputs, and current ecological health can all affect the ecological response to sea level rise. In turn, the animal species that depend on these habitats for activities such as foraging or nesting will vary in their responses to habitat changes, depending on species-specific responses to changes in inundation, salinity, vegetation structure and composition, and other habitat characteristics. Where it is used, shoreline armoring will influence the ability of both habitats and biota to adapt to sea level rise. The following bullets summarize the assumptions on potential responses of mid-Atlantic habitats to increasing rates of sea level rise and shoreline armoring, based on answers to CCSP 4.1 Questions 2 and 3[1]:

- Rising sea level can cause *tidal marshes* (e.g., salt, brackish, and freshwater tidal marshes) to erode at the waterward boundary; drown in place and convert to open water; vertically keep pace with sea level rise through sedimentation and peat formation; and/or expand inland as areas just above the level of the tides become inundated. If sea level rise increases the salinity of an estuary, the vegetation composition of brackish and freshwater marshes may shift to more salt-tolerant species. In areas where habitat is lost or degraded, the myriad species dependent on marshes—birds, fish, invertebrates, and mammals—may show decreased growth, reproduction, or survival.

- *Tidal freshwater swamp forests,* like marshes, can retreat at the waterward boundary; drown in place; keep pace with sea level rise; and/or expand inland. In addition, saltwater can induce vegetation shifts or cause swamps to convert to open water by oxidizing organic soils or inducing subsidence. Within the study region, these swamp forests are found primarily in the tributaries of Chesapeake Bay. With inundation, an associated increase in salinity in the upper reaches of rivers will cause larger trees to die, opening space for germination, settlement, and establishment of marsh macrophytes.

- *Marsh and bay islands* are found throughout the mid-Atlantic study region. These isolated areas provide nesting sites that are protected from predators and human disturbance for various bird species, particularly colonial nesting water birds. Because of their limited migration ability, these islands are particularly susceptible to sea level rise.

- *Sea level fens* are an extremely rare type of coastal wetland. These fens grow only under unusual circumstances—where a natural seep from a nearby slope provides nutrient-poor groundwater to support their unique vegetation and where the fens are protected from nutrient-rich tidal flow. Sea level fens are present in Delaware's Sussex County Inland Bays watershed, on Long Island's South Shore, and on the eastern shore of Virginia's Accomack County. Because sea level fen vegetation needs nutrient-poor

[1]Question 2: How does sea level rise change the ocean coastline? Among those lands with sufficient elevation to avoid inundation, which land along the Atlantic Ocean could potentially erode in the next century? Which lands could be transformed by related coastal processes? Question 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? In other words, will sea level rise cause the area of wetlands to increase or decrease?

waters, these unique wetlands might not survive inundation by sea level rise.

- In *nearshore waters*, rising sea levels and deepening waters will shade the deeper areas of submerged aquatic vegetation (SAV) beds, limiting photosynthesis. The landward edges of SAV may move inland onto areas that are currently tidal wetlands if the water bottoms have suitable sediments. Seagrasses (e.g., eelgrass and widgeon grass) provide food and shelter for a variety of fish and shellfish, food for the species that prey on those fish and shellfish, and physical protection from wave energy for shorelines. Scientists are not certain of the likely net change in SAV, which will depend on the balance between losses resulting from increasing depth in current beds and gains due to migration into inundated shoreline areas.

- *Tidal flats* may be readily lost with rising seas, but may also be created temporarily in areas where wetlands are inundated. Loss of tidal flats would eliminate a rich invertebrate food source for migrating birds.

- *Estuarine beaches* erode, but under natural conditions the landward and waterward boundaries usually retreat by about the same distance. In the built environment, structures can prevent the system from migrating inland, in effect causing the beaches to be squeezed between developed areas and the water. Society will preserve many beaches with sand replenishment (beach nourishment). In areas that do lose beaches, though, insects and other invertebrates such as sand diggers, sand fleas, and numerous crab species will lose their habitats. Shorebirds that rely on beaches for forage and nesting will also face more limited resources.[2]

- *Cliff areas* can experience increased erosion rates, or, if the cliff base is armored, the erosion rates can decrease. In the latter case, however, the armoring can eliminate habitat for species (e.g., Puritan tiger beetles and belted kingfishers) that depend on varying rates of cliff erosion.

This section gives a general description of vulnerable coastal habitats and potential ecological consequences of sea level rise and shoreline armoring in the U.S. mid-Atlantic region from Virginia to New York. The information presented here is based on current scientific understanding as well as the observations of local experts. In each section that follows this overview, we begin by describing the type of habitat (refer to the previous bulleted list), then discuss potential ecological responses to sea level rise and to shoreline armoring (if any) for that type of habitat, presenting case studies for specific bays, estuaries, and back barrier lagoons of the mid Atlantic from New York to Virginia.

Various general assumptions are made in this section based on other information from the CCSP and the scientific literature. Assumptions for marsh survival rely on the response to CCSP 4.1, Question 3 (Reed et al., Section 2.1), which describes accretion expectations under three sea level rise scenarios for marshes in the mid-Atlantic region. The three scenarios are (1) the current rate of sea level rise, (2) an increase of 2 mm/yr above the current rate, and (3) an increase of 7 mm/yr above the current rate. The accretion expectations take into account sediment inputs, marsh characteristics, and historical processes, among other considerations.

Changes in salinity are not directly considered in this section. In the absence of other factors, sea level rise is expected to drive the salt front farther upstream in estuaries and tributaries. For example, one estimate for the Delaware River is an 11 km movement upstream for the salt front.[3] More recent models, however, indicate that any concomitant changes in freshwater inputs to tributaries may negate the upstream drive of the

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[2]Lippson, A.J., and R.L. Lippson, 2006, *Life in the Chesapeake Bay,* 3rd ed., The Johns Hopkins University Press, Baltimore, MD, pp. 26–42. For more detail on beach habitats and the species that occur in them, see Section 3.1.7 of this section.

[3]Hull, C.H.J., and J.G. Titus, 1986, *Greenhouse Effect, Sea-Level Rise, and Salinity in the Delaware Estuary,* US EPA 230-05-86-010, U.S. EPA and Delaware River Basin Commission, Washington, DC, p. i.

salt wedge.[4] Although salinity change can have profound effects on both flora and fauna, we do not consider it in detail here because of the uncertainty associated with salinity.

Changes in water depth will be a function of the rate of sea level rise and the rate of sedimentation.[5] In embayments and estuaries where the tidal prism increases, increased water depth is likely.[6] In Chesapeake Bay, some researchers anticipate a water depth increase of almost 20 percent.[7] On the other hand, studies in England have indicated that estuarine channels might become both wider and shallower, which may be an effect of sedimentation and local geomorphology.[8] Increased tidal prism is also associated with an increase in interior ponding in marshes, along with tidal creek bank erosion, which can lead to catastrophic marsh loss (as in the Blackwater Wildlife Refuge on Maryland's Eastern Shore).[9] We assume that in areas where marshes are not expected to accrete sufficient sediment to remain in place, an increase in water depth will occur over any given area waterward of the marsh. Shoreline protections can further affect local water depths and are discussed in each section as necessary.

3.1.1 TIDAL MARSHES

Tidal marshes are characterized based on salinity. Freshwater marshes receive significant freshwater input and have waters that contain less than 0.5 parts per thousand (ppt) of ocean-derived salts. The waters of brackish (estuarine) marshes are less than 18 ppt. Salt marshes receive substantial inundation by ocean waters and have waters that can reach 30 ppt. As discussed in the following sections, numerous finfishes, birds, crustaceans, mollusks, reptiles, amphibians, and mammals rely on tidal marshes for at least part of their life cycle for resources such as food, shelter, nursery habitat, and nesting or spawning sites.

Salt marshes are among the most productive systems in the world, rivaling the productivity of agricultural lands. These marshes are the primary source of much of the organic matter and nutrients that form the basis of the estuarine food web.[10] Primary productivity includes both aboveground production (stalks and leaves) and belowground production (roots and tubers) by marsh plants as well as benthic algae. Much of the aboveground primary production is in the form of cellulose, which most animals cannot digest. Therefore, most vascular plant material is consumed by detritivores such as copepods, amphipods, annelids, snails, and insect larvae.[11] In turn, these organisms provide food for macroinvertebrates such as saltmarsh snails, ribbed mussels, and fiddler crabs, and small resident fishes such as mummichogs, sheepshead minnows, and Atlantic silversides.[12] The abundant invertebrates and small fishes of salt marshes are food for larger consumers. Bay anchovies, silversides, and other small schooling species use salt marshes as nursery grounds and are a food source for birds and piscivorous fish.[13,14]

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[4]Najjar, R.G., H.A. Walker, P.J. Anderson, E.J. Barron, R.J. Bord, J.R. Gibson, V.S. Kennedy, C.G. Knight, J.P. Megonigal, R.E. O'Connor, C.D. Polsky, N.P. Psuty, B.A. Richards, L.G. Sorenson, E.M. Steele, and R.S. Swanson, 2000, "The potential impacts of climate change on the mid-Atlantic Coastal Region," *Climate Research* 14: 219–233, pp. 224–225.
[5]National Research Council (U.S.), 1987, *Responding to Changes in Sea Level: Engineering Implications,* Committee on Engineering Implications of Changes in Relative Mean Sea Level, National Academy Press, Washington, DC, p. 36.
[6]Levin, D.R., 1995, "Occupation of a relict distributary system by a new tidal inlet, Quatre Bayou Pass, Louisiana," pp. 71–84 in *Tidal Signatures in Modern and Ancient Sediments,* B.W. Flemming and A. Bartoloma, eds., Special Publication of the International Association of Sedimentology (vol. 24.), Blackwell Science, Oxford, U.K.
[7]Stevenson, J.C., M.S. Kearney, and E.W. Koch, 2002, "Impacts of sea level rise on tidal wetlands and shallow water habitats: A case study from Chesapeake Bay," *American Fisheries Society Symposium* 32:23–36.
[8]Pethick, J., 1993, "Shoreline adjustments and coastal management: Physical and biological processes under accelerated sea-level rise," *The Geographical Journal* 159(2):162–168.
[9]National Research Council, 1987, p. 69 (see note 5).

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[10]Teal, J.M., 1986, *The Ecology of Regularly Flooded Salt Marshes of New England: A Community Profile,* U.S. Fish and Wildlife Service Biological Reports 85 (7.4), 69 pp.
[11]Currin, C.A., S.Y. Newell, and H.W. Paerl, 1995, "The role of standing dead *Spartina alterniflora* and benthic macroalgae in salt marsh food webs: Considerations based on multiple stable isotope analysis," *Marine Ecology Progress Series* 121:99–116.
[12]Teal, 1986, pp. 21–25 (see note 10).
[13]McBride, R.S., 1995, "Marine forage fish," pp. 211–217 in Dove, L.E., and R.M. Nyman (eds.), *Living Resources of the Delaware Estuary.* The Delaware Estuary Program.
[14]Lippson and Lippson, 2006, p. 212 (see note 2).

Photo 3.1: Marsh and tidal creek, Mathews County, Virginia[15]

Birds that feed on crustaceans, mollusks, and fish within salt marshes include clapper rails, black rails, least bitterns, and many species of terns and gulls. Fiddler crabs are common in the diets of clapper rails, egrets, blue crabs, diamondback terrapins, and raccoons. Some of the birds are marsh-nesting obligates; others nest frequently, but not exclusively, in marshes. Three species of terns (including Forster's tern), several species of gulls, and the seaside and salt marsh sharp-tailed sparrows all nest in coastal salt marshes.[16]

In addition to secondary production within the marsh, some primary production may ultimately contribute to the surrounding estuarine food web. Kneib proposes that this occurs via "trophic relays," which consist of juvenile fauna that draw on the detrital food web of the marsh and then transfer marsh-produced organic matter to larger consumers as part of the estuarine food web.[17]

Salt marshes are characterized by distinct vegetation zones based on the degree of tidal flooding and the salinity tolerance of marsh plants. Because they are regularly flooded by daily tides, low marsh soils tend to be more waterlogged, saline, and anoxic than high marsh soils.[18] Low marsh is characterized by monospecific stands of smooth cordgrass. Characteristic bird species of low marsh include clapper rail, willet, marsh wren, seaside sparrow, and American black duck. Ribbed mussels form dense clumps on cordgrass roots and fertilize them by contributing phosphorous and nitrogen-rich pseudofeces.[19] Fiddler crabs enhance *Spartina* spp. survival by aerating the marsh soils.[20]

Tidal creeks and channels frequently cut through low marsh areas, functioning to drain the marsh surface and serving as conduits for nekton (small fish and decapod crustaceans) to enter the wetlands during high tides and for nutrient-rich plant detritus to be flushed out into deeper water with receding tides (see Photo 3.1).[21] Several fish species that are marsh residents and use the low marsh when it is flooded at high tide are found in tidal creeks at low tide, including Atlantic silversides, mummichogs, striped killifish, and sheepshead minnows. Marsh creeks support significantly higher densities of these species than other intertidal habitats.[22]

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[15]All photos are courtesy of Jim Titus, except for Photo 3.3a by Elizabeth Strange.
[16]Erwin, R.W., G. M. Sanders, and D. J. Prosser, 2004, "Changes in lagoonal marsh morphology at selected northeastern Atlantic Coast sites of significance to migratory waterbirds," *Wetlands* 24(4):891–903.
[17]Kneib, R.T., 1997, "Tidal marshes offer a different perspective on estuarine nekton," *Annual Review of Oceanography and Marine Biology* 35:1–120.
[18]LaBranche, J., M. McCoy, and D. Clearwater, 2003, p. 17 in *Maryland State Wetland Conservation Plan,* prepared by Nontidal Wetlands and Waterways Division, Maryland Department of the Environment.
[19]Kreamer, G.R., 1995, Saltmarsh invertebrate community. pp. 81–89 in Dove and Nyman, 1995 (see note 14).
[20]Dove and Nyman, 1995, pp. 81–89 (see note 14).
[21]Lippson and Lippson, 2006, pp. 202–203 (see note 2).
[22]Rountree, R.A., and K.W. Able, 1992, "Fauna of polyhaline subtidal marsh creeks in southern New Jersey: Composition, abundance and biomass," *Estuaries* 15:171–185.

Characteristic macroinvertebrates of salt marsh creeks include eastern mud snails, daggerblade grass shrimp, longwrist hermit crabs, common Atlantic slippershells, northern quahogs, softshell clams, razor clams, blue crabs, and horseshoe crabs. Great blue herons and egrets are among the many colonial wading birds and other waterbirds that commonly feed on the small fish and benthic invertebrates found in tidal creeks. If creeks deepen, these species will have increasing difficulty foraging for essential food supplies.

High marsh is briefly flooded once or twice daily on fewer than 10 days per month and is dominated by salt hay and spike grass. High marsh sediment contains more organic material than low marsh.[23,24] High marshes may include a scrub-shrub community at the upland edge. Salt shrubs often mark the limit of the highest spring and storm tides. Characteristic shrubs include groundsel, saltmarsh elder, and pasture rose. The marsh edge is typically dominated by salt marsh elder, whereas groundsel usually dominates the upland edge. Grasses include those typical of high salt marsh, including salt meadow grass, black grass, and switchgrass. The invasive common reed sometimes occurs in a narrow fringe along the upland edge of marshes where salinities are lower because of less tidal flooding and greater freshwater runoff.

Characteristic birds of high salt marsh include saltmarsh sharp-tailed sparrows, black rails, and northern harriers. Many of these high marsh species are adapted to nesting only in the short grasses of the high marsh, such as salt hay and spike grass, and may not thrive in the tall grasses of the low marsh.

Brackish or estuarine tidal marshes in estuaries of the mid-Atlantic are typically dominated by species such as Olney three-square, saltmarsh bulrush, switchgrass, dwarf spike grass, black needlerush, narrow-leaved cattail, big cordgrass, and the invasive common reed. In mixed communities, the vegetation occurs in zones. Big cordgrass is the most common near mean high tide (MHT), Olney three-square at MHT, and switchgrass near the spring tide line. Brackish marshes support many of the same 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.[25]

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 fishes, including herring and shad, as well as marine transients such as Atlantic menhaden and drum species, are present in summer and fall. The most visible invertebrates of the brackish marshes include red-jointed fiddler crab, marsh periwinkle, Atlantic ribbed mussel, and common clam worm.[26]

Freshwater tidal marshes are characteristic of the upper reaches of tributaries of estuaries. They support a more diverse vegetation community than more saline marshes. Like salt and brackish marshes, freshwater tidal marshes can show three distinct vegetation zones, depending on the degree of tidal inundation. In general, the lower tidal zone, exposed only at low tide, consists of sparsely vegetated intertidal flats. The middle zone is dominated by wild rice, spatterdock, pickerelweed, and arrow arum. The upper tidal zone is dominated by cattails, often with a diversity of other species such as sensitive fern, river bulrush, and sweet flag, and sometimes the invasive common reed.[27]

In general, the species composition of freshwater marshes does not appear to be limited by seed availability. Instead, physical factors limit the species composition, especially through flooding. Some species germinate well when

[23]Brinson, M.M., R.R. Christian, and L.K. Blum, 1995, "Multiple states in the sea level induced transition from terrestrial forest to estuary," *Estuaries* 18(4):648–659.
[24]LaBranche et al., 2003, p.17 (see note 18).

[25]White, C.P., 1989, *Chesapeake Bay: Nature of the Estuary, A Field Guide,* Tidewater Publishers, Centreville, MD, pp. 107–123.
[26]White, 1989, p. 124 (see note 25).
[27]White, 1989, pp. 97–105 (see note 25).

completely submerged; others are relatively intolerant of flooding.[28]

Tidal freshwater marshes provide shelter, forage, and spawning habitat for numerous fish species, primarily cyprinids (minnow, shiner, carp); centrarchids (sunfish, crappie, bass); and ictalurids (catfish). Some estuarine fish and shellfish can also complete their life cycle in freshwater marshes.[29]

Freshwater tidal marshes are also important for a wide range of bird species, and some ecologists suggest that these marshes support the greatest diversity of bird species of any marsh type, including a variety of waterfowl; wading birds; rails and shorebirds; birds of prey; gulls, terns, kingfishers, and crows; arboreal birds; and ground and shrub species. [30] 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.[31]

In addition to food and shelter for various species, marshes also improve water quality in the surrounding river or estuary. The marshes serve as filters for water draining from surrounding upland areas. In particular, marshes work to remove nutrients from runoff, process chemical and organic wastes, and reduce the terrigenous sediment load to the water column.[32] Marsh processes remove nitrogen and phosphorus compounds (e.g., nitrates, ammonia, and phosphates) from the water stream. The denitrification process (bacterial conversion of ammonia or nitrates from organic wastes and fertilizer into nitrogen gas) provides significant benefits to water quality. High levels of nutrients in coastal waters from nonpoint source runoff lead to algal blooms and hypoxia, which can kill large numbers of fish. Marsh vegetation also retains much of the terrigenous sediment load from runoff, which can interfere with photosynthesis in the water column (e.g., for SAV) and can cause siltation in nearshore areas (e.g., SAV or oyster beds).

Effects of Sea Level Rise on Tidal Marshes

The ability of tidal marshes to migrate in response to sea level rise depends on the supply of sediment and organic matter that is available to raise the marsh surface, the local tidal range, and the slope of nearby lowland. In addition, shoreline protection structures can block inland migration. The placement of hard structures reduces sediment inputs from upland sources and increases erosion waterward of a structure.

Tidal marshes may keep pace with sea level rise through vertical accretion and inland migration, as long as there is a dependable source of terrigenous sediment and the marsh can maintain the same elevation relative to the tidal range. In areas where neither sufficient accretion nor migration can occur, increased tidal flooding can stress marsh plants through waterlogging and changes in soil chemistry, leading to a change in species composition and vegetation zones. If marsh plants become too stressed and die, the marsh will eventually convert to open water or mudflats (see Photo 3.2).[33,34]

Steadily increasing relative sea levels may cause more frequent events such as saltwater flooding, storm overwash, and wrack deposition. These events, in turn, can trigger changes in wetland ecosystems.[35] The ability of marsh vegetation to accrete terrigenous sediment and migrate inland will determine marsh survival.[36] Marsh types,

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[28]Mitsch, W.J., and J.G. Gosselink, 2000, *Wetlands*, 3rd ed., Van Nostrand Reinhold, New York, p. 275.
[29]Mitsch and Gosselink, 2000, p. 277 (see note 28).
[30]Mitsch and Gosselink, 2000, p. 279–280 (see note 28).
[31]White, 1989, pp. 107–109 (see note 25).
[32]Tiner, R.W., and D.G. Burke, 1995, *Wetlands of Maryland,* U.S. Fish and Wildlife Service, Region 5, Hadley, MA, pp. 146–147.

[33]Callaway, J.C., J.A. Nyman, and R.D. DeLaune, 1996, "Sediment accretion in coastal wetlands: A review and a simulation model of processes," *Current Topics in Wetland Biogeochemistry* 2:2–23.
[34]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 Section 3.11 on Hampton Roads.
[35]Brinson et al., 1995, p. 655 (see note 23).
[36]Ward, L.G., M.S. Kearney, and J.C. Stevenson, 1998, "Variations in sedimentary environments and accretionary patterns in estuarine marshes undergoing rapid submergence, Chesapeake Bay." *Marine Geology* 151:111–134.

Photo 3.2: Fringing March and Bulkhead, Monmouth County, New Jersey

however, have differing capacities for sediment accretion. Facing increasing rates of sea level rise, high marshes may not be able to trap and accrete sufficient sediment, whereas low tidal marshes, both fresh and estuarine, are more likely to have this ability. Marshes without riverine sediment input, such as those that fringe islands, are at the greatest risk from sea level rise.[37] Sediment transport in low marsh areas is facilitated by tidal creeks, which frequently occur in networks throughout broad areas. These networks are absent in more mature marshes and in upland areas, limiting sediment input for high marshes.[38]

If accretion does not maintain the marsh in place, migration is also a possible mechanism for marsh survival. In addition to artificial and natural barriers (e.g., armoring structures), sediment requirements also impede wetland migration. Bare patches and a more mineral sandy substrate are necessary for lower marsh vegetation species to migrate onto areas that once were high marsh. For successful transition, a variety of factors, including localized topographic changes, erosion, deposition of wrack on high marsh plants, and ponding, can contribute to deterioration of the high marsh organic-rich peat and allow for colonization by low-marsh *Spartina alterniflora*.[39] *S. alterniflora* can aggressively colonize high marsh areas that have been devegetated by wrack deposition from a storm or overwash event. Even though *S. alterniflora* can colonize deteriorated high marsh areas with suitable sediment types, factors that reduce wetland vegetation's ability to trap sediments (e.g., construction of roads across them or reductions in sediment supply) and the processes that drive deterioration (described previously) can continue even in the absence of further sea level rise, resulting in total marsh loss.[40]

Local variation in rates of terrigenous sedimentation and other processes such as erosion will determine accretion and migration at specific sites.[41] In addition to anthropogenic or natural physical barriers, storm-induced erosion and sediment deficits can preclude migration. In Chesapeake Bay, scientists estimate that "the influx of particulates is not high enough to keep pace with relative sea level rise" on a bay-wide scale.[42] A trend of decreasing sediment inputs from major mid-Atlantic rivers because of farmland abandonment in the mid-Atlantic

[37]Najjar et al., 2000, p. 223 (see note 4).
[38]Stevenson, J.C., and M.S. Kearney, 1996, "Shoreline dynamics on the windward and leeward shores of a large temperate estuary," pp. 233–259 in *Estuarine Shores: Evolution, Environments, and Human Alterations,* K.F. Nordstrom and C.T. Roman (eds.), John Wiley & Sons, New York; and Najjar et al., 2000, p. 223 (see note 4).

[39]Brinson et al., 1995, p. 655 (see note 23).
[40]Stevenson and Kearney, 1996, p. 238 (see note 38).
[41]Ward et al. (1998) (see note 36) found that accretion rates tend to decrease down-estuary in the Nanticoke, an eastern Bay tributary. Overall, rates in embayment marshes were close to or less than the local sea level rise and not as spatially patterned as the tributary marshes. A 0.24 cm/year accretion rate at the mouth of an estuarine tributary (the Nanticoke) compared to a 0.19 cm/year accretion rate for an interior marsh area ("Variations in sedimentary environments," p. 125). In Monie Bay, a low organic content was found, indicating a higher level of mineral soils and suggesting that accretion rates are lower than relative sea level rise ("Variations in sedimentary environments," p. 127).
[42]Stevenson and Kearney, 1996, p. 236 (see note 38).

region suggests that a lack of sediment may also affect wetlands outside of Chesapeake Bay.[43] Similarly, lagoonal marshes, areas within embayments or larger marsh systems, and marshes migrating inland that are remote from tributary sediment inputs may not be able to keep pace with sea level rise.[44] In areas without sufficient sediment, wetlands may transition to tidal flat or open water.

Vegetation type can also affect the ability of a marsh to accrete sediment. Greater rates of mineral and organic sediment trapping have been associated with common reed (as compared to *Spartina* spp.) in both a subsiding creek bank marsh and a laterally eroding marsh.[45] Researchers indicate that belowground productivity most likely plays a key role in the ability of the common reed to rapidly increase substrate level.[46] Given the greater ability of marshes dominated by common reed to meet increased rates of sea level rise, expected ecological effects are lower in these areas.[47]

Effects of Armoring on Tidal Marshes

Shoreline protection can affect both migration and accretion for wetlands. Increases in wave energy generated by armoring structures can eliminate marsh areas waterward of the structures.[48] Sediment scoured from bulkhead bases in estuaries can "cover spawning habitats formerly used by forage fish that spawn in the upper intertidal zone."[49] Marsh and tidal areas reinforced with armoring that prevents habitat migration will suffer the greatest loss of habitat.[50,51] Elimination of these wetland areas will also reduce the shoreline's ability to buffer the effects of erosion and floods and to filter nutrient and contaminant loads in runoff.

Ecological Effects on Tidal Marshes

Where tidal wetlands are lost, the myriad species that depend on marshes—birds, fish, invertebrates, amphibians, reptiles, and mammals—can show decreased growth, reproduction, or survival resulting from a decrease in habitat quantity or quality. If salt marsh areas are lost, avian marsh-nesting obligates such as Forster's terns, black rails, clapper rails, northern harriers, American black ducks, seaside sparrows, and sharp-tailed sparrows will lose habitat and are likely to suffer reproductive stress.[52] Lagoonal marshes and mid-embayment areas are particularly susceptible to changes induced by sea level rise. Tidal flats will be inundated, and although changes in extent might be localized at first, scientists anticipate an overall reduction in forage habitat for shorebirds.

Sea level rise is also advancing the salinity gradient upstream in some rivers, leading to shifts in vegetation composition and the conversion of some tidal freshwater marshes into oligohaline marshes.[53] High brackish marshes can deteriorate as a result of ponding and wrack-smothering of vegetation as salinity increases with rising seas and storms accentuate the fragmentation of the marshes.[54] This process may allow colonization by lower marsh species, but

[43]Najjar et al., 2000, p. 223 (see note 4).
[44]Erwin et al., 2004, p. 892 (see note 16).
[45]Rooth, J.E. and J.C. Stevenson, 2000, "Sediment deposition patterns in *Phragmites australis* communities: Implications for coastal areas threatened by rising sea-level," *Wetlands Ecology and Management* 8:173–183.
[46]Ibid.
[47]At Eastern Neck National Wildlife Refuge, Maryland, managers are leaving phragmites stands in place as a strategic action against erosion. See Section 3.17, Chesapeake Bay's Upper Bay, of this section.
[48]U.S. Geological Survey (USGS), 2003, "A summary report of sediment processes in Chesapeake Bay and watershed," p. 55 in *Water-Resources Investigations Report 03-4123,* USGS, Reston, VA.
[49]Small, D., and R. Carman, 2005, "Marine shoreline armoring in Puget Sound and the Washington State Hydraulic Code," p. 1 in *Proceedings of the 2005 Puget Sound Georgia Basin Research Conference, March 29-31, 2005.* Available at: http://www.engr.washington.edu/epp/psgb/2005psgb/2005proceedings/index.html from the University of Washington, College of Engineering.
[50]Galbraith, H., R. Jones, P. Park, J. Clough, S. Herrod-Julius, B. Harrington, and G. Page, 2002, "Global climate change and sea level rise: Potential losses of intertidal habitat for shorebirds, *Waterbirds* 25(2):173–183.
[51]Oyster Bay, New York, has experienced extensive marsh loss as a result of bulkheading. See Section 3.3, Long Island South Shore.
[52]For example, seaside and sharp-tailed sparrows are both prevalent in at-risk marshes on Virginia's Eastern Shore. See Section 3.19.
[53]Maryland Department of Natural Resources (DNR), 2005, Chapter 4, Part 2, p. 49 in *Wildlife Diversity Conservation Plan—Final Draft,* available at: http://www.dnr.state.md.us/wildlife/divplan_wdcp.asp (accessed February 28, 2007).
[54]Along the Patuxent River, Maryland, refuge managers have noted marsh deterioration and ponding with sea level rise. See Section 3.16 on the Western Shore.

that outcome is not certain.[55] Low brackish marshes may 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 the predators that consume them. Even though more ponding and "pannes" might provide some additional foraging areas as marshes deteriorate, the associated increase in salinity due to evaporative loss will drive vegetation changes to less diverse assemblages of salt-tolerant species.[56] In fact, high salt conditions will be lethal for many species.

If marshes can migrate, changes in vegetation assemblages will in turn affect the faunal species that forage, nest, spawn, and seek shelter in tidal marshes. Factors affecting fauna include reduced available oxygen, structural changes in vegetation, and reduction of foraging areas in tidal flats. In these hypoxic conditions, more salt-tolerant fishes such as mummichogs and killifishes become prevalent.[57]

In areas where marshes are reduced, remnant marshes might provide lower quality habitat and pose greater predation risk for a number of bird species that are marsh specialists and are also important components of marsh food webs. These species include the clapper rail, black rail, least bittern, Forster's tern, willet, and laughing gull.[58] Scientists estimate that as much as 80 percent of the Atlantic Coast breeding population of Forster's tern and 70 percent of laughing gull are at risk because of habitat loss due to sea level rise.[59] Populations of some noncolonial species are also at risk because of their already-low population sizes, estimated at about 142,000 for the clapper rail, 102,000 for the willet, and as little as 13,000 to 14,000 for the American black duck.[60] 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 ranged from 4.1 to 6.7 ha.[61] Particular species may require even larger marsh sizes; minimum marsh sizes for successful communities of the saltmarsh sharp-tailed sparrow and the seaside sparrow, both on the Partners in Flight WatchList, are estimated at 10 and 67 ha, respectively.[62]

Effects of marsh inundation on fish and shellfish species are likely to be complex. In the short term, inundation could make the marsh surface more accessible, increasing production.

The benefits, however, will decrease as submergence decreases total marsh habitat.[63] A marsh loss model, coupled with shrimp survey data from the National Marine Fisheries Service, suggests that losses in yields due to marsh loss could be as high as 50 percent.[64]

Deterioration and mobilization of marsh peat sediments increase the biological oxygen demand in the immediate vicinity and deplete oxygen levels to below requirement thresholds for many game fish such as striped bass. In these hypoxic conditions, more tolerant fish assemblages ,including mummichogs and killifish, become prevalent.[65]

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[55]Stevenson and Kearney, 1996, p. 236 (see note 38).
[56]Maryland DNR, 2005, p. 49 (see note 53).
[57]Stevenson et al., 2002, pp. 25–26 (see note 7).
[58]Erwin, R.M., G.M. Sanders, D.J. Prosser, and D.R. Cahoon, 2006, "High tides and rising seas: potential effects on estuarine waterbirds," pp. 214–228 in *Terrestrial Vertebrates of Tidal Marshes: Evolution, Ecology, and Conservation* (R. Greenberg, J. Maldonado, S. Droege, and M.V. McDonald, eds.). Studies in Avian Biology No. 32, Cooper Ornithological Society.
[59]Ibid.
[60]Ibid.
[61]Watts, B.D., 1993, *Effects of Marsh Size on Incidence Rates and Avian Community Organization within the Lower Chesapeake Bay,* Center for Conservation Biology Technical Report CCBTR-93-03, The College of William and Mary, Williamsburg, VA, 53 pp.
[62]Benoit, L.K., and R.A. Askins, 2002, "Relationship between habitat area and the distribution of tidal marsh birds," *The Wilson Bulletin* 114(3):314–323.
[63]Rozas, L.P., and D.J. Reed, 1993, "Nekton use of marsh-surface habitats in Louisiana (USA) deltaic salt marshes undergoing submergence," *Marine Ecology Progress Series* 96:147–157.
[64]Zimmerman, R.J., 1992, "Global warming: effects of sea level rise on shrimp fisheries," pp. 58–73 in *Proceedings of the Southeast Fisheries Science Center Shrimp Resource Review*, K.N. Baxter and L. Scott-Denton (eds.), NOAA Technical Memorandum, NMFS-SESC-299.
[65]Stevenson et al., 2002, pp. 25–26 (see note 7).

3.1.2 FRESHWATER SWAMP FORESTS

Limited by their requirements for low salinity water and high sediment inputs, tidal swamp forests occur primarily in the upper regions of tidal tributaries in Virginia, Maryland, Delaware, New Jersey, and New York.[66] Tidal hardwood swamps occur in all of Virginia's major eastern rivers, and are particularly pristine in the Pamunkey and Mattaponi rivers. In these rivers, pumpkin ash and swamp tupelo are the primary overstory species. In the Potomac River and farther north, green ash replaces pumpkin ash as the dominant species.[67] Parts of the Pocomoke River tidal floodplain forests are dominated by bald cypress. At the upland edges of tidal river floodplains, loblolly pine, sweetgum, and oaks can be present.[68] Farther north (into New Jersey and New York), varying tree species are present, and the habitat is classified as northern Atlantic coastal plain tidal swamp.[69] North Carolina contains large stands of forested wetlands, particularly cypress swamps, as discussed in the review of ecological impacts in North Carolina (see, for example, Photo 3.3b).[70]

Throughout the forested swamps, "hummock-and-hollow microtopography" dictates where trees can establish themselves on small elevated areas above the highest tide levels.[71] A species-rich herb vegetation layer includes a variety of species such as jewelweed, arrow arum, and sedges in the regularly flooded areas; marsh blue violet, water hemlock, greenfruit clearweed, false nettle, and ferns are found on the hummocks (vegetated mounds that rise above the adjacent wetland area).[72] Tidal swamps support a variety of wildlife, including the prothonotary warbler, the two-toed amphiuma salamander, and the bald eagle. Forested wetlands with thick understories provide shelter and food for an abundance of breeding songbirds.[73] Various rare and greatest conservation need (GCN) species reside in tidal swamps, including the Delmarva fox squirrel (federally listed as endangered), the eastern red bat, bobcats, bog turtles, and the red-bellied watersnake.[74]

Effects of Sea Level Rise on Tidal Freshwater Swamp Forests

Tidal freshwater swamp forests are considered globally uncommon to rare, and face a variety of threats, including sea level rise. According to Fleming and colleagues, "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" (see also Photo 3.3a).[75] Ecologists in Virginia note that where tree death is present, the topography is limiting inland migration of the hardwood swamp and the understory is being infilled with marsh species such as *Spartina*.[76]

Ecological Effects on Tidal Freshwater Swamp Forests

This pattern of crown dieback and marsh species migration is likely to continue with sea level rise acceleration. Salinity may increase as areas are inundated, eliminating vegetation that relies on the diluting effect of freshwater inputs. Loss of

[66]NatureServe, 2006, "NatureServe Explorer: An online encyclopedia of life" [Web application], Version 5.0, NatureServe, Arlington, Virginia, available at: http://www.natureserve.org/explorer, accessed September 1, 2006, and "Northern Atlantic coastal plain tidal swamp," CES203.282, accessed on September 1, 2006 at: http://www.natureserve.org/explorer/servlet/NatureServe?searchSystemUid=ELEMENT_GLOBAL.2.723205.
[67]Fleming, G.P., P.P. Coulling, K.D. Patterson, and K. Taverna, 2006, "The natural communities of Virginia: Classification of ecological community groups. Second approximation. Version 2.2," Virginia Department of Conservation and Recreation, Division of Natural Heritage, Richmond, VA, available at: http://www.dcr.virginia.gov/dnh/ncintro.htm, accessed June 19, 2007.
[68]Maryland DNR, 2005, *Wildlife Diversity Conservation Plan*, p. 1 (see note 53).
[69]Westervelt, K., E. Largay, R. Coxe, W. McAvoy, S. Perles, G. Podniesinski, L. Sneddon, and K. Strakosch Walz, 2006, *A Guide to the Natural Communities of the Delaware Estuary: Version 1*, NatureServe, Arlington, VA, pp. 270–273.
[70]Mark Brinson of East Carolina University is providing CCSP and USGS with an analysis of these wetlands. We hope to work with him to fully reflect these important wetlands.
[71]Fleming et al., 2006 (see note 67).
[72]Maryland DNR, 2005, p. 1 (see note 53).
[73]Lippson and Lippson, 2006, p. 218 (see note 2).
[74]Maryland DNR, 2005, p. 4 (see note 53).
[75]Fleming et al., 2006 (see note 67).
[76]Written communication, Gary Fleming, vegetation ecologist, Virginia Department of Conservation and Recreation, Division of Natural Heritage. Via email to Christina Bosch, Industrial Economics, September 11, 2006. Subject: Re: Sea level rise report wrap-up - please respond.

tidal swamp forests would detrimentally affect the varied fauna that reside there.

3.1.3 MARSH AND BAY ISLANDS

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.[77] Shorelines can be composed of marsh or rocky or sandy beaches. These islands are important habitats for birds because they provide protection from terrestrial predators such as the red fox. Birds such as gull-billed terns, common terns, black skimmers, and American oystercatchers nest on marsh islands.[78] Many islands provide secluded areas for important bird colonies (e.g., the colonies of the rare black-crowned night heron on North and South Brother islands in New York; see Section 3.2 on Long Island Sound). Salt marsh islands in the New Jersey back-barrier bays are feeding and/or nesting sites for a variety of birds and turtles, including several species of tern, oystercatchers, plovers, and diamondback terrapins (see Section 3.6 on New Jersey Shore). Artificially enhanced islands, generally created through dredge spoil, can provide similar benefits (e.g., Hart-Miller Island near Baltimore, Maryland); however, dredge spoil islands can be particularly susceptible to erosion (see Section 3.16, Chesapeake Bay's Western Shore, and discussion of Poplar Island in Section 3.18, Chesapeake Bay's Central Eastern Shore). Hummocks can also be considered a type of island (see Photo 3.4).

Photo 3.3a: Inundation and tree mortality in tidal freshwater swamp at Swan's Point, Lower Potomac River

Photo 3.3b. Cypress along Roanoke River, North Carolina

[77]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 Section 3.8 of this section.

[78]Rounds, R.A., R.M. Erwin, and J.H. Porter, 2004, "Nest-site selection and hatching success of waterbirds in coastal Virginia: Some results of habitat manipulation," *Journal of Field Ornithology* 75:317–329; Eyler, T.B., R.M. Erwin, D.B. Stotts, and J.S. Hatfield, 1999, "Aspects of hatching success and chick survival in gull-billed terns in coastal Virginia," *Waterbirds* 22:54–59; and Lauro, B., and J. Burger, 1989, "Nest-site selection of American oystercatchers (*Haematopus palliatus*) in salt marshes," *Auk* 106:185–192.

Photo 3.4: Marsh Drowning and Hummock in Blackwater Wildlife Refuge, Maryland

Barrier islands form where sand accumulates along sandy coasts with small or medium tide ranges and wide continental shelves.[79] They contain many fragile habitats such as sand dunes, maritime forests, and back-barrier marshes that provide critical habitat for many coastal species. Barrier islands are a common feature of the U.S. Atlantic Coast.

Effects of Sea Level Rise on Islands

Depending on their current elevations, sediment supply, and rates of erosion, wetland islands could become the first habitats to be eliminated as a result of sea level rise. Sea level rise poses a unique threat to islands, in that migration is not an option and sediment inputs may be limited. Some scientists believe that salt marsh islands in large coastal lagoons will be more vulnerable to inundation as sea level rises than fringing marshes because the lagoons lack inorganic sediments.[80] In some cases, rising sea level may cause additional islands to form, as portions of peninsulas erode and higher water levels separate high ground from the mainland. Many islands along the mid-Atlantic Coast, and particularly in Chesapeake Bay, have been lost or severely degraded because of sea level rise. Although armoring can be used to protect these islands, it is not generally employed because the islands are undeveloped.

Without human interference, barrier islands often maintain a state of dynamic equilibrium between sediment exchange, wave energy, and sea level, migrating inland through a process often called "overwash" or "barrier island rollover." Under some circumstances, however, rising sea level can increase the frequency of inlets, and under extreme circumstances, sea level rise can cause the islands to disintegrate or reform several kilometers inland. The relatively slow rise in sea level during the last several centuries has enabled many barrier islands to widen far beyond their critical width; it follows that accelerated sea level rise would tend to cause most barrier islands to narrow.

Ecological Effects on Islands

For island-nesting bird species, the loss of wetland islands to flooding and erosion is a serious problem. A shift to mainland marshes is generally not an option for these species because of predators present in those marshes. Numerous species of special concern, including the piping plover, nest in the protected back-dune areas of barrier islands. Loss of these habitats could have a serious effect on such rare species. To the extent that estuarine and riverine beaches, particularly on islands, survive better than barrier islands, shorebirds like oystercatchers might be able to migrate to these shores.[81]

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[79] The information presented here on barrier islands is very limited because CCSP4.1 has at least two nationally recognized barrier-island experts from USGS; hence this background report is unlikely to be used for the CCSP discussions of barrier islands.

[80] Erwin et al., 2004, pp. 891–903 (see note 16).

[81] McGowan, C.P., T.R. Simons, W. Golder, and J. Cordes, 2005, "A comparison of American oystercatcher reproductive success on barrier beach and river island habitats in coastal North Carolina," *Waterbirds* 28:150–155.

3.1.4 SEA LEVEL FENS

The mid-Atlantic region contains a few areas of the globally rare sea level fen habitat. These fens are unique combinations of plant species, present in Delaware's Sussex County Inland Bays watershed, on Long Island's South Shore, and on the eastern shore of Virginia's Accomack County.[82] Sea level fens generally occur just above the upper high tide mark, at the bases of slopes.[83] Groundwater seepage from the slopes provides sea level fens with nutrient-poor fresh water. The fens occur only where they are protected from nutrient-rich tidal flow by a barrier such as a fronting tidal marsh.

The nutrient-poor environment and acidic soils support a unique mix of vegetation species, including both freshwater tidal species and northern bog species, in sea level fens.[84] Red maple, blackgum, sweetbay, and southern bayberry form the overstory; the herb layer typically includes twig rushes, beaked spikerushes, and beakrushes. Carnivorous plants, including sundew and bladderworts, are also present.[85] The eastern mud turtle and the smallest northeastern dragonfly (*Nanothemis bella*) are two faunal species known to occur in the fens.[86] The animal and plant species listed here are not exclusive to sea level fens, but many are rare species.

Effect of Sea Level Rise on Sea Level Fens

Because these fens are located at the bases of slopes, they are likely to be inundated by sea level rise. The Virginia Natural Heritage Program identifies sea level rise as a primary threat to sea level fens because of the increase in salinity and nutrient-rich water inputs.[87] The location of fens below slopes limits the possibility for migration. During the development of this report, no studies of the effects of armoring on sea level fens were identified.

Ecological Effects on Sea Level Fens

The unique vegetation assemblages and little-studied animal communities of sea level fens are likely to be eliminated by sea level rise. The plant assemblages are unique, but the animal species identified are present in other habitats. The habitat is likely to convert to more usual tidal marsh vegetation and faunal assemblages following the increased incursion of higher salinity waters. However, given the slopes at the landward edges of the fens, migration will be restricted and survival of any marsh areas will depend on accretion rates.

3.1.5 NEARSHORE WATERS AND SUBMERGED AQUATIC VEGETATION (SAV)

Nearshore shallow water habitats perform a variety of roles in the aquatic ecosystem. Key ecological features of the nearshore shallow water habitat include SAV, oyster reefs, and nektonic (e.g., fish and decapod crustaceans) and planktonic inhabitants. In areas without SAV or oyster reefs, muddy and sandy substrates similar to those found on tidal flats are present.[88] Oyster reefs are a key resource in intertidal and nearshore waters; however, they are not addressed in detail here because many factors currently affect their success. Over harvest, nutrient levels, and disease have all significantly affected oyster reefs.. Changes related to sea level rise may additionally affect the resource. For example, if salinity were to increase, oysters might be able to successfully colonize farther up estuaries, but in their current areas they would suffer greater losses from predators and disease. These possibilities, though, are difficult to estimate in the presence of annual variability. This section therefore focuses on SAV, which provides a wide array of ecological services and

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[82]For additional discussion, see Sections 3.8, Maryland and Delaware Coastal Bays; 3.3, Long Island's South Shore; and 3.19, Virginia's Eastern Shore.
[83]Virginia Natural Heritage Program, Virginia Department of Conservation and Recreation. Natural Heritage Resources Fact Sheet: Virginia's rare natural environments: Sea-level fens. Accessed on July 17, 2007 at: http://www.dcr.virginia.gov/natural_heritage/documents/fsslfen.pdf.
[84]Ibid.
[85]Fleming et al., 2006 (see note 67).
[86]Virginia Natural Heritage Program (see note 83).
[87]Fleming et al., 2006 (see note 67).
[88]Lippson and Lippson, 2006, pp. 126–127 (see note 2).

is very sensitive to water depth and substrate. SAV includes submerged, vascular rooted plants found in the subtidal and, occasionally, in the intertidal zone.[89] SAV can occur as isolated patches or form extensive beds. Aquatic vegetation 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 and sea lettuce). During low tides, SAV can be exposed on estuarine beaches and tidal flats.[90]

Nearshore vegetation plays a strong role in estuarine and bay ecology, regulating dissolved oxygen, reducing suspended sediments and nutrients, stabilizing bottom sediments, and reducing wave energy.[91] SAV communities regulate the production, uptake, and storage of nitrogen, carbon, and oxygen in the ecosystem.[92] Optimum growing conditions for SAV are highly dependent on light levels for photosynthesis. Various interferences—such as increased turbidity, epiphyte growth on leaves, and increased water depth—can decrease the light available to the plants for photosynthesis. Plants at either end of the growing zone are stressed by overexposure or sunlight limits. Nutrient runoff (which boosts algal growth that shades the SAV) as well as boating and mollusk dredging (which cause physical disturbance to the beds) can all have detrimental effects on SAV.[93]

Except for a high predominance of sea lettuce in New York's Jamaica Bay and the subtidal reaches stretching from Little Egg Harbor south to Cape May in New Jersey, the more northerly SAV beds are largely eelgrass. Research in New Jersey's coastal bays found a reduced habitat quality of SAV in areas dominated by sea lettuce.[94]

Seagrasses (e.g., eelgrass and widgeon grass) provide food and shelter for a variety of fish and shellfish, food for the species that prey on them, and physical protection from wave energy for shorelines. Organisms that forage in seagrass beds feed on the plants themselves, on the detritus and the epiphytes on plant leaves, or on the small organisms found within the SAV bed.[95] Invertebrates that are common in eelgrass meadows include polychaetes such as the common clam worm; mollusks such as bay scallop and northern quahog; crustaceans such as blue crabs, hermit crabs, and mud crabs; and amphipods such as *Lysianopsis alba* and the small, shrimp-like *Ampelisca abdita*. The commercially valuable blue crab hides in eelgrass during its molting periods, when it is more vulnerable to predation. Blue crabs in the postlarval phase (megalopae) preferentially inhabit eelgrass beds.[96]

These invertebrates are in turn consumed by fish and other predators.[97,98] In Chesapeake Bay, summering sea turtles frequent eelgrass beds. The endangered Kemp's Ridley sea turtle forages in eelgrass beds and flats, feeding on

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[89]Hurley, L.M., 1990, *Field Guide to the Submerged Aquatic Vegetation of Chesapeake Bay*, U.S. Fish and Wildlife Service, Chesapeake Bay Estuary Program, Annapolis, MD, 48 pp.
[90]Maryland DNR, 2005, pp. 22–23 (see note 53).
[91]Short, F.T., and H.A. Neckles, 1999, "The effects of global climate change on seagrasses." *Aquatic Botany* 63(1999):169–196.
[92]Buzzelli, C.P., 1998, "Dynamic simulation of littoral zone habitats in lower Chesapeake Bay. I. Ecosystem characterization related to model development," *Estuaries* 21(48):659–672; Buzzelli, C.P., R.L. Wetzel, and M.B. Meyers, 1998, "Dynamic simulation of littoral zone habitats in lower Chesapeake Bay. II. Seagrass habitat primary production and water quality relationships," *Estuaries* 21(48):673–689.
[93]Orth, R.J., J.R. Fishman, A. Tillman, S. Everett, and K.A. Moore, 2001, *Boat Scarring Effects on Submerged Aquatic Vegetation in Virginia (Year 1),* Final Report to the Virginia Saltwater Recreational Fishing Development Fund; Moore, K.A., and R.J. Orth. 1997, *Evidence of Widespread Destruction of Submersed Aquatic Vegetation (SAV) from Clam Dredging in Chincoteague Bay, Virginia,* Report to the Virginia Marine Resources Commission. Both reports are available from VIMS at: http://www.vims.edu/bio/sav/savreports.html (Accessed October 16, 2007).
[94]Sogard, S.M., and K.W. Able, 1991, "A comparison of eelgrass, sea lettuce macroalgae, and marsh creeks as habitats for epibenthic fishes and decapods," *Estuarine, Coastal and Shelf Science* 33:501–519.
[95]For blue crabs, see Stockhausen, W.T., and R.N. Lipcius, 2003, "Simulated effects of seagrass loss and restoration on settlement and recruitment of blue crab postlarvae and juveniles in the York River, Chesapeake Bay," *Bulletin of Marine Science* 72(2):409–422. For fish, see Wyda, J.C., L.A. Deegan, J.E. Hughes, and M.J. Weaver, 2002, "The response of fishes to submerged aquatic vegetation complexity in two ecoregions of the mid-Atlantic Bight: Buzzards Bay and Chesapeake Bay," *Estuaries* 25:86–100.
[96]van Montfrans, J., C.H. Ryer, and R.J. Orth, 2003, "Substrate selection by blue crab *Callinectes sapidus* megalopae and first juvenile instars," *Marine Ecology Progress Series* 260:209–217.
[97]USEPA, 1982, *Chesapeake Bay: Introduction to an Ecosystem,* USEPA, Washington, DC, , 33 pp.
[98]Lippson and Lippson, 2006, p. 181 (see note 2).

blue crabs in particular.[99] Various water birds feed on SAV, including brant, canvas back duck, and American black duck, which is a U.S. Fish and Wildlife Service species of concern.[100] Forage for piscivorous birds and fish is provided by a number of small fishes that are residents of nearby marshes and move in and out of seagrass beds with the tides, including mummichog, Atlantic silverside, naked goby, northern pipefish, and threespine and fourspine sticklebacks. Juveniles of many commercially and recreationally important estuarine and marine fishes (including 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 that provide both food and protection from predators.[101] Adults of estuarine and marine species such as sea trout, bluefish, perch, pickerel, and drum search for prey in the SAV beds.

Effect of Sea Level Rise on Nearshore Waters and SAV

Sea level rise may harm seagrass beds through inundation, increased turbidity, and saltwater intrusion.[102] In subtidal areas, rising sea levels and deepening waters will shade seagrass and limit photosynthesis. Extensive armoring coupled with areas of limited natural migration could significantly decrease seagrass abundance. Although plants in some portion of a seagrass bed could decline as a result of such factors, landward edges may migrate inland depending on shoreline slope and substrate suitability. The extent of ecological effects is uncertain because most changes in seagrass beds occur on a significantly shorter time scale than can be attributed to sea level rise.[103]

Under optimal conditions, seagrasses could migrate into deteriorating marshes. For example, populations of widgeon grass were observed in marsh potholes that developed as canals formed through organic marsh deposits.[104] Kentula and McIntire documented eelgrass expansion into a basin created by sand deposition.[105] Preliminary studies of eelgrass in marsh areas being inundated by relative sea level rise have, however, shown that the sediment composition of the low marsh areas may not be suitable for eelgrass colonization. In areas where inundation exposed underlying sand, eelgrass beds extended into the areas, but areas of exposed peat were not colonized. The difficulty in colonization was tied to the impermeability of the substrate (prohibiting seed settlement and germination) and the high levels of nutrients in the sediment, particularly nitrogen. These factors changed the morphology of the eelgrass, making it less suited to the energy level of its environment.[106] Unlike most wetland plants, seagrasses generally require a low organic content for optimal growth.[107] When tidal marshes, which have a high organic content, are submerged, SAV such as *Ruppia maritima* can have difficulty revegetating the substrate. SAV grows significantly better in areas where erosion provides sandy substrates rather than fine-grained or high-organic-matter substrates.[108]

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[99]Chesapeake Bay Program sea turtles guide, 2003, available at: http://www.chesapeakebay.net/seaturtle.htm, accessed February 27, 2007.
[100]Perry, M.C. and A.S. Deller, 1996, "Review of factors affecting the distribution and abundance of waterfowl in shallow-water habitats of Chesapeake Bay," *Estuaries* 19:272–278.
[101]NOAA Chesapeake Bay Office, 2007, "Underwater grasses and submerged aquatic vegetation," accessed June 19, 2007 at: http://noaa.chesapeakebay.net/HabitatSav.aspx; Wyda et al., 2002, pp. 86–100 (see note 95).
[102]Short and Neckles, 1999, pp. 169–196 (see note 91).
[103]USFWS Chesapeake Bay Field Office, n.d., "Nutrient pollution," accessed on July 20, 2006 at: http://www.fws.gov/chesapeakebay/nutrient.htm.
[104]Christian, R.R., 1981, referenced in Brinson et al. 1995, p. 654 (see note 23).
[105]Kentula, M.E., and C.D. McIntire, 1986, "The autecology and production dynamics of eelgrass (L. *Zostera marina*) in Netarts Bay, Oregon," *Estuaries* 9(3):188–193.
[106]Wicks, E.C., 2005, *The Effect of Sea Level Rise on Sea Grasses: Is Sediment Adjacent to Retreating Marshes Suitable for Seagrass Growth?* Thesis, Marine, Estuarine, and Environmental Science Program, University of Maryland, College Park; and preliminary research by Koch.
[107]Kemp, W.M., R. Batuik, R. Bartleson, P. Bergstrom, V. Carter, G. Gallegos, W. Hunley, L. Karrh, E. Koch, J. Landwehr, K. Moore, L. Murray, M. Naylor, N. Rybicki, J.C. Stevenson, and D. Wilcox, 2004, "Habitat requirements for submerged aquatic vegetation in Chesapeake Bay: Water quality, light regime, and physical-chemical factors," *Estuaries* 27:363–377.
[108]Stevenson et al. 2002, pp. 26, 32 (see note 7).

The effect of sea level rise on the tidal range will also have an impact on seagrass, although it 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, which will increase plant stress.[109] 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.[110]

Effects of Armoring on Nearshore Waters and SAV

Areas of shoreline armoring are likely to experience the biggest losses of seagrass. Movement of seagrass beds shoreward will be impeded by shoreline construction and armoring in developed areas.[111] Where inland migration is not possible, seagrass will decline or be eliminated as a result of inundation and increased salinity as seas rise. Nearshore fishes have been found to be significantly less abundant at bulkheaded sites, in part because seagrass is not present.[112] Bulkheads and other hard structures tend to affect the geomorphology of their locations as well as any adjacent seagrass habitats. Particularly during storm events, wave reflection off of revetments can increase water depth and magnify swash runup on downcoast beaches.[113] A USGS sedimentation study notes that these structures tend to increase erosion at their bases by reflecting wave energy across the nearshore bottom.[114] Similarly, a study of armoring in estuaries found that "wave energy reflected from bulkheads causes an increase in turbulence and erosional energy waterward of the structure that can result in substrate coarsening and lowering of the beach profile."[115] These physical changes in turn affect the habitats.

As sea level rises in armored areas, accompanied by erosional energy at the bottom, the nearshore area deepens with no ability to migrate. In addition to the effects of increased reflectional wave energy, which can be dissipated to a large degree by healthy seagrass communities, light attenuation increases with the deepening water, restricting and finally eliminating seagrass growth. Optimum growing conditions for most SAV require light levels typically found at up to 1 to 2 meters in depth, generally starting below the mean lower low watermark.[116] Light reductions from water clarity and epiphyte growth in most SAV beds are now at 1 meter or less in depth.[117]

In addition to the effects of light quantity and turbulence, high nutrient levels in the water are also a limiting factor. Despite the protection from wave energy provided in their interior, breakwaters appear to be detrimental to seagrass in the long term. Sediment trapping behind the breakwater, which increases the organic content, can limit eelgrass success. Low-profile armoring, including stone sills and other "living shoreline" projects, have a more limited impact on seagrass growth.[118] New designs for seagrass-friendly breakwaters that allow rollover at high tide might serve to flush out the interior of the breakwater and eliminate excess nutrient buildup.[119]

Ecological Effects on Nearshore Waters and SAV

The extent of ecological effects is uncertain, because most changes in SAV beds occur on a significantly shorter time scale than can be attributed to sea level rise.[120] Some species of seagrass could survive the effects of sea level

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[109] Koch and Beer, 1996, referenced in Short and Neckles, 1999, p. 179 (see note 91).
[110] Short and Neckles, 1999, pp. 179–180 (see note 91).
[111] Short and Neckles, 1999, p. 178 (see note 91).
[112] Byrne, D.M., 1995, "The effect of bulkheads on estuarine fauna: a comparison of littoral fish and macroinvertebrate assemblages at bulkheaded and non-bulkheaded shorelines in a Barnegat Bay Lagoon," *Second Annual Marine Estuarine Shallow Water Science and Management Conference*: 53–56.
[113] Plant, N.G. and G.B. Griggs, 1992, "Interactions between nearshore processes and beach morphology near a seawall." *Journal of Coastal Research* 8: 183–200, p. 190.
[114] USGS, 2003, p. 50 (see note 48).
[115] Small and Carman, 2005, p. 1 (see note 49).
[116] Kemp et al., 2004 (see note 107).
[117] Orth, R.J., and K.A. Moore, 1984, "Distribution and abundance of submerged aquatic vegetation in Chesapeake Bay: An historical perspective," *Estuaries* 7:531–540; Kemp et al., 2004, p. 365 (see note 107).
[118] See, for example, National Academy of Sciences, 2006, *Mitigating Shore Erosion along Sheltered Shores*, The National Academies Press. Washington, DC, pp. 46, 57.
[119] Koch, E.W., L.P. Sanford, S.-N. Chen, D.J. Shafer, and J.M. Smith, 2006, Waves in Seagrass Systems: Review and Technical Recommendations. Final Report prepared for the U.S. Army Corps of Engineers, System-Wide Water Resources Research Program and Submerged Aquatic Vegetation Restoration Research Program, ERDC TR-06-15, p. 16.
[120] USFWS, n.d., Nutrient pollution (see note 103).

rise by expanding inland. Submerged vegetation cannot grow and survive, however, where increased water depth or increased turbidity severely restrict the amount of light available for photosynthesis. Short and Neckles 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 percent, reducing seagrass growth in current bed areas by 30 to 40 percent.[121] Such reductions in seagrass could have a significant effect on the many fauna found in seagrass beds. For example, research indicates that the abundance, biomass, and diversity of fishes are higher near seagrass beds than in unvegetated areas.[122]

In areas where seagrass is lost, the primary productivity, the habitat provided to key species, and the shoreline protection benefits will all be affected.[123] The extent of primary productivity impact is unknown; autotrophs like phytoplankton and sediment microalgae are generally not considered capable of providing the extent of primary production contributed by SAV.[124] In Chesapeake Bay, the microbenthic algal community comprises between 3 and 5 percent of the total annual primary production from all sources.[125] Vegetation also increases the dissolved oxygen content of the water; low dissolved oxygen in summer (common in many Atlantic waterways) is a major stressor on biota such as the blue crab, Atlantic sturgeon, and striped bass.[126] Wrack from submerged aquatic vegetation also plays an important role in beach communities, providing cover and food to a variety of amphipods, isopods, and insects, which are in turn fed on by shorebirds such as plovers.[127]

Loss of SAV affects the large number of species that depend on the vegetation beds for protection and food. As noted previously, blue crabs are particularly dependent on seagrass beds, although some types of shoreline structures (e.g., riprap and jetties) can provide similar protective cover to juvenile crabs.[128] By one estimate, a 50 percent reduction in SAV results in a roughly 25 percent reduction in striped bass production.[129] Fish abundance and species richness are also affected by degradation of SAV habitat. A decline in SAV also affects larger predators, including shorebirds and sea turtles. Birds that are primarily herbivorous are directly affected by the loss of SAV. For diving and dabbling ducks, researchers have noted a decrease in SAV in their diets since the 1960s. With the decline of SAV, the diet of geese and swans has shifted to agricultural field wastes. For canvasback ducks, SAV consumption has been replaced by a diet high in invertebrates and crustaceans. Such diet shifts have not been possible for all SAV-reliant species. The decreased SAV in Chesapeake Bay is cited as a major factor in the substantial reduction in wintering waterfowl such as redhead ducks.[130]

3.1.6 TIDAL FLATS

Tidal flats are found in the intertidal zone. They have muddy substrates, typically composed of silt and clay, that support sparse or no vegetation. In brackish area flats, vegetation is rare, consisting of occasional clumps of

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121Short and Neckles, 1999, p. 178 (see note 91).
122Wyda et al., 2002, pp. 86–100 (see note 95).
123Duarte, C.M., 2002, "The future of seagrass meadows," *Environmental Conservation* 29(2):192–206.
124Borum, 1996, in Duarte, 2002, p. 199 (see note 123); reviewed in Buzzelli 1998, p. 659 (see note 92).
125Wendker, S., H.G. Marshall, and K.K. Nesius, 1997, "Benthic primary production within shallow water sites in Chesapeake Bay," pp. 148–151 in *Proceedings of the Second Marine and Estuarine Shallow Water Science and Management Conference, U.S. Environmental Protection Agency, Philadelphia, PA,* EPA 903/R/97009, USEPA, Washington, DC.
126For blue crabs, see Mistiaen, J.A., I.E. Strand, and D. Lipton, 2003, "Effects of environmental stress on blue crab (*Callinectes sapidus*) harvests in Chesapeake Bay tributaries," *Estuaries* 26(2A):316–322. For Atlantic sturgeon, see Niklitschek, E.J., and D.H. Secor, 2005, "Modeling spatial and temporal variation of suitable nursery habitats for Atlantic sturgeon in the Chesapeake Bay," *Estuarine, Coastal, and Shelf Science* 64(2005):135–148. For striped bass, see Coutant, C.C., and D.L. Benson, 1990, "Summer habitat suitability for striped bass in Chesapeake Bay: Reflections on a population decline," *Transactions of the American Fisheries Society* 119:757–778.
127Dugan, J.E., D.M. Hubbard, M.D. McCrary, and M.O. Pierson, 2003, "The response of macrofauna communities and shorebirds to macrophyte wrack subsidies on exposed sandy beaches of southern California," *Estuarine, Coastal and Shelf Science* 58S:25–40.
128Maryland Sea Grant, 2001, p. 10 in *Research Needs for Sustainable Blue Crab Production in Maryland, A Workshop Report,* publication number UM-SG-TS-2001-01, prepared by Maryland Sea Grant College, College Park.
129Kahn, J.R., and W.M. Kemp, 1985, "Economic losses associated with the degradation of an ecosystem: The case of submerged aquatic vegetation in Chesapeake Bay," *Journal of Environmental Economics and Management* 12:246–263.
130Perry and Deller, 1996, p. 273, 276 (see note 100).

saltmarsh cordgrass. Freshwater flats, common in Chesapeake Bay tributaries, can support herbaceous species. Tidal flats are critical foraging areas for numerous birds, including wading birds, migrating shorebirds, and dabbling ducks such as mallards and the American black duck.

Photo 3.5: Estuarine beach and bulkhead along Arthur Kills, New Jersey

Effects of Sea Level Rise on Tidal Flats

In areas with low sediment supplies, marsh will revert to unvegetated flats and eventually to open water.[131] For example, in New York's Jamaica Bay, several hundred acres of low salt marsh have converted to open shoals (see Section 3.4). Except in high-sediment supply areas and in locations where migration is possible, tidal flats will gradually become inundated as sea levels rise.

Effects of Armoring on Tidal Flats

In areas where sediments accumulate in shallow waters and shoreline protection prevents landward migration of salt marshes, flats could become vegetated as low marsh encroaches waterward, accelerating sediment deposition at the waterward edge of the vegetated area and leading to an increase in low marsh at the expense of tidal flats.[132] If sediment inputs are insufficient, tidal flats will convert to subtidal habitats.

Ecological Effects on Tidal Flats

Loss of tidal flats would eliminate a rich invertebrate food source for migrating birds. Shorebirds feed on all trophic levels of beach invertebrate communities, including primary consumers (herbivorous insects, amphipods, and isopods as well as suspension-feeding crabs and bivalves) and the secondary consumers that feed on them (crabs, isopods, polychaetes, and beetles).[133] As tidal flat area declines, increased crowding in remaining areas will lead to exclusion and mortality of many shorebirds.[134] In some cases, reversion of *Spartina* marsh to unvegetated flats could benefit foraging by wading birds and dabbling ducks. As the flats become more deeply inundated, however, they will become unavailable to short-legged shorebirds.[135] Modeling by Galbraith and colleagues predicted that under a 2°C global warming scenario, sea level rise could inundate significant areas of intertidal flats in some regions.[136] Although this may initially lead only to crowding of remaining

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[131]Brinson et al. 1995, p. 650 (see note 23).
[132]Redfield, A.C., 1972, "Development of a New England salt marsh," *Ecological Monographs* 42:201–237.

[133]See, for example, M.D. Bertness, 1999, Chapter 6, "Soft sediment habitats," pp. 249–312 in *The Ecology of Atlantic Shorelines*, Sinauer Associates, Inc., Sunderland, MA.
[134]Galbraith et al., 2002, p. 173 (see note 50).
[135]Erwin et al., 2004, p. 902 (see note 16); and Erwin, R.W., n.d., Atlantic Sea Level Rise, Lagoonal Marsh Loss, and Wildlife Habitat Implications. Accessed at: http://www.pwrc.usgs.gov/reshow/erwin1rs/erwin1rs.htm on March 16, 2006.
[136]Galbraith et al., 2002, p. 178 (see note 50).

tidal flat forage areas, Galbraith and coinvestigators further noted that increased crowding will lead to the exclusion and mortality of shorebirds.[137] Ponds within marshes might become more important foraging sites for these birds as mudflats are inundated by sea level rise.[138]

3.1.7 ESTUARINE BEACHES

Estuarine beaches are unconsolidated sandy shores that are inundated by the tidal cycle. Throughout most of the mid-Atlantic region and its tributaries, these beaches front the base of low bluffs and high cliffs as well as bulkheads and revetments. The beaches are characterized by steep foreshores and broad, flat, low tide terraces (see Photo 3.5).[139] Beaches can also occur in front of marshes, sometimes retreating back over them through storm-driven overwash processes. Plants are typically sparse in beach areas, surviving only above the high tide line with adaptations for the harsh beach environment, such as waxy leaves or strong root systems. In Chesapeake Bay, such plant species include seabeach and marsh orach (*Atriplex cristata*), sea rocket (*Cakile edentula*), Russian thistle (*Salsola kali*), and sea blite.[140]

The most abundant beach organisms are microscopic invertebrates (meiofauna) that live between sand grains, feeding on bacteria and single-celled protozoans. It is estimated that more than 2 billion of these organisms can be found in a single square meter of sand. [141] The meiofauna play a critical role in beach food webs as a link between bacteria and larger consumers.

The most conspicuous invertebrates of beaches are the macroinvertebrates that burrow in sediments or hide under rocks. These include hermit crabs, beach fleas, worms, beach amphipods, bivalves, and snails. Various rare and endangered beetles also live on sandy shores. Diamondback terrapins and horseshoe crabs bury their eggs in beach sands. Piping plover (federally listed as threatened), American oystercatcher, and sandpipers feed on beetles, larvae, marine worms, mollusks, and other insects and crustaceans, as well as on horseshoe crab eggs.[142] In mid-Atlantic bays, particularly Delaware Bay and southern Chesapeake Bay, horseshoe crabs rely on estuarine beaches for spawning during high spring tides.[143] Migrating shorebirds and resident gulls and terns feed on the horseshoe crab eggs. The diamondback terrapin nests in sandy areas above the high tide mark and may hibernate along embankments on muddier shorelines.[144]

Eggs of species that nest on estuarine beaches and invertebrate infauna provide forage for numerous bird species, including migratory shorebirds and species that nest on nearby barrier islands, such as the piping plover (federally listed as threatened). Shorebirds feed on all trophic levels of beach invertebrate communities (see Photo 3.6).[145] The insects, isopods, and amphipods found in wrack deposits on estuarine beaches are also an important source of forage for birds (see Photo 3.7).[146] The abundance of these organisms has been shown to be highest at sites with greater wrack. In addition, the abundance of shorebird species is positively correlated with the abundance of wrack and wrack-associated invertebrates.[147]

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[137]Galbraith et al., 2002, p. 173 (see note 50).
[138]Erwin et al., 2004, p. 902 (see note 16).
[139]Jackson, N.L., K.F. Nordstrom, and D.R. Smith, 2002, “Geomorphic-biotic interactions on beach foreshores in estuaries,” *Journal of Coastal Research Special Issue* 36:414–424.
[140]Lippson and Lippson, 2006, p. 28 (see note 2).
[141]Bertness, 1999, 256–257 (see note 133).
[142]USFWS, 1988, *Endangered Species Information Booklet: Piping Plover,* USFWS, Arlington, VA.
[143]Lippson and Lippson, 2006, p. 32 (see note 2); Dove and Nyman, 1995 (see note 14).
[144]Chesapeake Bay Program, 2006, Diamondback terrapin, available at: http://www.chesapeakebay.net/diamondback_terrapin.htm, accessed June 13, 2006.
[145]Dugan et al., 2003, p. 26 (see note 127).
[146]Jackson et al., 2002 (see note 139).
[147]Dugan et al., 2003, pp. 32–33 (see note 127).

Photo 3.6. Dinnertime along Peconic Estuary Beach, Long Island, New York

Photo 3.7: Beach with beach wrack and marsh in New Jersey

Effects of Sea Level Rise on Estuarine Beaches

As with vegetated tidal wetlands, the fate of estuarine beaches depends on their ability to migrate or on the presence of sufficient sediment to allow accretion. Beaches can migrate through marshes, generally through a process of overwash and dune building, as exhibited by barrier islands.[148,149] The general lack of vegetation on the beaches, however, frequently limits the ability to retain sediment. In front of shoreline protection structures, or where the land behind the existing beach has too little sand to sustain it, beaches that are not nourished will erode and eventually drown as sea level rises. If impediments to migration exist or natural sediment inputs decline, beaches will be lost. Through nourishment efforts, society will preserve many beaches at risk of erosion. But in many areas where homes are built on the shoreline, beach loss will be inevitable.

Effects of Armoring on Estuarine Beaches

Many shoreline protections interfere with the survival of estuarine beaches by both blocking migration and affecting sediment retention. Because of the sediment trapping effects of many shore protections, armoring that traps sand in one area can limit or eliminate longshore transport. This, in turn, diminishes the constant replenishment of sand necessary for beach retention in nearby locations. Areas with bulkheads frequently have artificially

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[148]Jackson et al., 2002, p. 418 (see note 139).
[149]The overwash process is also observed on peninsulas (e.g., the migration of Bethel Beach over marsh area in Mathews County, Virginia). See Section 3.12, Chesapeake Bay's Middle Peninsula.

elevated land areas, or headlands, because not all structures are built in a straight line. In areas with sufficient sediment input relative to sea level rise (e.g., upper tributaries and upper Chesapeake Bay), accretion may keep beaches in place in front of armoring.

In armored areas between headlands, the beach is likely to become steeper and the sediments coarser. Waterward of the bulkheaded headlands, the foreshore habitat will be lost, often even without sea level rise.[150] If the areas between these headlands are not armored, in most cases sediment input will be reduced and inundation will occur with rising sea level.

In many developed areas, estuarine beaches may be maintained with beach nourishment, although the ecological effects of nourishment remain uncertain.[151] Beach nourishment will allow retention in areas with a sediment deficit, but could reduce habitat value through effects on sediment characteristics and beach slope.[152] Some think that benthic organisms on the shallow, low tide terrace of estuarine beaches are less tolerant of burial as a result of beach nourishment than organisms of the subtidal zone of more energetic beaches.[153] The viability of horseshoe crab eggs depends on sediment characteristics that promote drainage and aeration, and therefore some coastal geomorphologists predict that egg survival could be low on beaches that are modified through beach nourishment. [154] On the other hand, Delaware plans to nourish beaches that lie in front of marsh for the purpose of preserving horseshoe crab habitat.[155]

[150]Jackson et al., 2002, p. 420 (see note 139).
[151]Peterson, C.H. and M.J. Bishop, 2005, "Assessing the environmental impacts of beach nourishment," *BioScience* 55:887–896.
[152]Peterson and Bishop, 2005 (see note 151).
[153]Nordstrom, K.F., 2005, "Beach nourishment and coastal habitats: Research needs to improve compatibility," *Restoration Ecology* 13:215–222, p. 217.
[154]Jackson et al., 2002, p. 421 (see note 139).
[155]See, for example, Smith, D., N. Jackson, S. Love, K. Nordstrom, R. Weber, and D. Carter, 2002, *Beach Nourishment on Delaware Shore Beaches to Restore Habitat for Horseshoe Crab Spawning and Shorebird Foraging,* prepared for The Nature Conservancy, Delaware Bayshores Office, Wilmington, DE, accessed on June 19, 2007 at: http://www.dnrec.state.de.us/fw/hcrabs/FINAL%20Beach%20Habitat%20Restoration%20Report.pdf.

Ecological Effects on Estuarine Beaches

Where beaches are lost, the many invertebrates that burrow in the sand and species that spawn on beaches will lose critical habitat. Using high-precision elevation data from nest sites, researchers are beginning to carefully examine the effects that sea level rise will have on oystercatchers and other shore birds.[156] To the extent that estuarine and riverine beaches, particularly on islands, survive better than barrier islands, shorebirds like oystercatchers might be able to migrate to these shores.[157] Loss of beach will also cause local elimination of beach-dependent species such as the rare beetles found in Calvert County, Maryland. Although the northeastern beach tiger beetle is able to migrate in response to changing conditions, suitable beach habitat must be available nearby.[158]

The degree to which horseshoe crab populations will decline as beaches are lost is currently unclear. Early results of ongoing research funded by New Jersey Sea Grant indicate that horseshoe crabs also lay eggs in other intertidal habitats in addition to estuarine beaches, such as sandbars and the sandy banks of tidal creeks.[159] Nonetheless, if these habitats are also inundated, they will provide only temporary refuges for horseshoe crabs.

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, which is a candidate for the federal endangered species list. The red knot feeds almost exclusively on horseshoe crab eggs, and, to continue its migration, the bird nearly doubles its weight by feeding on crab eggs. Researchers from Virginia Tech and the New

[156]Rounds, R. and R.M. Erwin, 2002, "Flooding and sea level rise at waterbird colonies in Virginia," presented at Waterbird Society Meeting, November 2002, accessed on June 19, 2007 at: http://www.vcrlter.virginia.edu/presentations/rounds0211/rounds0211.pdf.
[157]McGowan et al., 2005, p. 150 (see note 81).
[158]USFWS, 1994, Recovery Plan for the Northeastern Beach Tiger Beetle (*Cicindela dorsalis dorsalis*), USFWS, Hadley, MA.
[159]Research by Dr. Mark Botton of Fordham College and Dr. Bob Loveland of Rutgers University, funded by New Jersey Sea Grant; summarized online and accessed on June 19, 2007 at: http://www.njmsc.org/Sea_Grant/Research_News/The_Importance_Of_Marginal_and_Restored_Habitats.htm.

Jersey Division of Fish and Wildlife report that the number of horseshoe crab eggs is the most important factor determining the use of mid-Atlantic back-barrier beaches by red knots, and documented a reduction in the number of red knots throughout the Delaware Bay correlated with a decline in horseshoe crabs (see also Section 3.9 on Maryland and Delaware Coastal Bays.[160]

3.1.8 CLIFFS

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 because of constant erosion. Eroding sediment augments nearby beaches. Cliffs are present on Chesapeake Bay's western shore and tributaries and its northern tributaries (see Photo 3.8), as well as in Hempstead Harbor on Long Island's North Shore.

Erosion is driven by two key processes: freeze/thaw and wave undercutting. Recession rates for cliffs are higher in areas where undercutting is the dominant erosion method; for example, Wilcock and coworkers reported historical erosion rates between 0.3 and 1 ft/yr for freeze/thaw areas of Maryland's Calvert Cliffs and rates between 2 and 3 ft/yr for wave undercut areas.[161] On the Sassafras, near its entrance at the north end of Chesapeake Bay, the cliffs are receding at rates of 0.9 to 1.4 ft/yr.[162] Areas dominated by the freeze/thaw mechanism frequently have beaches at their base (a higher toe elevation) that protect the bottom of the slope from wave energy.[163]

Effect of Sea Level Rise on Cliffs

Sea level rise may increase rates of cliff erosion by decreasing the toe elevation, but ecological impacts of such an increase in erosion rate are uncertain. If erosion rates are too high, sudden losses of the cliff face can endanger species that depend on unvegetated cliffs (e.g., Puritan tiger beetles). The armoring that is in place, or that might be increased in response to accelerated sea level rise, poses more evident threats to the cliff ecology.

[160] Karpanty, S., J. Fraser, J. Berkson, L. Niles, A. Dey, and E. Smith, 2006, "Horseshoe crab eggs determine red knot distribution in Delaware Bay habitats," *Journal of Wildlife Management,* 70:1704–1710.

[161] Wilcock, P.R., D.S. Miller, R.H. Shea, and R.T. Kerhin, 1998, "Frequency of effective wave activity and the recession of coastal bluffs: Calvert Cliffs, Maryland," *Journal of Coastal Research* 14(1):256–268.

[162] Maryland DNR, 2002, *Sassafras Natural Resources Management Area Land Unit Plan,* Maryland DNR Resource Planning Program, accessed on June 19, 2007 at http://www.dnr.state.md.us/resourceplanning/sassafras.pdf.

[163] Toe elevation is the height of the beach before the bluff/cliff begins.

Photo 3.8. Emerald Beach along the Elk River in Maryland

Effects of Armoring on Cliffs

Cliffs and headlands could experience increased erosion rates resulting from disruption in longshore sediment transport as a result of nearby sediment-trapping shoreline protections (e.g., groinfields).[164] Alternatively, if the cliff base is armored, the erosion rates could decrease. Either outcome could eliminate habitat for endangered species that depend on varying rates of erosion. According to the Maryland Department of Natural Resource's wildlife diversity conservation plan, naturally eroding cliffs are "severely threatened by shoreline erosion control practices."[165] Because of the sediment-trapping effects of many types of shore protection, armoring in one area can diminish the constant replenishment of sand necessary for beach retention in nearby locations. Introducing shoreline protections can subject adjacent cliff areas to wave undercutting and higher recession rates. Development and shoreline stabilization structures that interfere with natural erosional processes are cited as threats to bank-nesting birds (e.g., bank swallows and belted kingfishers) as well as two species of tiger beetles (federally listed as threatened) at Maryland's Calvert Cliffs.[166,167] The majority of the identified Puritan tiger beetles live in the Calvert Cliffs, particularly in Calvert Cliffs State Park on Chesapeake Bay's western shore.

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[164]Wilcock et al., 1998, p. 259 (see note 161).
[165]Maryland DNR, 2005, p. 13 (see note 53).

[166]USFWS, 1993, Puritan Tiger Beetle (*Cicindela puritana* G. Horn) Recovery Plan, Hadley, MA; USFWS, 1994 (see note 158).
[167]The Center for Conservation Biology at William & Mary, 1996, "Fieldwork concluded on bank-nesting bird study," in *Cornerstone Magazine*, accessed on June 21, 2006, at https://www.denix.osd.mil/denix/Public/ES-Programs/Conservation/Legacy/Cornerstone/corner.html.

3.2 North Shore, Long Island Sound and Peconic Estuary

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Species and habitats along Long Island Sound are potentially at risk because of sea level rise. This brief literature review considers this risk for the New York portion of Long Island Sound (hereafter the Sound), including the shorelines of Westchester, Bronx, Nassau, and Suffolk counties as well as the Peconic Estuary at the far eastern end of Long Island. These Long Island shorelines contain important habitats for a variety of fish, shellfish, and birds, and a great deal is known about their ecology and habitat needs (see Map 3.1). Based on existing literature and the knowledge of local scientists, this review discusses the coastal species in areas that could be at risk because of further habitat loss resulting from sea level rise and shoreline protection. There are locations in the study area with naturally steep shorelines that will interfere to varying degrees with marine transgression of tidal wetlands in response to rising seas. Although it is possible to make qualitative statements about the possible impacts if sea level rise causes a total loss of habitat, our ability to discern what the impact might be if only a portion of the habitat is lost is more limited.[168]

TIDAL MARSH

In 2003, the Long Island Sound Habitat Restoration Initiative reported that there were 8,425.6 ha (20,820 acres) of tidal wetlands in the Sound, including all tidal wetland types, with 85 percent of the total in Connecticut.[169] Most of the remaining 15 percent of tidal wetlands found in the New York State portion of the Sound are along the shores of Westchester and Bronx counties.[170] In Westchester County, ecologically important tidal wetlands occur in the county-owned Marshlands Conservancy property.[171] The Marshlands Conservancy site is the only mainland breeding area for yellow-crowned night herons in the region.[172]

Tidal wetlands are also uncommon along the north shore of Long Island because of the steep uplands and sea cliffs created by the terminal moraine of glaciers, and therefore wetlands are

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[168]EPA's ambitious goal for these reviews would have had us address the four possible outcomes resulting from different rates of sea level rise (or wetland accretion) and whether shores are protected. In a typical case where area of wetlands is 5 times the area of land that might become new wetlands as sea level rises, the four possible outcomes are:
a. Existing wetlands are lost, shore protection prevents new wetlands forming inland (100% loss).
b. Existing wetlands keep pace, shore protection prevents new wetlands forming inland (no change, in total acreage, but possible loss of plants that inhabit the upper portion of the tide range).
c. Existing wetlands lost, no shore protection allows wetlands to form inland (80% loss).
d. Existing wetlands keep pace, no shore protection allows wetlands to form inland (20% gain).
We focus on the implication of case a, because the implication of a total loss of habitat is understood at least qualitatively. The literature is often insufficient for us to distinguish whether case c is more similar to "no impact" or to the total loss implied by case a, and hence, depending on context, the prose that follows may imply either that such large scale loss is similar to total loss, or that because some wetlands will continue to survive, that the impact is similar to "no impact." In the case of beaches and possibly mudflats, the absence of shore protection generally allows the system to survive. We did not examine cases b or d at all.

[169]Holst, L, R. Rozsa, L. Benoit, S. Jacobsen, and C. Rilling, 2003, Long Island Sound Habitat Restoration Initiative, Technical Support for Habitat Restoration, Section 1: Tidal Wetlands. EPA Long Island Sound Office, Stamford, CT, p. 1-7, Available at: http://www.longislandsoundstudy.net/habitat/index.htm; and Rosza, R., 1995, "Human impacts on tidal wetlands: History and regulations, Chapter 2 in G.D. Dyer and W.A. Neiring, eds., *Tidal Marshes of Long Island Sound, Ecology History and Restoration,* The Connecticut College Arboretum, Bulletin No. 34, December. Available at: http://arboretum.conncoll.edu/publications/34/FRAME.HTM.

[170]Holst et al., 2003, p. 1-1 (see note 169).

[171]New York State (NYS) Department of State, Division of Coastal Resources, 2004, *Significant Coastal Fish and Wildlife Habitats*. Long Island Sound and Long Island, Marshlands Conservancy. Coastal Resources Online. Available at http://nyswaterfronts.com/waterfront_natural_narratives.asp.

[172]USFWS, 1997, *Significant Habitat and Habitat Complexes of the New York Bight Watershed*. USFWS, South New England, New York Bight Coastal Ecosystems Program, Charlestown, RI; The Narrows, Complex #20, pp. 611–619.

largely confined to former drowned "kettle hole" embayments such as Mount Sinai.[173] There are some notable areas of marsh in and around Stony Brook Harbor and West Meadow, bordering the Nissequogue River,[174] and along the Peconic Estuary. Some marshes around the three large bays western Long Island Sound (Little Neck Bay, Manhasset Bay, and Hempstead Harbor) provide feeding and nesting areas for green-backed heron, clapper rail, and American black duck, as well as feeding areas for wading birds.[175]

Marshes will be lost where the shorelines are backed by steep slopes or where shorelines are hardened. There has already been a significant loss of the historical area of vegetated tidal wetlands in Long Island Sound.[176] In fact, local scientists have observed marsh submergence for decades.[177] The full extent and causes of marsh losses are unknown, but some local scientists believe that sea level rise may be an important factor.[178] Authors of the Long Island Sound Habitat Restoration Initiative reported that emergent marsh, especially low marsh, is converting to intertidal flat along the shores of many of the tidal rivers that drain into the Sound, and concluded that "the biophysical changes in these marshes bear a striking resemblance to other eastern seaboard wetlands that scientists attribute to accelerated relative sea level rise."[179]

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) (see Section 3.1). Low marsh also provides foraging areas sheltered from predators for dozens of fish species, including small resident fishes such as mummichog, striped killifish, and sheepshead minnow, and early life stages of estuarine and marine transients, which use the tidal creeks and low marsh for a nursery area (Section 3.1). Many of these transient fish species such as weakfish and winter flounder enter local commercial and recreational fisheries as adults.[180] Diamondback terrapin live in the creeks of the low marsh, where they feed on plants, mollusks, and crustaceans.[181] Marsh invertebrates of the Sound's low marsh zones include rough periwinkles, ribbed mussels, fiddler crabs, striped sea anemone, and the common clamworm.[182]

Some wetlands along Long Island Sound will be allowed to respond naturally to sea level rise, and where migration is possible, preservation of local biodiversity and some regionally rare species is possible. For example, local planners believe that Peconic Estuary shorelines around Shelter Island, Robins Island, the Conscience Point National Wildlife Reserve, the E.A. Morton National Wildlife Reserve, Novack, Sag Harbor, Orient Point and Orient Beach, and Napeague Bay will be allowed to respond naturally to sea level rise. Local planners also expect that coastal lands designated for preservation, conservation, or recreation in northern Suffolk County will remain unprotected.

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173 Ron Rosza, coastal ecologist with the Connecticut Office of the Long Island Sound Program, email entitled Opportunity to comment on U.S. EPA-sponsored papers related to sea level rise and related impacts on habitat and species, to Karen Scott, EPA, 2/20/07 (discussing visual observations).
174 NYS Department of State, Division of Coastal Resources, 2004 (see note 171). Wetland losses will also occur along shorelines with steep slopes, even though they are not hardened—a common characteristic of the north shore of Long Island.
175 USFWS, 1997, The Narrows, Complex #20, p. 613 (see note 172).
176 Holst et al., 2003, p. 1-8 (see note 169).
177 Ron Rosza, written communication to EPA, 2/20/07 (discussing personal observations) (see note 173).
178 Mushacke, F., 2003, "Wetland loss in the Peconic Estuary," abstract of presentation at the Long Island Sound Tidal Wetland Loss Workshop, June 24–25, Stony Brook, NY, *Workshop Proceedings and Recommendations to the Long Island Sound Study*, p. 18. Available at: http://www.longislandsoundstudy.net/habitatrestoration/more.htm. In this abstract, Fred Mushacke, a marine biologist with the New York State Department of Environmental Conservation, who has conducted GIS analyses to determine areas of marsh loss in the Peconic Estuary, stated that "the extent and causes of vegetative losses are currently unknown and can only be surmised. It is, however, a synergy of anthropogenic and natural causes, and may include, but is not limited to, sediment budget disruption, sea level rise, erosion, subsidence, and eutrophication."
179 Holst et al., 2003, p. 1-8 (see note 169).
180 See, for example, NYS Department of State, Division of Coastal Resources, 2004, p. 3 (see note 171).
181 Long Island Sound Foundation, n.d., Plants & Animals of Hammonasset, available at: http://www.lisfoundation.org/coastal_access/hamm_wildlife.html The Long Island Sound Foundation has been collecting and disseminating information on the sound for the public since 1992.
182 Warren, R.S. and P.E. Fell, 1996, "*Phragmites australis* on the lower Connecticut River: Patterns of invasion and spread. As cited on p. 1-2 of Holst et al., 2003 (see note 169).

Some preservation of species may occur where "soft" protection is the preferred protection alternative. For example, local planners believe that shore protection to hold back rising seas is "likely" or "almost certain" along the shorelines of Flanders Bay, where the Flanders Bay Wetlands occur. The New York State Department of State, Division of Coastal Resources has concluded that if protection is considered necessary, alternatives such as vegetation-based approaches should be explored. This agency has asserted that shoreline hardening "may result in loss of productive habitat areas which support the fish and wildlife resources of Flanders Bay Wetlands." Several rare bird species are found in the Flanders Bay Wetlands, including least tern, common tern, piping plover, black skimmer, osprey, and common loon. Waterfowl also feed in and around the wetlands. Midwinter aerial surveys averaged 125 birds per year in the wetlands and 700 birds per year in the adjacent bays over the period 1986–1996. Diamondback terrapin are also found in the marshes and beaches along Flanders Bay.[183]

Sea Level Fen

A sea level fen vegetation community grows along Flanders Bay.[184] This rare type of coastal wetland grows only under the unusual circumstances where there is a natural seep from a nearby slope providing nutrient-poor groundwater to support its unique vegetation, and where there is protection from nutrient-rich tidal flow (see Section 3.1). Because of the need of sea level fen vegetation for nutrient-poor waters, the Flanders Bay sea level fen may not survive inundation by sea level rise.

[183]NYS Department of State, Division of Coastal Resources, 2004, Long Island Sound and Long Island, Flanders Bay Wetlands, pp. 1–4 (see note 171).
[184]NYS Department of State, Division of Coastal Resources, 2004, Flanders Bay Wetlands, p. 1 (see note 171).

Estuarine Beaches

Barrier beaches are less common than tidal wetlands in the Long Island Sound study area, but beaches may be at greater risk because sea level rise will accelerate shoreline erosion. Headland erosion is the dominant type of beach development along the Sound's Long Island shoreline.[185]

Notable undeveloped barrier beaches along the north shore of Long Island include those fronting Hempstead Harbor,[186] the beach-wetland system on Eatons Neck Point,[187] the Port Jefferson Beaches near the Town of Brookhaven,[188] the Nissequogue Inlet Beaches at the mouth of the Nissequogue River in the Town of Smithtown,[189] and Cedar Point Peninsula in the Peconic Estuary.[190]

The sandy barrier-beach system fronting Hempstead Harbor is typical of these beach systems, and shows a characteristic community progression from the foreshore to the bay side, or backshore. The foreshore occurs between the highest and lowest tide zones. The abundant invertebrate fauna characteristic of this area provide forage for sanderling, semipalmated plovers, and other shorebirds that stop over during migrations.[191] Shorebirds feed on all trophic levels of beach invertebrate communities, including primary consumers (herbivorous insects, amphipods, and isopods, as well as suspension-feeding crabs and bivalves) and the secondary consumers that feed on them (crabs, isopods, polychaetes, and beetles).[192] The maritime beach community between the mean

[185]Long Island Sound Habitat Restoration Initiative, 2003, *Technical Support for Habitat Restoration, Section 5: Coastal Barriers, Beaches, and Dunes.* November 2003. EPA Long Island Sound Office, Stamford, CT, p. 5-1. Available at: http://www.longislandsoundstudy.net/habitat/index.htm.
[186]NYS Department of State, Division of Coastal Resources, 2004, Hempstead Harbor (see note 171).
[187]NYS Department of State, Division of Coastal Resources, 2004, Eatons Neck Point (see note 171).
[188]NYS Department of State, Division of Coastal Resources, 2004, Port Jefferson Beaches (see note 171).
[189]NYS Department of State, Division of Coastal Resources, 2004, Nissequogue Inlet Beaches (see note 171).
[190]NYS Department of State, Division of Coastal Resources, 2004, Cedar Point Peninsula (see note 171).
[191]Long Island Sound Habitat Restoration Initiative, 2003, p. 5-2 (see note 185).
[192]See, for example, Bertness, 1999 (see note 133).

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 federally listed threatened northeastern beach tiger beetle, and horseshoe crab. Dunes and the upper limit of the backshore beach is used for nesting by diamondback terrapin.[193] They also nest on dredged sands and have been observed nesting on artificial dikes in the town of Fairfield, Connecticut.[194]

One study involving interviews with local planners found that nearly all of the Long Island shoreline of the Sound is "almost certain" to be protected in response to sea level rise. The study assumed that property owners fund their own shore protection. Moreover, 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." [195]

Tidal Flats

Longshore drift, which usually occurs from east to west along the Sound's Long Island shoreline, carries some of the material that erodes from bluffs and later deposits it to form tidal flats and barrier spits or shoals.[196] Shoals along the Long Island shoreline, particularly around Duck Point, Baiting Hollow, and the Port Jefferson area, provide forage for numerous bird species as well as habitat for shellfish.[197] There is hard clam habitat around the northern bays.[198] One of the largest areas of tidal mudflats on the north shore is near Conscience Bay, Little Bay, and Setauket Harbor west of Port Jefferson. Large beds of hard clams, soft clams, American oysters, and ribbed mussels are found in this area.[199] In western Long Island Sound, low marsh is converting to tidal flats as seas rise.[200] 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.[201] It is known, for example, that shorebird abundance is directly correlated with the abundance of invertebrate forage.[202]

NEARSHORE SHALLOW WATERS AND SUBMERGED AQUATIC VEGETATION (SAV)

Eelgrass distribution along the Sound is limited to the Peconic Estuary.[203] The Marine Program of Cornell Cooperative Extension of Suffolk County is monitoring sites in Bullhead Bay, Gardiners Bay, Northwest Harbor, Orient Harbor, Southold Bay, and Three Mile Harbor (see Map 3.1).[204] The U.S. Fish and Wildlife Service reports that eelgrass beds of statewide significance are in Orient Bay[205] and Cedar

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[193]Long Island Sound Habitat Restoration Initiative, 2003, pp. 5-3, 5-4 (see note 185).
[194]Ron Rosza, email to EPA 2/20/07 (discussing visual observations) (see note 173).
[195]Long Island Sound Habitat Restoration Initiative, 2003, p. 5-7 (see note 185).
[196]Long Island Sound Habitat Restoration Initiative, 2003, pp. 5-1, 5-2 (see note 185).
[197]Important Ecological Areas in and Around Long Island Sound, Map Panel 9 of 10 – Riverhead Area and Map Panel 8 of 10 – Port Jefferson Area, n.d., produced by the USFWS Service, Coastal Ecosystems Program, Charlestown, RI, for Long Island Stewardship Initiative. Available at: www.rpa.org/maps/lismaps.html.
[198]USFWS, 1997 (see note 172)

[199]NYS Department of State, Division of Coastal Resources, 2004, Conscience Bay, Little Bay and Setauket Harbor, p. 1 (see note 171).
[200]Ron Rosza, email to EPA, 2/20/07 (discussing visual observations) (see note 173).
[201]Erwin, R.M., D.R. Cahoon, D. J. Prosser, G.M. Sanders, and P. Hensel, 2006, "Surface elevation dynamics in vegetated *Spartina* marshes versus unvegetated tidal ponds along the mid-Atlantic coast, USA, with implications to waterbirds," *Estuaries and Coasts* 29:96–106, p. 103.
[202]See, for example, Evans, P.R., and P.J. Dugan, 1984, "Coastal birds: Numbers in relation to food resources," in P.R. Evans, J.D. Goss-Custard, and W.G. Hale (eds.), *Coastal Waders and Wildfowl in Winter*, Cambridge University Press, Cambridge, U.K.
[203]Eelgrass does not occur along northern Long Island Sound because of nutrient enrichment.
[204]Schott, S. 2003. Eelgrass Monitoring: Historic Distribution and Current Trends. Presentation at the Long Island Sound Tidal Wetland Loss Workshop, June 24–25, 2003, Stony Brook, New York, Workshop Proceedings and Recommendations to the Long Island Sound Study. Available at: http://www.longislandsoundstudy.net/habitatrestoration/more.htm; Tiner, R., H. Bergquist, T. Halavik, and A. MacLachlan. 2003. Eelgrass Survey for Eastern Long Island Sound, Connecticut and New York. U.S. Fish and Wildlife Service, National Wetlands Inventory Program, Northeast Region, Hadley, MA. National Wetlands Inventory report.
[205]NYS Department of State, Division of Coastal Resources, 2004, Orient Bay, p. 1 (see note 171).

Point/Hedges Bank Shallows.[206] A recent survey found 15.7 acres of eelgrass on the north shore at Mulford Point, and 194 acres on Fisher's Island.[207]

The estuary's eelgrass beds provide food, shelter, and nursery habitats to a diversity of species, including worms, shrimp, scallops and other bivalves, crabs, and fish.[208] 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. Atlantic silverside is an important prey species that spawns here; silverside eggs provide an important food source for seabirds, waterfowl, and blue crab, and adults are prey for bluefish, summer flounder, rainbow smelt, white perch Atlantic bonito, and striped bass. The Cedar Point/Hedges Bank Shallows eelgrass beds are known for supporting a bay scallop fishery of statewide importance.[209]

The consequences of sea level rise for SAV are unknown. However, Short and Neckles (1999) predicted that a 50 cm (19.7 in.) increase in water depth as a result of sea level rise, which could occur in this century, could reduce the light available for seagrass photosynthesis by 50 percent, which would reduce eelgrass growth by 30–40 percent.[210] In turn, this would result in reductions in the productivity and functional values of seagrass beds. This implies that reductions in the growth and survival of eelgrass beds around the Peconic Estuary could harm local populations of scallops, which support a valuable fishery, as well as horseshoe crabs and other species that are prey for many species of commercial, recreational, and ecological value.

[206]NYS Department of State, Division of Coastal Resources, 2004, Cedar Point/Hedges Bank Shallows, p. 1 (see note 171).
[207]Tiner et al., 2003 (see note 204); see also http://counties.cce.cornell.edu/suffolk/habitat_restoration/projectpage/StT/eeprojectsStT.htm.
[208]Peconic Estuary Program, 2001, Peconic Estuary Comprehensive Conservation and Management Plan, sponsored by the USEPA under Sec. 320 of the Clean Water Act, Suffolk County Department of Health Services, Program Office, p. 4-4.
[209]NYS Department of State, Division of Coastal Resources, 2004, Cedar Point/Hedges Bank Shallows, p. 2 (see note 171).
[210]Short, and Neckles, 1999, p. 175 (see note 91).

The movement of eelgrass beds shoreward as seas rise could be impeded by steep shores or erosion and water turbidity in front of shoreline protection structures. Local planners believe that shorelines around Shelter Island, Robins Island, the Conscience Point National Wildlife Reserve, the E.A. Morton National Wildlife Reserve, Novack, Sag Harbor, Orient Point and Orient Beach, and Napeague Bay will be allowed to respond naturally to sea level rise. Other shorelines of the Peconic Estuary are considered "likely" or "almost certain" to be protected, and if these shorelines are hardened, SAV will be unable to migrate in response to sea level rise.

MARSH AND BAY ISLANDS

Several offshore islands in western Long Island Sound are significant for their colonial wading bird rookeries. The most important are Huckleberry Island, Great Captain Island, North Brother Island, South Brother Island, and Pelican Island. These islands are rocky and mostly covered by deciduous forest; their rocky shorelines provide habitat for species such as shellfish, sea stars, and barnacles. North and South Brother islands have the largest black crowned night heron colony in New York State, along with snowy egret, great egret, cattle egret, and glossy ibis.[211] The islands' bird colonies are of regional significance, and loss of island area with sea level rise could have far-reaching consequences.

[211]USFWS, 1997, pp. 612–614 (see note 172).

The Long Island Sound Study considers Plum Island, Little Gull Island, and Great Gull Island off Orient Point "exemplary" colonial waterbird habitat, with sites "of national—if not international—significance."[212] The islands are relatively small and covered with grassy and herbaceous vegetation. According to the North Fork Audubon Society, Great Gull Island hosted 1,500 pairs of the endangered roseate tern in 1996 and 7,750 pairs of common tern.[213] The Long Island Sound Study reports that this population is the second largest breeding population of the roseate tern in North America.[214]

Gardiners Island,[215] Robins Island,[216] and Cow Neck[217] in Little Peconic Bay are in private ownership, and therefore staff of the Suffolk County Department of Planning believe that the shorelines of these properties will be left in a natural state. These islands provide habitats for many rare species such as roseate tern, common tern, least tern, northern harrier, red-tailed hawk, eastern mud turtle, and diamondback terrapin. Even if some protection of the islands' shorelines does occur, it seems likely that it will involve vegetation-based approaches rather than shoreline hardening to help preserve these valuable habitats.[218]

[212]Long Island Sound Study, LIS Stewardship Initiative**,** a cooperative effort involving researchers, regulators, user groups and other concerned organizations and individuals. Accessed December 4, 2007 at: http://www.longislandsoundstudy.net/stewardship/stewardship_sites.htm.

[213]Fact sheet by North Fork Audubon Society entitled *Great Gull Island IBA*. Accessed December 4, 2007 at: http://www.northforkaudubon.org/Gui/Content.aspx?Page=IBAGreatGull.

[214]Long Island Sound Study (see note 212).

[215]NYS Department of State, Division of Coastal Resources, 2004, Gardiners Island (see note 171).

[216]NYS Department of State, Division of Coastal Resources, 2004, Robins Island (see note 171).

[217]NYS Department of State, Division of Coastal Resources, 2004, Cow Neck (see note 171).

[218]For example, see NYS Department of State, Division of Coastal Resources, 2004, Robins Island, p. 5 (see note 171).

Map 3.1. Locations and Types of Habitat Discussed in this Report: Long Island

3.3 Long Island's South Shore Barrier Island/ Lagoon System

Author: **Elizabeth M. Strange, Stratus Consulting Inc.**

Species and habitats along the south shore of Long Island are potentially at risk because of sea level rise. The large back-barrier bays of the south shore include, from west to east, Hempstead Bay, South Oyster Bay, Great South Bay, Moriches Bay, and Shinnecock Bay.[219] These bays contain regionally significant habitats for fish, shellfish, and birds, and a great deal is known about their ecology and habitat needs.

Based on existing literature and the knowledge of local scientists, this brief literature review discusses the coastal species in the region that could be at risk because of further habitat loss resulting from sea level rise and shoreline protection (see Map 3.1). Although it is possible to make qualitative statements about the possible impacts if sea level rise causes a total loss of habitat, our ability to discern what the impact might be if only a portion of the habitat is lost is more limited. A total loss of habitat is possible if shores are protected with hard structures and the wetlands are unable to keep pace with sea level rise.

Back-Barrier Salt Marshes

There are extensive salt marshes to the west of Great South Bay in southern Nassau County.[220] These marshes are particularly notable because much of the historically large area of marsh on the mainland shoreline of southern Nassau County has been lost to development and shoreline armoring, including the mainland marshes of South Oyster Bay[221] and the Hempstead Bay–South Oyster Bay habitat complex.[222]

Based on existing studies, a panel of accretion experts, convened by EPA for this report, expect that the back-barrier marshes adjacent to Jones Inlet are keeping pace with the current rate of sea level rise and may continue to keep pace if the rate increases by 2 mm/yr. Under this scenario, wider marshes may survive this modest increase in the rate of sea level rise, but fringing marshes are likely to be lost. These scientists also indicated that if the rate of sea level rise increases by 7 mm/yr, all of the marshes adjacent to Jones Inlet will be lost. To the east of Jones Inlet, the extensive back-barrier and fringing salt marshes surrounding Great South Bay, Moriches Bay, Shinnecock Bay, and Southampton are keeping pace with current rates of sea level rise, but the accretion panel predicted that their ability to keep pace will be marginal if the rate of sea level rise increases by 2 mm/yr, and marshes will be lost if rates increase by 7 mm/yr (see Reed et al., Section 2.1).

Opportunities for marsh migration along Long Island's south shore will be limited. Much of the mainland shoreline in southern Nassau County is bulkheaded, and the rural areas that remain in eastern Suffolk County are likely to be developed in the future. The state requires a 75-foot buffer around tidal wetlands to make marsh migration possible, but outside of this buffer

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[219]One other back-barrier bay, Jamaica Bay, is discussed in Section 3.4, New York City, because it is most often considered as part of management programs in that area (e.g., the New York/New Jersey Harbor Estuary Program).

[220]USFWS, 1997, Great South Bay Habitat Complex #14, pp. 447–467 (see note 172).

[221]NYS Department of State and USFWS, Southern New England–New York Bight Coastal Ecosystems Program, 1998, *Shorebirds*, South Shore Estuary Reserve, Technical Report Series. Available at: http://www.nyswaterfronts.com/Final_Draft_HTML/Tech_Report_HTM/PDFs/C8A_Index_pdf.htm.

[222]USFWS, 1997, Hempstead Bay–South Oyster Bay, Habitat Complex #15, p. 483–494 (see note 172).

development and shoreline protection are permitted. Moreover, where wide areas of marsh do not keep pace, there will be a net loss even if marshes can migrate.

Increases in tidal creeks and channels with a modest increase in sea level rise (2 mm/yr) could benefit marsh fishes, including many commercially and recreationally important marine and estuarine transient species that move into the marshes for spawning and nursery habitat. However, where marshes are lost as the rate of sea level rise increases to 7 mm/yr, local populations may eventually move elsewhere in search of suitable nursery and foraging areas. An overall loss of nursery habitat and forage could reduce the productivity of the area's highly valued fishery resources.

The recovery of a number of at-risk bird species could be impeded if additional marsh area is lost as a result of sea level rise. 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.[223] These marshes are also the only area in New York State where black rails are currently found on a regular basis and the only documented breeding location for sora rails on Long Island.[224]

The northern diamondback terrapin feeds and grows along marsh edges and the nearshore bays of the south shore. Sites on the south shore where terrapins reportedly are found include Captree State Park, east of the Robert Moses State Park on the Fire Island National Seashore, the marshes and ditches of Tobay Sanctuary near Guggenheim Park, and the western section of the Ocean Parkway, where there are signs announcing "Turtle Crossings" to protect terrapins from automobile traffic.[225] A local terrapin expert believes that additional marsh loss could lead to a "very serious reduction" in their already low abundance.[226]

Back-Barrier Beaches

As sea levels rise, the back-barrier beaches will erode in front of shoreline protection structures, and will be lost without continual beach nourishment. Eggs of species that nest on estuarine beaches and abundant invertebrate fauna provide forage for numerous bird species, including migratory shorebirds and species that nest on nearby barrier islands, such as the federally threatened piping plover. Shorebirds feed on all trophic levels of beach invertebrate communities, including herbivorous insects, amphipods, isopods, crabs, and bivalves.[227]

The back-barrier beaches of the south shore provide nesting sites for the northern diamondback terrapin,[228] the endangered roseate tern,[229] and horseshoe crabs.[230] Cedar Beach in Great South Bay is considered important for the recovery of roseate tern.[231] Shorebirds feed preferentially on horseshoe crab eggs during their spring migrations,[232] and local biologists believe that the large numbers of shorebirds west of Shinnecock Inlet may be due in part to horseshoe crab spawning in the area.[233] Loss of this food resource could have a significant effect on migrating shorebirds such as red knot, which feed almost exclusively on horseshoe crab eggs during their spring migration, when they must

[223]USFWS, 1997, p. 418 in Shinnecock Bay Habitat Complex #12 (see note 172).
[224]NYS Department of State, Division of Coastal Resources, 2004 (see note 171).
[225]NYS Department of State and USFWS, Southern New England-New York Bight Coastal Ecosystems Program, 1998 (see note 221).

[226]Dr. Russell Burke, Department of Biology, Hofstra University, Hempstead, NY. August 1, 2006. "Diamondback terrapin and sea level rise." Email to E. Strange, Stratus Consulting, expressing his opinion about the implications of marsh loss in southern Long Island for terrapins. (Russell Burke has operated an annual diamondback terrapin conservation project at the Jamaica Bay Wildlife Refuge in the Gateway National Recreational Area since 1998.)
[227]Dugan et al., 2003 (see note 127).
[228]NYS Department of State, Division of Coastal Resources, 2004, Great South Bay-West, p. 3 (see note 171).
[229]USFWS, 1997, p. 454 in Great South Bay, Complex #14 (see note 172).
[230]NYS Department of State and USFWS, Southern New England–New York Bight Coastal Ecosystems Program, 1998 (see note 221).
[231]USFWS, 1997, Great South Bay. Complex #14 (see note 172).
[232]USFWS, 2005, Red knot, *Calidris canutus rufa*. Fact sheet available at: http://www.fws.gov/northeast/redknot/facts.pdf.
[233]NYS Department of State and USFWS, Southern New England-New York Bight Coastal Ecosystems Program. 1998 (see note 221).

double in weight to support long-distance migrations.[234] A reduction in the area of back-barrier beach habitat would also negatively impact nesting by diamondback terrapins. Although exact numbers are unknown, a diamondback terrapin expert who has conducted field studies in the area estimates that currently only a few hundred female diamondback terrapins still nest on the back-barrier beaches of Long Island's south shore.[235]

Tidal Flats

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,[236] in the Hempstead Bay–South Oyster Bay complex,[237] and around the Moriches and Shinnecock inlets.[238] These flats are important foraging areas for birds and provide habitat for several edible shellfish species, including soft clam, northern quahog (hard clam), bay scallop, and blue mussel. In Shinnecock Bay, the Shinnecock Reservation has developed a subsistence aquaculture program that includes northern quahog and American oyster.[239]

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.[240] The John F. Kennedy Bird Sanctuary is a particularly important feeding area for birds in South Oyster Bay. In summer, the state threatened least tern and a variety of herons and egrets forage here, along with the federally endangered roseate tern. The sanctuary also provides overwintering habitat for abundant waterfowl, including American black duck, blue-winged, and green-winged teal.[241] Shinnecock Bay supports populations of wintering waterfowl of statewide significance.[242]

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 could have insufficient foraging areas to support 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." These scientists note that local populations of black-bellied plover, whimbrel, red knot, sanderling, semipalmated sandpiper, least sandpiper, and short-billed dowitcher are already showing declines.[243]

Nearshore Shallow Waters and Submerged Aquatic Vegetation (SAV)

Seagrass beds occur along much of the southern shoreline of Long Island.[244] The consequences of sea level rise for SAV are unknown. However, Short and Neckles predicted that a 50 cm (19.7 in.) increase in water depth as a result of sea level rise, which could occur during this century, could reduce the light available for seagrass photosynthesis by 50 percent, resulting in a 30-40 percent reduction in eelgrass growth. These researchers suggested that this will, in turn, result in reduced productivity and functional values of seagrass beds.[245] The importance of eelgrass beds for the secondary production of the south shore is indicated by a study of the Great

[234]USFWS, 2005, Red knot. Fact sheet (see note 232).
[235]Dr. Russell Burke, email to E. Strange, Stratus Consulting (see note 226).
[236]USFWS, 1997, p. 449 in Great South Bay Habitat Complex #14 (see note 172).
[237]USFWS, 1997, p. 484 in Hempstead–South Oyster Bay, Habitat Complex #15 (see note 172).
[238]NYS Department of State and USFWS, Southern New England–New York Bight Coastal Ecosystems Program, 1998, p. 4 (see note 221).
[239]USFWS, 1997, Shinnecock Bay Habitat Complex #12 (see note 172).
[240]Erwin, M.R., 1996, "Dependence of waterbirds and shorebirds on shallow water habitats in the Mid-Atlantic coastal region: An ecological profile and management recommendations," *Estuaries* 19:213–219, p. 213.
[241]USFWS, 1997, p. 487 in Hempstead–South Oyster Bay, Habitat Complex #15 (see note 172).
[242]NYS Department of State, Division of Coastal Resources, 2004, Shinnecock Bay, p. 2 (see note 171).
[243]NYS Department of State and USFWS, Southern New England-New York Bight Coastal Ecosystems Program, 1998, p. 1 (see note 221).
[244]NOAA, Benthic Habitat Mapping. SAV map accessed December 4, 2007 at: http://www.csc.noaa.gov/benthic/data/northeast/longisl.htm.
[245]Short and Neckles, 1999, p. 178 (see note 91).

South Bay by Briggs and O'Connor (1971), who found that 23 of 40 recorded fish species clearly preferred naturally vegetated bottom to unvegetated areas.[246]

Marsh and Bay Islands

Increased flooding and erosion of marsh and dredge spoil islands could reduce habitat for bird species that forage and nest on these islands, particularly gulls and terns. Erosion on Warner Island is reducing nesting habitat for roseate tern and increasing flooding risk during nesting.[247] 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. Hempstead Bay is the primary nesting area in Long Island for yellow-crowned night-herons. Waterfowl such as brant and American black duck feed and rest in the shallow waters around the islands and tidal flats of the complex. An average of 25,000 waterfowl have been counted on midwinter aerial surveys.[248] Lanes Island and Warner Island in Shinnecock Bay support colonies of the state-listed common tern and the federally endangered roseate tern.[249] Carter's Island has supported nesting by the state endangered least tern.[250] Local planners have indicated that eroding marsh islands such as those in Great South Bay may need to be artificially protected to maintain the vegetated wetlands.

[246]Briggs, P.T. and J.S. O'Connor, 1971, "Comparison of shore-zone fishes over naturally vegetated and sand-filled bottoms in Great South Bay," *New York Fish and Game Journal* 18(1):15–41; cited in NYS Department of State and USFWS, Southern New England–New York Bight Coastal Ecosystems Program, 1998, *Estuarine Fish,* p. 8 (see note 221).
[247]NYS Department of State and USFWS, Southern New England–New York Bight Coastal Ecosystems Program, 1998, *Coastal Colonial Waterbirds*, p. 6 (see note 221).

[248]USFWS, 1997, p. 486 in Hempstead Bay-South Oyster Bay, Habitat Complex #15 (see note 172).
[249]USFWS, 1997, p. 418 in Shinnecock Bay, Habitat Complex #12 (see note 172).
[250]USFWS, 1997, p. 432 in Moriches Bay, Habitat Complex #13 (see note 172).

3.4 New York City, the Lower Hudson River, and Jamaica Bay

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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 region is one of the most heavily urbanized areas along the U.S. Atlantic Coast, there are nonetheless regionally significant habitats for fish, shellfish, and birds in the area, and a great deal is known about the ecology and habitat needs of these species.

Based on existing literature and the knowledge of local scientists, this brief literature review discusses those species that could be at risk because of further habitat loss resulting from sea level rise and shoreline protection (see Map 3.2). 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.

Most shorelines in the New York metropolitan area are heavily modified. Because the remaining coastal land is at a premium, planners indicate that most of the shoreline is almost certain to be protected. The remaining undeveloped land along the shore continues to be developed and armored.[251] Where protection occurs, New York City's Waterfront Revitalization Program (WRP) requires the use of nonstructural alternatives such as beach nourishment, dune construction, and vegetation wherever possible. Planners expect that the only sizeable areas in the New York City metropolitan area that are unlikely to be protected are portions of the three Special Natural Waterfront Areas (SNWAs) designated by the city: Northwest Staten Island/Harbor Heron SNWA; East River–Long Island Sound SNWA; and Jamaica Bay SNWA.

TIDAL WETLANDS

Staten Island. Hoffman Island and Swinburne Island are National Park Service properties lying off the southeast shore of Staten Island; the former has important nest habitat for herons, and the latter is heavily nested by cormorants.[252] The Northwest Staten Island/Harbor Herons SNWA is an important nesting and foraging area for herons, ibises, egrets, gulls, and waterfowl.[253] The so-called Harbor Herons Complex includes three island heronries of regional significance, including Shooters Island, Pralls Island, and Isle of Meadows (see subsequent section on islands). Several tidal emergent, salt, brackish, and fresh water marshes provide foraging areas for the birds of the island heronries, including Arlington

[251] George Frame, National Park Service, in email entitled Comments on NYHarbor&RaritanBay papers EPA feb07, to Karen Scott, EPA, 2/20/07, suggests that "many urban planners are not preserving undeveloped lands along the shores of the estuary; even today they are building and hardening in many areas."

[252] George Frame, 2/20/07 email (see note 251).

[253] USFWS, 1997, p. 578 in Arthur Kill Complex, Complex #18 (see note 172).

Marsh, Sawmill Creek Marsh, Gulfport Marsh, Merrill's Marsh, Old Place Creek, Neck Creek Marsh, and Fresh Kills.[254] With the exception of Fresh Kills, shoreline protection is considered almost certain in these areas. Loss of these marshes could have a significant negative impact on the island heronries because of a lack of alternative foraging sites nearby.

The Fresh Kills wetland system is one of the largest tidal wetland systems in the region, covering an estimated 405 ha (1,000 acres).[255] Local planners expect that these wetlands will probably be allowed to respond naturally to sea level rise, but migration may not be possible because of the relatively steep slopes that have formed near the shore as a result of landfilling activities.

Manhattan. Most of the shoreline of Lower Manhattan and the Battery has been bulkheaded and filled. An exception is the natural shoreline and wetlands at the mouth of the Harlem River at New York City's Inwood Hill Park.[256] The park contains low salt marsh and a broad mudflat that runs from the marsh to the channel of the Harlem River Ship Canal. Great blue herons are found along the flat in winter and snowy and great egrets are common from spring through fall.[257]

The Lower Hudson River. Although the tidal Hudson River extends upstream to the dam at Troy, New York State's tidal wetland regulations apply to the Hudson River shoreline only up to the Tappan Zee Bridge. This is the estuarine portion of the tidal river. Along this stretch of the river there is relatively little marsh, with the exception of brackish marshes at the mouth of the Croton River, in Piermont Marsh, and in a network of marshes behind Grassy Point near Haverstraw Bay.[258]

Piermont Marsh is a 411.6 ha (1,017 acre) brackish wetland on the western shore of the lower Hudson River just below the Tappan Zee Bridge, in the town of Orangetown, in Rockland County.[259] The New York State Department of State has designated the marsh a Significant Coastal Fish and Wildlife Habitat, and it has been designated part of the Hudson River National Estuarine Research Reserve by the National Oceanic and Atmospheric Administration and the New York State Department of Environmental Conservation (NYDEC).[260]

Piermont Marsh is dominated by common reed and narrow-leaved cattail, along with some salt marsh species that include smooth cordgrass, salt-meadow cordgrass, and spike grass, making it the location of the northernmost occurrence of salt marsh species on the Hudson. Breeding birds known to use the marsh for nesting include relatively rare species such as Virginia rail, swamp sparrow, black duck, least bittern, and sora rail. A small number of osprey sometimes gather in the marsh, particularly during spring migration. Anadromous and freshwater fish use the marsh's tidal creeks as a spawning and nursery area. Killfish, mummichog, fiddler crab, and blue crab use shallow marsh areas. Diamondback terrapin, a federal species of concern, reportedly nest in upland areas along the marsh.[261]

Jamaica Bay, located between the boroughs of Brooklyn and Queens, is the largest area of protected wetlands in a major metropolitan area along the U.S. Atlantic Coast. The bay includes

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[254] USFWS, 1997, p. 579 in Arthur Kill Complex, Complex #18 (see note 172).
[255] USFWS, 1997, p. 580 in Arthur Kill Complex, Complex #18 (see note 172).
[256] USFWS, 1997, p. 630 in Lower Hudson River Estuary, Complex #21 (see note 172).
[257] Fact sheet by New York City Department Of Parks and Recreation, Inwood Hill Park—Salt Marshes in New York City Parks. Accessed December 4, 2007 at: http://www.nycgovparks.org/sub_your_park/historical_signs/hs_historical_sign.php?id=12864.
[258] USFWS, 1997, p. 631 in Lower Hudson River Estuary, Complex #21 (see note 172).
[259] Fact sheet on Piermont Marsh Component of the Hudson River Reserve by the Hudson River Reserve Program, National Estuarine Research Reserve System. Accessed December 4, 2007 at:http://nerrs.noaa.gov/HudsonRiver/PiermontMarsh.html.
[260] USFWS, 1997, pp. 629, 633 in Lower Hudson River Estuary, Complex #21 (see note 172).
[261] USFWS, 1997, p. 633 in Lower Hudson River Estuary, Complex #21 (see note 172).

the Jamaica Bay Wildlife Refuge,[262] which has been protected since 1972 as part of the Jamaica Bay Unit of the Gateway National Recreation Area, administered by the National Park Service. The refuge includes numerous salt marsh islands that are sheltered from the Atlantic Ocean by the Rockaway Peninsula.

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 region. [263] The bay provides overwintering habitat for brant, mallards, American black duck, canvasback duck, and other waterfowl, and intertidal mudflats for foraging migrants such as black skimmer, plovers, and knots.[264] 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. These areas combined have been designated as a Significant Coastal Fish and Wildlife Habitat by the New York State Department of State and as a Critical Environmental Area by the NYDEC.[265]

Spring Creek Park[266] is one of only two remaining areas of salt marsh in the northern tributaries of Jamaica Bay. Yellow-crowned night heron, little blue heron, and willet are found in these marshes.[267] The nearby Four Sparrow Marsh is the other remaining salt marsh in this part of the bay. It is a particularly noteworthy as an undisturbed nesting habitat for four native species of sparrows that are in decline, the sharp-tailed, seaside, swamp, and song sparrows, and as a stopover site for some 326 species of migrating birds. Several species of ducks, gulls, and wading birds also nest in Four Sparrow Marsh and feed on marsh mollusks and crustaceans.[268]

Because of its importance as an area of significant biodiversity and its uniqueness as a wildlife sanctuary in a highly developed urban setting, planners expect that Jamaica Bay's wetlands will be allowed to respond naturally to sea level rise. However, wetlands in some parts of the bay are currently showing substantial losses. Researchers studying the salt marsh islands near the John F. Kennedy International Airport (including Yellow Bar Hassock, Black Wall Marsh, Big Egg Marsh, East High Meadow Marsh, Elders Point Marsh, and Jo Co Marsh) estimated that marsh loss in the area averaged 12 ha (29.7 acres) per year from 1974 to 1999, even though the area is a national park. [269] This represents an increase in marsh loss of 8 ha (19.8 acres) per year over preceding decades when the area was not yet part of the Gateway National Recreation Area. The estimated rate of loss has been increasing, averaging 18 ha (44.5 acres) per year over the period 1994 to 1999.[270] The reasons for this accelerating trend in marsh loss aren't completely clear, though sea level rise has been implicated as one possible cause.[271,272] However, the Jamaica Bay researchers noted that the significant marsh loss that is already occurring "implies that accretion rates in Jamaica Bay may

[262]Jamaica Bay Wildlife Refuge is managed by the National Park Service, as part of the Jamaica Bay Unit of the Gateway National Recreation Area. The refuge was originally created by the New York City Parks department in 1951. See "Brochure: The Jamaica Bay Wildlife Refuge", National Park Service, accessed November 27, 2006 at: http://www.nps.gov/archive/gate/jbu/jbu_nature.htm. Many people mistakenly call the refuge "Jamaica Bay *National* Wildlife Refuge," but national wildlife refuges are managed by the US Fish and Wildlife Service, not the National Park Service.

[263]USFWS, 1997, p. 532 in Jamaica Bay and Breezy Point, Complex #16 (see note 172).

[264]Hartig, E.K., V. Gornitz, A. Kolker, F. Mushacke, and D. Fallon, 2002, Anthropogenic and climate-change impacts on salt marshes of Jamaica Bay, New York City, *Wetlands* 22:71–89. p. 74, citing Wells (1998).

[265]USFWS, 1997, p. 532 in Jamaica Bay and Breezy Point, Complex #16 (see note 172).

[266]See fact sheet on Spring Creek Park by the New York City Department of Parks and Recreation at http://nycgovparks.org/sub_your_park/historical_signs/hs_historical_sign.php?id=11227.

[267]USFWS, 1997, p. 532 in Jamaica Bay and Breezy Point Complex #16 (see note 172).

[268]See fact sheet on the Four Sparrow Marsh Preserve by the New York City Department of Parks and Recreation, available at: http://www.nycgovparks.org/sub_about/parks_divisions/nrg/forever_wild/site.php?FWID=21.

[269]Hartig, et al., 2002 (see note 264).

[270]Hartig et al., 2002, p. 71 (see note 264).

[271]Hartig et al., 2002, p. 75 (see note 264).

[272]George Frame, 2/20/07 email (see note 251), suggests that "the catastrophic loss of salt marshes in Jamaica Bay could be due mainly to input of nutrients and contaminants from wastewater treatment plants. Also, past dredging and subaqueous borrow pits may act as a sediment sink, starving salt marshes. Sea level rise might be less important."

be insufficient, even at present rates of sea level rise, to compensate for losses due to erosion and other factors."[273]

There are significant ecological implications of marsh loss in this area. Annual marsh primary production ranges from 700 to 1,500 g/m^2 in Jamaica Bay marshes.[274] This primary production is essential for the larger estuarine food web, including the production of commercially and recreationally valuable fish species that use marshes as nursery areas.[275] Kneib (2003) developed models of marsh nekton production resulting from marsh primary production in Georgia marshes and estimated that nekton production ranges from 15 to 42 kg/ha/yr, a third of which represents the production of commercial and recreational species that use the marshes as nursery areas.[276] Thus, loss of these wetlands, even if the current rate of 18 ha/yr does not increase as sea level rise increases, would have an important impact, not just on marsh primary production but also on the production of fish and shellfish within both the marsh and the surrounding estuary. In fact, state and federal governments with holdings in the area indicate that some form of protection may be necessary to protect the significant ecological value of the bay, including applying sediment to raise the marsh surface.

Estuarine Beaches

Among the relatively few areas of beach remaining in the New York City Metropolitan Area are the beaches of the Rockaways, Coney Island, and the South Shore of Staten Island. Beach nourishment is planned or under way for all of these areas.

Jamaica Bay has been designated and mapped as a protected beach unit pursuant to the federal Coastal Barrier Resources Act.[277] Much of the bay's shoreline has been hardened with seawalls and bulkheads, so estuarine sandy beach habitat is now uncommon.[278] Remaining estuarine beaches occur off Belt Parkway (e.g., Plumb Beach) and on the bay islands.[279]

Several islands in Jamaica Bay contain mountains of dredged sand (on top of salt marshes), so they now have sandy beaches. Sandy beach also exists from Breezy Point tip to Fort Tilden (at Flatbush Avenue). Floyd Bennett Field is entirely on top of former saltmarsh and estuarine beach; this artificial island now has sandy beach along more than half of its shoreline, although portions have a bulkhead farther inland.[280]

Mud snails are common throughout this habitat, up to the high tide mark. The snails graze on sea lettuce and old horseshoe crab shells. Beach wrack, consisting primarily of straw from smooth cordgrass and common reed, with small proportions of sea lettuce, contains insects, isopods, and amphipods that also provide forage for shorebirds.[281] The abundance of shorebird species is positively correlated with the abundance of beach wrack and associated invertebrates.[282]

Horseshoe crabs lay their eggs on the small pockets of beach in the bay, many of which are found on the bay islands. The shore of Plumb Beach is a popular horseshoe crab nesting site.[283]

Diamondback terrapin also nest on sandy habitats. Diamondback terrapins are the only

[273]Hartig et al., 2002 p. 82 (see note 264).
[274]Hartig et al., 2002, p. 71 (see note 264).
[275]Teal, 1986 (see note 10).
[276]Kneib, R.T., 2003, "Bioenergetics and landscape considerations for scaling expectations of nekton production from intertidal marshes," *Marine Ecology Progress Series* 264:279–296. (The modeled nekton production estimates were based on an estimated annual above ground primary production of 1,250 grams dry weight per square meter derived from field data, which is within the range of the annual primary production estimated for Jamaica Bay marshes.)

[277]USFWS, 1997, pp. 531–532 in Jamaica Bay and Breezy Point, Complex #16 (see note 172).
[278]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. (Mr. Riepe has served as director of the Northeast Chapter of the American Littoral Society for 25 years. He is also the organization's "Jamaica Bay Guardian," and has personally observed most of the estuarine shores in this area.)
[279]Ibid.
[280]George Frame, personal visual observations, 2/20/07 email (see note 251).
[281]Don Riepe, 2006 email (see note 278).
[282]Dugan et al., 2003 (see note 127).
[283]USFWS, 1997, p. 535 in Jamaica Bay and Breezy Point, Complex #16 (see note 172).

turtles found in brackish waters. In general, nesting terrapins show a strong preference for sandy back-barrier beaches compared to the ocean-facing beaches of barrier islands.[284,285] One reason for this may be that the back-barrier beaches are closer to the *Spartina* marshes where terrapins feed and grow.[286] In Jamaica Bay, terrapins nest in uplands, usually above the beaches; the filled wetlands of Jamaica Bay provide most of the nest sites for terrapins in this area.[287]

Nesting and migrating shorebirds feed on the invertebrates of the beaches in the study region. Many of these species nest along the marine barrier beach at Breezy Point, including the federally threatened piping plover, the state endangered least tern, and the state threatened common tern. These species feed on the small invertebrates of estuarine and ocean beaches as well as area mudflats. Breezy Point is also a concentration area for raptors, waterfowl, and landbirds passing through the area. Migrating raptors include the federally endangered peregrine falcon and the state threatened northern harrier and osprey.[288]

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.[289] In addition to the forage provided by the abundant mud snails and the small organisms of beach wrack, horseshoe crab eggs are a critical food source for migrating shorebirds.[290] In addition, continued loss of the few remaining sandy habitats in the study region would be particularly serious for diamondback terrapin, which only nest in these habitats. Because so few beaches remain, local planners indicate that beach nourishment in the face of sea level rise is likely for most remaining beach habitat in this area.

Tidal Flats

Relatively few tidal flats remain along the highly modified shorelines of the study region. There is only a narrow band of shallow subtidal flats along Lower Manhattan and the Battery.[291] However, tidal mudflats are increasing as salt marshes disappear.[292]

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.[293] Tidal flats provide substrate for algae such as sea lettuce (*Ulva lactuca*), an important food for brants.[294]

Tidal flats in Jamaica Bay are frequented by shorebirds and 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.[295] The most abundant shorebirds feeding on Jamaica Bay's tidal flats in fall include plovers, sandpipers, ruddy turnstone, sanderling, dunlin, short-billed dowitcher, and greater yellowlegs. In addition to these species, red knot is seen during the spring migration. Area mudflats are also important for waterfowl in winter.[296]

Inundation with rising seas will eventually make flats unavailable to short-legged shorebirds,

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[284] Roosenburg, W.M.,1991, "Nesting habitat of diamondback terrapin: A geographic comparison," *Wetland Journal* 6:8–11.
[285] Dr. Russell Burke, 2006 email to E. Strange (personal visual observation) (see note 226).
[286] Feinberg, and Burke, 2003, "Nesting ecology and predation of diamondback terrapins, *Malaclemys terrapin*, at Gateway National Recreation Area, New York," *Journal of Herpetology* 37:517–526, p. 520.
[287] George Frame, 2/20/07 email (personal visual observations) (see note 251).
[288] USFWS, 1997, p. 536 in Jamaica Bay and Breezy Point, Complex #16 (see note 172).
[289] Jackson, et al., 2002 (see note 139), reviewing the findings of J.K. Sullivan, 1994, "Habitat status and trends in the Delaware estuary," *Coastal Management* 22:49–79; and Dove and Nyman, 1995, pp. 441–447 (see note 14).
[290] Karpanty et al., 2006 (see note 160).
[291] USFWS, 1997, p. 630 in Lower Hudson River Estuary, Complex #21 (see note 172).
[292] George Frame, 2/20/07 email (personal visual observations) (see note 251).
[293] USFWS, 1997, p. 633 in Lower Hudson River Estuary, Complex #21 (discussing the ecological significance and uniqueness of Piermont Marsh) (see note 172).
[294] George Frame, 2/20/07 email (personal visual observations) (see note 251).
[295] 1984 study by Joanna Burger of Rutgers University, cited on p. 3 in New York State Department of State and USFWS, 1998 (see note 221).
[296] USFWS, 1997, p. 537 in Jamaica Bay and Breezy Point Complex #16 (discussing the significance of Jamaica Bay, in particular the bay islands, as a stopover site for migratory shorebirds) (see note 172).

unless they can shift feeding to marsh ponds and pannes.[297] At the same time, disappearing saltmarsh islands in the area are transforming into intertidal mudflats.[298] This increases habitat for shorebirds at low tide, but leaves less habitat for refuge at high tide.

Shallow Nearshore Waters and Submerged Aquatic Vegetation (SAV)

There is extensive shallow water habitat and high biological productivity in the part of the Hudson River from Stony Point south to Piermont Marsh, just below the Tappan Zee Bridge in Rockland County. This wide, shallow area is where the estuary's seasonal (and annual) salt front occurs, which is the area of greatest mixing of ocean and freshwater. The salt front functions to concentrate nutrients and plankton, resulting in a high level of both primary and secondary productivity. Thus, this part of the Hudson is a major habitat area 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. Some SAV is also found here, dominated by water celery, sago pondweed, and horned pondweed.[299] Sea level rise will affect this productive area through salinity changes that will influence the composition and diversity of nearshore vegetation and associated fauna. However, changes in the upstream extent of the salt wedge as a result of sea level rise have not been analyzed, nor has anyone considered the ecological implications of such a change.

Marsh and Bay Islands

Regionally important populations of egrets, herons, and ibises are 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. 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.[300] The population of the heronries of Shooter's Island, Prall's Island, and Isle of Meadows, known collectively as the Harbor Herons Complex, constitutes about 25 percent of all nesting wading birds in New York, New Jersey, and Connecticut.[301] The available research provides no basis for expecting that these colonial nesting birds could survive if these islands were inundated.

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, including Canarsie Pol, Jo Co Marsh, and Silver Hole Marsh, with smaller numbers at Duck Creek Marsh, East High Meadow, Ruffle Bar, and Subway Island. The heronry on Canarsie Pol also supports nesting by great black-backed gull, herring gull, and American oystercatcher. 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.[302]

Hoffman Island and Swinburne Island are National Park Service properties lying off the southeast shore of Staten Island; the former has important nest habitat for herons, and the latter is heavily nested by cormorants.[303]

Diamondback terrapin nest in large numbers along the sandy shoreline areas of the islands of Jamaica Bay, primarily Ruler's Bar Hassock.[304] Local experts have reported observing about

[297]Erwin et al., 2004, p. 901 (see note 16). (Discussing mudflats at Forsythe National Wildlife Refuge, New Jersey, and other northeastern Atlantic coast sites.)
[298]George Frame, 2/20/07 email (personal visual observation) (see note 251).
[299]USFWS, 1997, p. 630 in Lower Hudson River Estuary, Complex #21 (see note 172).
[300]USFWS, 1997, p. 614 in The Narrows, Complex #20 (see note 172).
[301]Steinberg, N. D.J. Suszkowski, L. Clark, and J. Way, 2004, Health of the Harbor: The First Comprehensive Look at the State of the NY/NJ Estuary, a report to the NY/NJ Harbor Estuary Program, Hudson River Foundation, New York, pp. 12–13.
[302]USFWS, 1997, p. 537 in Jamaica Bay and Breezy Point, Complex #16 (see note 172).
[303]George Frame, 2/20/07 email (personal visual observation) (see note 251).
[304]USFWS, 1997, p. 538 in Jamaica Bay and Breezy Point, Complex #16 (see note 172).

2,000 females nesting in the area.[305] Although bay islands may offer more protection from predators than the mainland, in recent years a large percentage of terrapin eggs have been depredated.[306] Other possible causes of low egg survivorship include so-called "root predation," whereby the roots of beach plants "invade" a nest and penetrate the eggs and absorb their nutrients.[307]

It is estimated that between 1974 and1994, the smaller islands of Jamaica Bay lost nearly 80 percent of their vegetative cover.[308] There has been an accelerating trend in the loss of marsh area, reaching an average annual rate of 18 ha (44.5 acres) per year between 1994 and 1999.[309] Further loss of bay island habitat with rising seas could eliminate nesting sites for island-nesting birds, having significant impacts on the populations of these species, particularly those with already diminished population sizes such as the state threatened common tern. A local terrapin expert has speculated that marsh loss, combined with loss of beach nesting sites, could greatly reduce the remaining local population of diamondback terrapin.[310]

[305]Dr. Russell Burke, 2006 email to E. Strange (see note 226). See also Feinberg, J.A., and R.L. Burke, 2003 (see note 286), and Ner, S.E., and R.L. Burke, n.d., Direct and indirect effects of urbanization on diamond-back terrapins of the Big Apple: Distribution and predation in a human-modified estuary, Unpublished manuscript, Department of Biology, Hofstra University, Hempstead, NY.

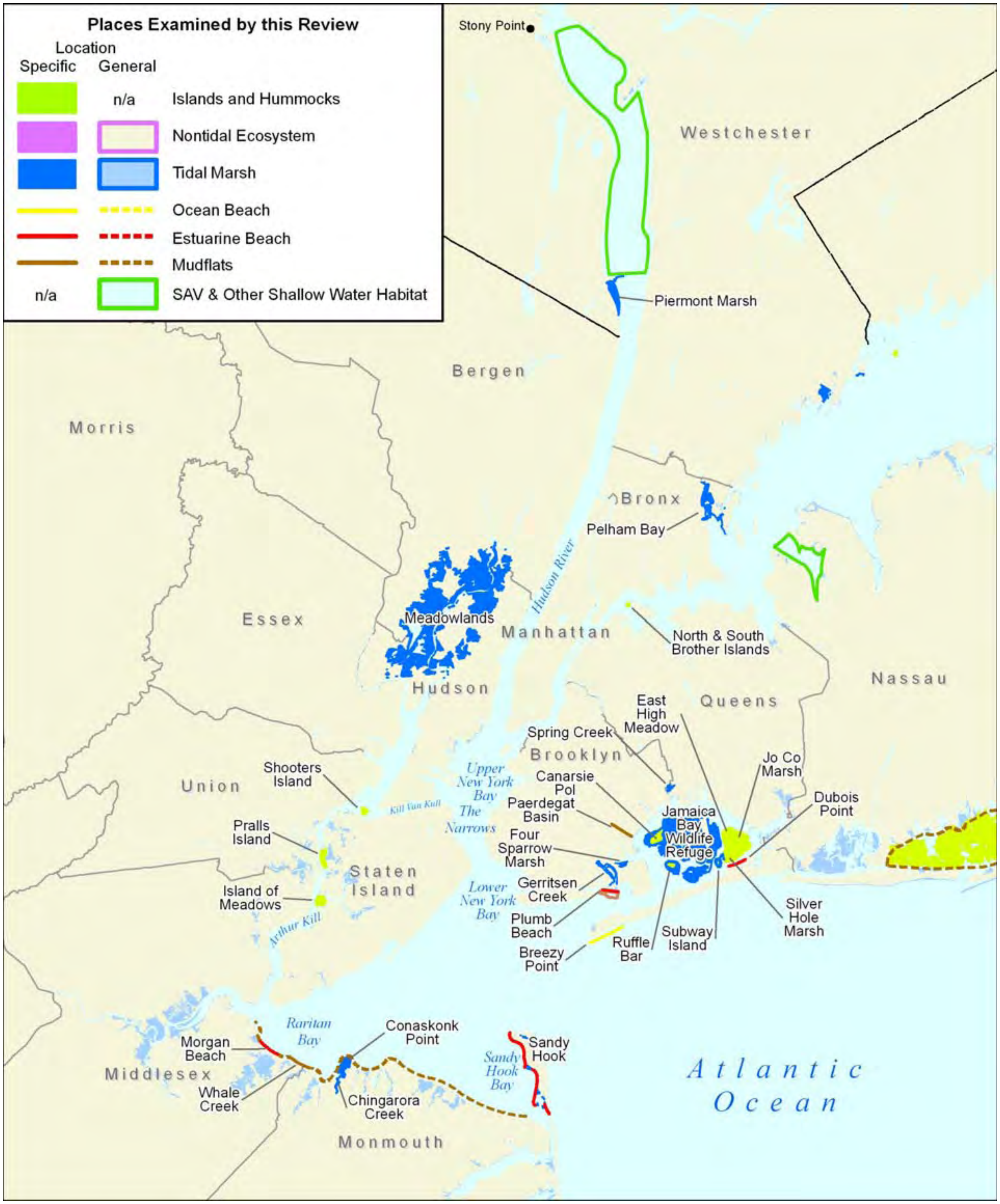
[306]Ner and Burke, n.d. (see note 305).

[307]Feinberg and Burke, 2003, pp. 517 and 523, and references therein (see note 286).

[308]Hartig et al., 2002, p. 71 (see note 264).

[309]Hartig et al., 2002, p. 78 (see note 264).

[310]Dr. Russell Burke, 2006 email to E. Strange (see note 226).



Map 3.2 Locations and Types of Habitat Discussed in this Report: New York Harbor and Raritan Bay

3.5 Raritan Bay and the Hackensack Meadowland, New Jersey

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Species and habitats in the tidal marshes of Raritan Bay and the Hackensack Meadowlands are potentially at risk because of sea level rise. Raritan Bay is part of the Raritan Bay–Sandy Hook Bay habitat complex at the "apex" of the New York Bight. The apex is where the east-west oriented coastline of New England and Long Island intersects the north-south oriented coastline of the mid-Atlantic at Sandy Hook. This is very significant ecologically, because the two coastlines tend to concentrate species migrating between the two areas.[311]

Based on existing literature and the knowledge of local scientists, this brief literature review discusses the coastal species in the region that could be at risk because of further habitat loss resulting from sea level rise and shoreline protection (see Map 3.2). Although it is possible to make qualitative statements about the possible impacts if sea level rise causes a total loss of habitat, our ability to discern what the impact might be if only a portion of the habitat is lost is more limited. A total loss of habitat is possible if shores are protected with hard structures and the wetlands are unable to keep pace with sea level rise.

Tidal Marshes

Tidal marshes in this region are mostly estuarine marsh or saline fringing marsh, with small areas of freshwater tidal marsh along South River and Raritan River. According to a panel of accretion experts, the dominant accretionary processes in these marshes are peat accumulation and inputs of river sediments, both of which they anticipate will increase in the future depending on marsh type and local conditions.

As a result of the high productivity and the potential for peat accumulation of tidal freshwater marshes in the region, the accretion panel believes that freshwater tidal marshes along the South and Raritan rivers will accumulate sufficient sediment to accrete and even expand as sea level rise increases, even with a 7 mm/yr increase in the current rate (Section 2.1).

However, the accretion panel anticipates that peat accumulation in estuarine and saline fringe marsh will increase only up to a threshold level, which is currently unknown. The panel projects that beyond that threshold these marshes will become marginal if the rate of sea level rise increases by 2 mm/yr, and will not survive if the rate increases by 7 mm/yr. Even at the modest rate of increase of 2 mm/yr, these marshes will be lost if hardened shorelines prevent migration or the marshes are degraded by human activities (see Section 2.1).

The shorelines of Raritan Bay have the most natural estuarine and saline fringing marsh remaining in the region. The southern portion of Raritan Bay includes large tracts of fringing salt marsh at Conaskonk Point and from Flat Creek to Thorn's Creek.[312] Local planners expect that much of the region's shoreline will be protected from sea level rise; in developed areas, bulkheading is already common. Therefore, migration of brackish and saline fringing marsh will not be possible along most, if not all, of the shoreline.

As estuarine and saline fringing marshes are lost, there will be increasing competition for habitat among the species found in these marshes, and eventually all of the marsh inhabitants that

[311]USFWS, 1997, p. 553 in Raritan Bay-Sandy Hook Bay Complex, Complex #17 (see note 172).

[312]Ibid.

depend on these marshes for nesting and other critical activities will need to move to similar habitat elsewhere to survive. Marsh loss will also eliminate the high primary production and detrital food web of the marsh, which are important for secondary production throughout the surrounding estuary.[313]

These marshes are critical for numerous nesting and migrating bird species. The salt marsh at Conaskonk Point provides breeding areas for green heron, clapper rail, willet, American oystercatcher, marsh wren, seaside sparrow, and saltmarsh sharp-tailed sparrow, as well as feeding areas for herons, egrets, common tern, least tern, and black skimmer. In late May and early June, sanderlings, ruddy turnstones, semipalmated sandpipers, and red knots feed on horseshoe crab eggs near the mouth of Chingarora Creek.[314] Diamondback terrapin feed in the marshes and creeks in this area.[315]

Saltmarsh along the backside of the Sandy Hook spit is dominated by low marsh cordgrass.[316] Characteristic fauna of low marsh include invertebrates such as ribbed mussel and marsh fiddler crab, and resident marsh fish species such as mummichog and sheepshead minnow.[317] The young of a number of marine fish species find forage and protection in low marsh, including winter flounder, Atlantic menhaden, bluefish, and striped bass.[318] Characteristic bird species of the low marsh also inhabit the area, including clapper rail, willet, and marsh wren.[319]

New Jersey's Hackensack Meadowlands, in Hudson and Bergen counties, are renowned for containing the largest single tract of estuarine tidal wetland in the New York/New Jersey Harbor Estuary.[320] Before European settlement, the area included a combination of fresh, brackish, and saline wetlands as well as large areas of forest. Subsequently, the Meadowlands were dramatically altered by a variety of human activities. Of the remaining wetlands in Hudson and Bergen counties, only about 1,928 ha (4,763 ac) are tidal wetlands.

The tidal marshes that remain provide regionally significant habitat for a number of federally or state-listed species. Diamondback terrapin, a federal species of concern, is common in the Sawmill Wildlife Management Area.[321] The state-listed endangered least tern, black skimmer, and pied-billed grebe use Kearney Marsh as a feeding area.

Much of the tidal marsh of the Meadowlands are dominated by the invasive common reed (*Phragmites*), a species found in degraded wetlands with decreased tidal flow.[322] As a result of recent restoration activities, parts of Harrier Meadow and the Riverbend Wetlands Preserve now support a mixture of open water and native high saltmarsh vegetation.[323]

One result of sea level rise in the Meadowlands may be conversion of some *Phragmites*-dominated marshes into salt marshes dominated by the native cordgrass, *Spartina alterniflora*. This may benefit some bird species, because the dense physical structure of *Phragmites* limits access to the marsh surface by foraging shorebirds, waders, waterfowl, and other taxa.[324,325]

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[313]Teal, 1986 (see note 10).
[314]Barnes, S., n.d., New Jersey Audubon Society, Sandy Hook Bird Observatory, *Guide to Birding in Raritan Bay*. Available at: http://www.njaudubon.org/Centers/SHBO/Conaskonk.html.
[315]USFWS, 1997, p. 556 in Raritan Bay–Sandy Hook Bay Complex, Complex #17 (see note 172).
[316]USFWS, 1997, p. 554 in Raritan Bay–Sandy Hook Bay Complex, Complex #17 (see note 172).
[317]USFWS, 1997, pp. 554–555 in Raritan Bay–Sandy Hook Bay Complex, Complex #17 (see note 172); Rader, D.N., 1984, Salt-marsh benthic invertebrates: Small-scale patterns of distribution and abundance, *Estuaries* 7(4A):413–420.
[318]Boesch, D.F., and R. E. Turner, 1984, "Dependence of fishery species on salt marshes: The role of food and refuge," *Estuaries* 7(4A):460–468, p. 465.
[319]USFWS, 1997, p. 556 in Raritan Bay–Sandy Hook Bay Complex, Complex #17 (see note 172).
[320]USFWS, 1997, p. 595 in Hackensack Meadowlands, Complex #19 (see note 172).
[321]USFWS, 1997, p. 599 in Hackensack Meadowlands, Complex #19 (see note 172).
[322]USFWS, 1997, p. 597 in Hackensack Meadowlands, Complex #19 (see note 172).
[323]See, for example, Seigel, A., C. Hatfield, and J. M. Hartman, 2005, "Avian response to habitat restoration of urban tidal marshes in the Hackensack Meadowlands, New Jersey," *Urban Habitats* 3:87–116. Available at: http://www.urbanhabitats.org.
[324]Seigel et al., 2005, p. 88 and references therein (see note 323).
[325]However, George Frame, 2/20/07 email (see note 251), noted that common reed provides habitat for some species, e.g., birds such as red-winged blackbirds and spring peepers (*Hyla crucifer*) and other amphibians and reptiles.

Estuarine Beaches

A local marine biologist with the National Marine Fisheries Service reports that there are small areas of estuarine beach all along the shorelines of this region where there is no shoreline hardening or marsh, except in low current areas where mud flats predominate.[326] Portions of the estuarine beaches of Sandy Hook are bulkheaded or armored.[327] Sandy beaches are common along the shores of Staten Island from Tottenville to Ft. Wadsworth, whereas hardened shores are more common on the New Jersey side of Raritan Bay. The southern shoreline of Raritan Bay includes a number of beaches along Sandy Hook Peninsula and from the Highlands to South Amboy. There are also beaches on the Perth Amboy side, some of which (e.g., Keansburg) are popular summer amusement beach areas. Other beaches are found on some of the shorelines around small islands within the Shrewsbury-Navesink River system.[328]

The estuarine beaches in the region are extremely important spawning areas for horseshoe crabs, and the dry, upper beach is used by nesting terrapins. Many other coastal birds such as terns, gulls, and black skimmers use the open sandy areas of beaches for resting and some nest on the beaches as well.[329] The New Jersey Audubon Society reports that its members have observed gulls and terns at the Raritan Bay beach at Morgan on the southern shore, including some rare species such as black-headed gull, little gull, Franklin's gull, glaucous gulls, black tern, sandwich tern, and Hudsonian godwit.[330] Recently, area beaches, especially those on Sandy Hook Bay, have become important resting places for several species of seals that frequent the area during the winter.[331]

Beaches are also important foraging grounds for birds, especially migrating shorebirds such as sanderlings, yellowlegs, and oystercatchers looking for clams and other invertebrates. Red knots, ruddy turnstones, and laughing gulls feed on horseshoe crab eggs in the sand of area beaches. [332] Mud snails are common on estuarine beaches, and beach wrack contains insects, isopods, and amphipods. The abundance of shorebird species is positively correlated with the abundance of beach wrack and associated invertebrates.[333] Recent research indicates that beach wrack traps horseshoe crab eggs, making them more available for shorebirds.[334]

Local planners anticipate that most of the shoreline along the beach/dune systems of Raritan Bay and Sandy Hook are almost certain to be protected as sea level rises. However, it is uncertain whether beach nourishment or shoreline armoring will be more common.

If the beaches are armored, beaches will erode and sediments will not be available for natural replenishment of sand,.[335] This will eliminate the beach nesting areas of terrapins and horseshoe crabs and the forage provided to birds by small beach organisms. The loss of horseshoe crab eggs will be especially critical for red knot, which feed almost exclusively on crab eggs during their spring migration.

If beaches are nourished, their geomorphic characteristics may be altered in ways that some scientists believe are unsuitable for many beach invertebrates, including horseshoe crabs.[336] Sandy Hook is considered almost certain to be protected using approaches that retain natural shores. The Park Service is currently planning to build a sand bypass system to replenish a narrow section of the spit.

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[326]Frank Steimle, National Marine Fisheries Service marine biologist. In July 14, 2006 email to E. Strange, Stratus Consulting, entitled "Comments on draft report on HRE-Hackensack/Raritan Bay," describing the area's estuarine beaches. Frank Steimle has closely observed the New York/New Jersey Harbor Estuary for over two decades.
[327]George Frame, 2/20/07 email (personal visual observations) (see note 251).
[328]Frank Steimle, 2006 email to E. Strange (see note 326).
[329]Ibid.
[330]Barnes, n.d., New Jersey Audubon Society (see note 314).
[331]USFWS, 1997, pp. 555–-556 in Raritan Bay–Sandy Hook Bay Complex, Complex #17 (see note 172).

[332]Frank Steimle, 2006 email to E. Strange (personal visual observations) (see note 326).
[333]Dugan et al., 2003, p. 32 (see note 127).
[334]Jackson et al., 2002, p. 418 (see note 139).
[335]Nordstrom, 2005 (see note 153).
[336]Jackson, et al., 2002, p. 420 (see note 139), reviewing the findings of Nelson, W.G, 1993, "Beach restoration in the southeastern U.S.: Environmental effects and biological monitoring," *Ocean and Coastal Management*, 19:157–182, and Rudloe, A., 1981, Aspects of the biology of juvenile horseshoe crabs, *Limulus polyphemus. Bulletin of Marine Sciences* 31:125–133.

Tidal Flats

We have been unable to find any papers analyzing whether the tidal flats in this region could keep pace with accelerated sea level rise. Therefore, in this discussion we consider the species that would be at risk if the flats are unable to keep pace.

The area's flats are known foraging grounds for numerous bird species, diamondback terrapin,[337] and horseshoe crabs.[338] The thousands of birds that pass through or reside in and around Raritan and Sandy Hook bays depend on intertidal invertebrate food resources as well as the many small adult and juvenile fishes that feed in these areas.

The south shore of the Raritan and Sandy Hook bays, from the confluence of the Shrewsbury and Navesink rivers west to the mouth of the Raritan River, consists of a narrow band of salt marsh habitat, tidal creek, beaches, dunes, and remnant forests. Some 1,460 ha (3,600 acres) of intertidal flats extend offshore from these habitats an average of 0.4 km (0.25 miles).[339] The flats are important foraging and staging areas for migrating shorebirds, averaging more than 20,000 birds, mostly semipalmated plover, sanderling, and ruddy turnstone.[340] Tidal flats are also habitat for hard and soft shell clams, which are important for recreational and commercial fishermen where not impaired by poor water quality.

The flats at the mouth of Whale Creek near Pirate's Cove (see Map 3.2) attract gulls, terns, and shorebirds year-round.[341] The intertidal and shallow water macroalgae beds provide forage for brant and dabbling ducks.[342] Midwinter waterfowl surveys indicate that an average of 60,000 birds migrate through the area in winter.[343]

Shallow Waters and Submerged Aquatic Vegetation (SAV)

Little eelgrass is found in this region, primarily because of poor water quality resulting from high levels of nutrients and suspended solids.[344] Therefore, in this region sea level rise is not an impact of concern for SAV. Sea lettuce and other algae substitute for eelgrass as an important food for Brants and as habitat for invertebrates and small fishes.[345]

[337] Dr. Russell Burke, email to E. Strange (personal visual observations of terrapins) (see note 226).
[338] Frank Steimle, July 14, 2006 email to E. Strange (personal visual observations of numerous species) (see note 326).
[339] USFWS, 1997, p. 553 in Raritan Bay–Sandy Hook Bay Complex, Complex #17 (see note 172).
[340] USFWS, 1997, pp. 553 and 556 in Raritan Bay–Sandy Hook Bay Complex, Complex #17 (see note 172).
[341] Barnes, n.d. (see note 314).
[342] Frank Steimle, July 14, 2006 email to E. Strange (personal visual observations) (see note 326).
[343] USFWS, 1997, p. 556, Raritan Bay–Sandy Hook Bay Complex, Complex #17 (see note 172).
[344] USFWS, 1997, p. 559,Raritan Bay–Sandy Hook Bay Complex, Complex #17 (see note 172).
[345] George Frame, 2/20/07 email (personal visual observations) (see note 251).

3.6 New Jersey's Coastal Bays

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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 fish, invertebrates, terrapins, and birds, and a great deal is known about the ecology and habitat needs of these species. Based on existing literature and the knowledge of local scientists, this summary discusses those species that could be at risk because of further habitat loss resulting from sea level rise and shoreline protection (see Map 3.3). 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.

Ocean County has two coastal barrier islands, Island Beach to the north and Long Beach Island to the south. Behind these barrier islands are the bays of the Barnegat Estuary, including Barnegat Bay, Manahawkin Bay, and Little Egg Harbor; three inlets; several tidal creeks; and numerous finger canals.[346] The Barnegat Bay National Estuary Program (BBNEP) includes the shoreline from the Point Pleasant Canal south to the Little Egg Harbor Inlet.[347]

Atlantic County has the back-barrier bays and tidal wetlands of the Brigantine Bay and marsh complex, which extends from Little Egg Inlet south to the Great Egg Harbor Inlet,[348] and the Great Egg Harbor Estuary[349] contained within southern Atlantic County and northern Cape May County. Cape May County has the important environmental areas of the Cape May Peninsula, which include the coastal ponds of Cape May Meadows at the tip of the peninsula and a network of salt marsh islands and small, shallow bays connected by a network of channels and tidal creeks on the peninsula's Atlantic Ocean side.[350]

There have been many efforts to conserve and restore species and habitats in the barrier island/ back-barrier lagoon system of the study region. Some of the larger parks and wildlife areas in the region are 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,[351] the Cape May Point State Park,[352] and TNC's Cape May Migratory Bird Refuge.[353] The peninsula is renowned as one of the primary stopover sites for migrating birds along the U.S. Atlantic Coast. The North Brigantine Natural

[346] See USFWS, 1997, Barnegat Bay Complex, Complex #6. pp. 317–330 (see note 172) .

[347] The website for the Barnegat Bay National Estuary Program is http://www.bbep.org/.

[348] See USFWS, 1997, Brigantine Bay and Marsh Complex, Complex #4. pp. 281–307 (see note 172).

[349] See USFWS, 1997, Great Egg Harbor Estuary, Complex #3. pp. 261–268 (see note 172).

[350] See USFWS, 1997, Cape May Peninsula, Complex #1. pp. 177–195 (see note 172).

[351] See http://www.fws.gov/northeast/capemay/.

[352] See http://www.state.nj.us/dep/parksandforests/parks/capemay.html.

[353] See http://www.nature.org/wherewework/northamerica/states/newjersey/work/art17205.html.

Area is a critical nesting area for least terns and piping plovers and a critical stopover habitat for a number of migrating shorebirds. 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. 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. Marsh islands behind this inlet system and behind Stone Harbor host the largest concentration of nesting laughing gulls in the world.[354] The TNC refuge alone supports an estimated 317 bird species, 42 mammal species, 55 reptile and amphibian species, finfish, shellfish, and other invertebrates.[355] All of these areas are likely to be placed at increased risk by rising sea levels.

Tidal Marshes 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. 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) (see Section 2.1).

There is potential for wetland migration in the unprotected parts of Island Beach State Park, the Forsythe Refuge, and other parks and wildlife management areas in Ocean County.[356] Wetlands may also be allowed to migrate along the undeveloped shorelines of the Mullica and Great Egg Harbor rivers in Atlantic County.[357]

However, with the exception of beaches and a few areas such as the Forsyth Refuge, most estuarine shorelines are hardened.[358] Local planners indicate that the developed mainland and barrier island shorelines of Ocean, Atlantic, and Cape May counties will almost certainly be protected. 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. Below Barnegat Inlet natural shorelines are considered likely to remain because the sea would have to rise many feet before it would reach US Highway 9.[359] 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. The invasive common reed may spread into areas where higher sea levels cause groundwater discharge to migrate up slope with greater volume.[360]

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.[361] 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. Sampling of larval fishes in high salt marsh on Cattus Island, Beach

[354]Dave Jenkins, acting chief, New Jersey Division of Fish and Wildlife, Endangered and Nongame Species Program, Trenton, NJ. E-mail entitled Opportunity to comment on a US EPA-sponsored paper concerning sea level rise, to Karen Scott of EPA, 7/18/07. (personal visual observations).
[355]Fact sheet by National Park Service on the New Jersey Coastal Heritage Trail Route. Accessed December 4, 2007 at: http://www.nps.gov/archive/neje/migsites.html.

[356]Ibid.
[357]Ibid.
[358]Stanton Hales, Richard Stockton College, Biology & Marine Sciences Programs, Pomona, NJ. E-mail entitled Reviews of USEPA-sponsored papers, to Karen Scott of EPA 7/25/07. (personal visual observations).
[359]Ibid.
[360]Barry Truitt, The Nature Conservancy. Email entitled Review of Atlantic coast side of the VES, to Karen Scott of EPA, 7/25/07.
[361]Weinstein, M.P., 1979, "Shallow marsh habitats as primary nurseries for fishes and shellfish, Cape Fear River, North Carolina," *U.S. Fisheries Bulletin* 77:339–357.

Haven West, and Cedar Run in Ocean County showed that high marsh is important for production of mummichog, rainwater killfish, spotfin killifish, and sheepshead minnow. The flooded marsh surface and tidal and nontidal ponds and ditches appear to be especially important for the larvae of these species.[362] 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.[363] Long-legged waterbirds such as yellow-crowned night heron, which forages almost exclusively on marsh crabs (fiddler crab and others), will lose important food resources. High marsh nesting birds such as northern harrier, black rail, clapper rail, and willet may be most at risk.[364] 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 stop over on New Jersey's shores during their annual migrations.[365] Waterfowl also forage and overwinter in area marshes. Midwinter aerial waterfowl counts in Barnegat Bay alone average 50,000 birds.[366] 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.[367] 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.[368]

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 tenfold and reducing population sustainability because of lower per capita food resources and disease from crowding.[369]

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 syntheses of published studies in Greenlaw and Rising, and Poole and Gill, 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.[370] Loss and alteration of suitable marsh habitats are the primary conservation concerns for these and other marsh-nesting passerine birds.[371] Nonpasserine marsh nesting

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[362]Talbot, C.W., and K.W. Able, 1984, "Composition and distribution of larval fishes in New Jersey high marshes," *Estuaries* 7:434–443.
[363]Erwin et al., 2004 (see note 16).
[364]Dave Jenkins (see note 354).
[365]Cooper, M.J.P., M.D. Beevers, and M. Oppenheimer, 2005, *Future Sea Level Rise and the New Jersey Coast,* Science, Technology, and Environmental Policy Program, Woodrow Wilson School of Public and International Affairs, Princeton University, Princeton, NJ, p. 3, citing the New Jersey Coastal Management Program.
[366]USFWS, 1997, Barnegat Bay Complex, Complex #6. p. 323 (see note 172).
[367]See USFWS, 1997, Cape May Peninsula, Complex #1. pp. 177–195 (see note 172).
[368]USFWS, 1997, Barnegat Bay Complex, Complex #6. p. 324 (see note 172).
[369]Erwin et al., 2006 (see note 58).
[370]Greenlaw, J.S., and J.D. Rising, 1994, "Sharp-tailed sparrow (*Ammodramus audacutus*)," in Poole, A. and F. Gill, (eds.), *The Birds of North America,* No. 127, The Academy of Natural Sciences, Philadelphia and the American Ornithologists' Union, Washington, DC; and Post, W. and J. S. Greenlaw, 1994, Seaside sparrow (*Ammodramus maritimus*), in Poole and Gill, as cited in Chapter 6 of *The Barnegat Bay Estuary Program Characterization Report*. Prepared by the Barnegat Bay National Estuary Program (Scientific and Technical Advisory Committee), January 2001. Available at: http://www.bbep.org/char_rep.htm
[371]Chapter 7 of *The Barnegat Bay Estuary Program Characterization Report.* Prepared by the Barnegat Bay National Estuary Program (Scientific and Technical Advisory

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.

Bulkheading is also under way to protect the vulnerable freshwater ecosystems of the Cape May Meadows (The Meadows), which is located behind the eroding dunes of the Cape May Canal. 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.[372] 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.[373] Because of its vulnerability to sea level rise and its status as an ecologically important area, local planners expect that The Meadows will continue to be protected in the future.

Estuarine Beaches

Estuarine beaches could largely disappear as a result of erosion and inundation of sandy habitat as seas rise. This would eliminate the billions of invertebrates that are found within or on the sandy substrate or beach wrack along the tide line of estuarine beaches.[374] 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 (see details in Section 3.1).

To protect estuarine beaches, beach nourishment is being implemented in developed portions of the Ocean County shore, particularly in the northern part, while bulkheading continues to be used on the bayside shores of the county. TNC, the U.S Army Corps of Engineers (USACE), and the New Jersey Department of Environmental Protection (NJDEP) are undertaking 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.[375]

Loss of horseshoe crab eggs as a result of beach erosion or beach nourishment could have important implications for the 1.5 million migratory shorebirds that stop over on New Jersey's shores to refuel during their annual migrations.[376] Many shorebirds feed preferentially on horseshoe crab eggs in spring (e.g., red knot), [377,378] and loss of this food source could reduce the growth and survival of migrants if there are insufficient alternative foraging sites nearby.[379] Sanderling, red knot, and ruddy turnstone prefer sandy beaches for foraging.[380] In spring these migrants must feed nearly continuously to gain sufficient weight for nesting and to continue their long-distance migrations.[381]

Northern diamondback terrapin nests on estuarine beaches in the Barnegat Bay area. [382] Loss of these habitats will make terrapins even more dependent on areas modified by humans (roadways). Local scientists consider coastal

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Committee), January 2001. Available at: http://www.bbep.org/char_rep.htm/Ch7/Chapter%207.htm.

[372] Fact sheet by New Jersey Department of Environmental Protection on Cape May Point State Park. Accessed December 5, 2007 at: http://www.state.nj.us/dep/parksandforests/parks/capemay.html.

[373] Fact sheet by Paul Kerlinger, Outdoors Columnist, entitled "Birding, The Cape May Migratory Bird Refuge." Accessed December 5, 2007 at: http://www.capemaytimes.com/birds/capemay-meadows.htm.

[374] Bertness, 1999, pp. 256–257, gives an estimate of more than 2 billion microscopic invertebrates per square meter (see note 133).

[375] Fact sheet by The Nature Conservancy on the Cape May Migratory Bird Refuge. Accessed December 5, 2007 at: http://www.nature.org/wherewework/northamerica/states/newjersey/work/art17205.html.

[376] Cooper et al., 2005, p.3, citing the New Jersey Coastal Management Program (see note 365).

[377] USFWS, 2005 (see note 232).

[378] Karpanty et al., 2006 (see note 160).

[379] Although in spring the principal food source of shorebirds is typically horseshoe crab eggs, the BBNEP reports that in Barnegat Bay shorebirds feed on invertebrates in marsh mudflats and beaches. See Chapter 7 of *The Barnegat Bay Estuary Program Characterization Report* (see note 371).

[380] Chapter 7 of *The Barnegat Bay Estuary Program Characterization Report* (see note 371).

[381] USFWS, 2005 (see note 232).

[382] Chapter 7 (and references therein) of *The Barnegat Bay Estuary Program Characterization Report* (see note 371).

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.[383]

Loss of estuarine beach could also have negative impacts on rare tiger beetles. Two subspecies of *Cicindela dorsalis* are found on New Jersey's coastal shoreline: the northeastern beach tiger beetle, *C. dorsalis dorsalis*, which is a federally listed threatened species and a state species of special concern and regional priority, and *C. dorsalis media*, which is considered rare, though it has not been considered for state listing. In the mid-1990s, the northeastern beach 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.[384] The current abundance and distribution of the northeastern beach tiger beetle in the coastal bays is a target of research.[385] At present, there are plans to reintroduce the species in the study region at locations where natural ocean beaches remain.[386]

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. Tidal flats are found in almost all of the coastal bays, and support invertebrates such as insects, worms, clams, and crabs that provide an 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.[387]

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.[388,389] The USFWS estimates that the extensive tidal flats of the Great Bay alone total 1,358 ha (3,355 acres). 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.[390, 391] 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.[392]

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 meter (3.28 feet), 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,[393] particularly locations where water depths are above 1 meter (3.28 feet), such as portions of Great South Bay.[394]

Seagrass surveys from the 1960s through the 1990s revealed an overall decline in seagrass in Barnegat Estuary from 6,823 ha (16,847 acres) in

[383]See the website of the Wetlands Institute's terrapin conservation program at http://www.terrapinconservation.org.
[384]USFWS, 1997, Barnegat Bay Complex, Complex #6, pp. 317–330 (see note 172).
[385]State of New Jersey, 2005, New Jersey Comprehensive Wildlife Conservation Strategy for Wildlife of Greatest Conservation Need, August 2005 Draft, Table C1, p. 61, available at: http://www.njfishandwildlife.com/ensp/waphome.htm.
[386]State of New Jersey, 2005 (see note 385).
[387]Chapter 7 of *The Barnegat Bay Estuary Program Characterization Report* (see note 371).
[388]See USFWS, 1997, Barnegat Bay Complex, Complex #6, p. 317 (see note 172).
[389]USFWS, 1997, Brigantine Bay and Marsh Complex, Complex #4, p. 281 (see note 172).
[390]Galbraith et al., 2002, p. 173 (see note 50).
[391]Erwin et al., 2004, p. 892 (see note 16).
[392] Stanton Hales (expert judgment based on a career largely devoted to these issues) (see note 358).
[393]USFWS, 1997, Barnegat Bay Complex, Complex #6. pp. 317–330 (see note 172).
[394]USFWS, 1997, Mullica River-Great Bay Estuary, Complex #5. pp. 295–307 (see note 172).

a 1968 survey to an average of 5,677 ha (14,029 acres) of seagrass beds from 1996 to 1998.[395, 396]

Numerous studies indicate that eelgrass has high ecological value as a source of both primary[397] and secondary production[398] 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. In addition, many species graze on eelgrass, including gastropods, fishes, ducks, and muskrats.[399]

Short and Neckles 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 percent, resulting in a 30–40 percent reduction in seagrass growth. The researchers suggested that this will, in turn, result in reduced productivity and functional values of eelgrass beds.[400]

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. These bulkheaded areas have reduced abundances of fishes compared to sites that were not bulkheaded sites.[401]

The Barnegat Estuary has 14 yacht clubs, with 4 on Long Beach Island alone. Sailing and sailboat racing are less popular in Atlantic and Cape May counties,[402] with their relatively small and shallow bays. One possible benefit of the conversion of marsh to open water would be increased recreational sailing in the larger barrier bays that might form. On the other hand, deeper water would make Little Egg Harbor Bay less hospitable to windsurfing.[403]

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 several species of conservation concern, including gull-billed tern, common tern, Forster's tern, least tern, black skimmer, American oystercatcher, and piping plover. Diamondback terrapin, a state species of special concern and a regional priority, is also known to feed on marsh islands in the bays.[404]

Some of the small islands in Barnegat Bay and Little Egg Harbor are several feet above mean spring high water,[405] but portions of other islands are very low, and some low islands are currently disappearing. Many of these vulnerable islands are used by nesting common terns, Forster's terns, black skimmers, and American oystercatchers.[406] 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. Members of the land trust have documented a 37 percent 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

[395]Chapter 7 of *The Barnegat Bay Estuary Program Characterization Report* (see note 371).
[396]According to an 7/21/06 email to E. Strange, Stratus Consulting, from Dr. Paul A. X. Bologna of the Department of Biology and Molecular Biology at Montclair State University, Dr. Bologna has conducted SAV monitoring in the Barnegat Estuary since 1998, but these data are not yet analyzed.
[397]Thayer, G.W., W.J. Kenworthy, and M.S. Fonseca, 1984, The Ecology of Eelgrass Meadows of the Atlantic Coast: A Community Profile, U.S. Fish and Wildlife Service, FWS/OBS-84/02.
[398]Jackson, E.L., A.S. Rowden, M.J. Attrill, S. Bossey, and M. Jones, 2001, The importance of seagrass beds as habitat for fishery species, *Oceanography and Marine Biology Annual Review* 39:269–303.
[399]Chapter 7 of *The Barnegat Bay Estuary Program Characterization Report* (see note 371).
[400]Short and Neckles, 1999 (see note 91).
[401]Byrne, 1995 (see note 112).
[402]Of 32 yacht clubs in New Jersey, 14 are in Ocean County, and 6 are in Atlantic and Cape May counties combined. The other 12 are evenly divided between Delaware River, Monmouth County, and North Jersey. Don Robertson's Marine Marketplace: Yacht Clubs with Web Sites. Available at: http://www.yachtsales.com/yclubs/nj.html.
[403]Titus, J., 1998, Windsurfing in a warmer world, *Windsurfing Magazine*, March (Windsurfing is more convenient when water is 3–4 ft deep than when over one's head.)
[404]USFWS, 1997, Barnegat Bay Complex, Complex #6. pp. 317–330 (see note 172).
[405]Personal visual observation by James G. Titus, U.S. EPA.
[406] Dave Jenkins (personal visual observation) (see note 354).

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.[407] The island is also a strategically located nesting island for many of New Jersey's threatened and endangered species, and it contains a moderate-size black skimmer colony, common terns, and most recently, a very small colony of royal terns.[408]

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[407]Mordecai Land Trust web site, available at: http://www.mordecaimatters.org.
[408]Dave Jenkins (personal visual observation) (see note 354).

Map 3.3 Locations and Types of Habitat Discussed in this Report: New Jersey Shore

3.7 Delaware Bay

Authors: ***Danielle Kreeger, Partnership for the Delaware Estuary Inc., and James G. Titus, U.S. Environmental Protection Agency***

Delaware Bay is part of the larger Delaware Estuary Ecosystem, the second largest estuary in North America and home to hundreds of species of ecological, commercial, and recreational value. Unlike other estuaries in the Mid-Atlantic, the Delaware estuary's tide range is greater than the ocean tide range, generally about 2 meters. Beaches account for 52 percent of the bay's shore, with marsh and eroding peat accounting for most of the remainder.[409]

This brief literature review discusses species that could be at risk because of further habitat loss resulting from sea level rise and shoreline protection.

Tidal Marshes

Much of the land along Delaware Bay, and for several kilometers inland, is tidal wetland (see Map 3.4). The Delaware Estuary has one of the largest freshwater tidal prisms in the world. As result, the tidal wetlands vegetation must be adapted for a wide range in salinity. Delaware Bay and its tributary creeks have tidal freshwater, brackish, and salt marshes. These wetlands are characterized by zones of different vegetation types, which reflect small differences in topography and tidal flooding regimes. All three classes are essential habitat for wildlife, waterfowl, fish, and other living resources.

In the salt marshes fringing Delaware Bay, the low marsh is flooded at least once daily and is generally found between the mean tide level and mean high water. The bay's low marsh is dominated by smooth cordgrass, *Spartina alterniflora*. The less frequently flooded high marsh zone has higher plant diversity, and typically includes *Spartina patens*, *Iva frutescens*, and *Baccharis halimifolia*. High marsh is less common than low marsh and is likely to be much more vulnerable to sea level rise. Black rail and the coastal plain swamp sparrow depend on high marsh habitat. Almost the entire breeding range of the coastal swamp sparrow is in the Delaware Estuary.

Historically, much of the bay's shoreline was diked to reclaim wetlands for farming. However, in recent decades, dikes have been removed to support wetland restoration.[410] At the same time, there has been an expansion of the common reed, *Phragmites australis*, at higher elevations and in many of the formerly diked areas.[411] Marsh areas dominated by common reed are thought to provide lower quality wildlife and fishery habitat compared to natural cordgrass marshes.[412]

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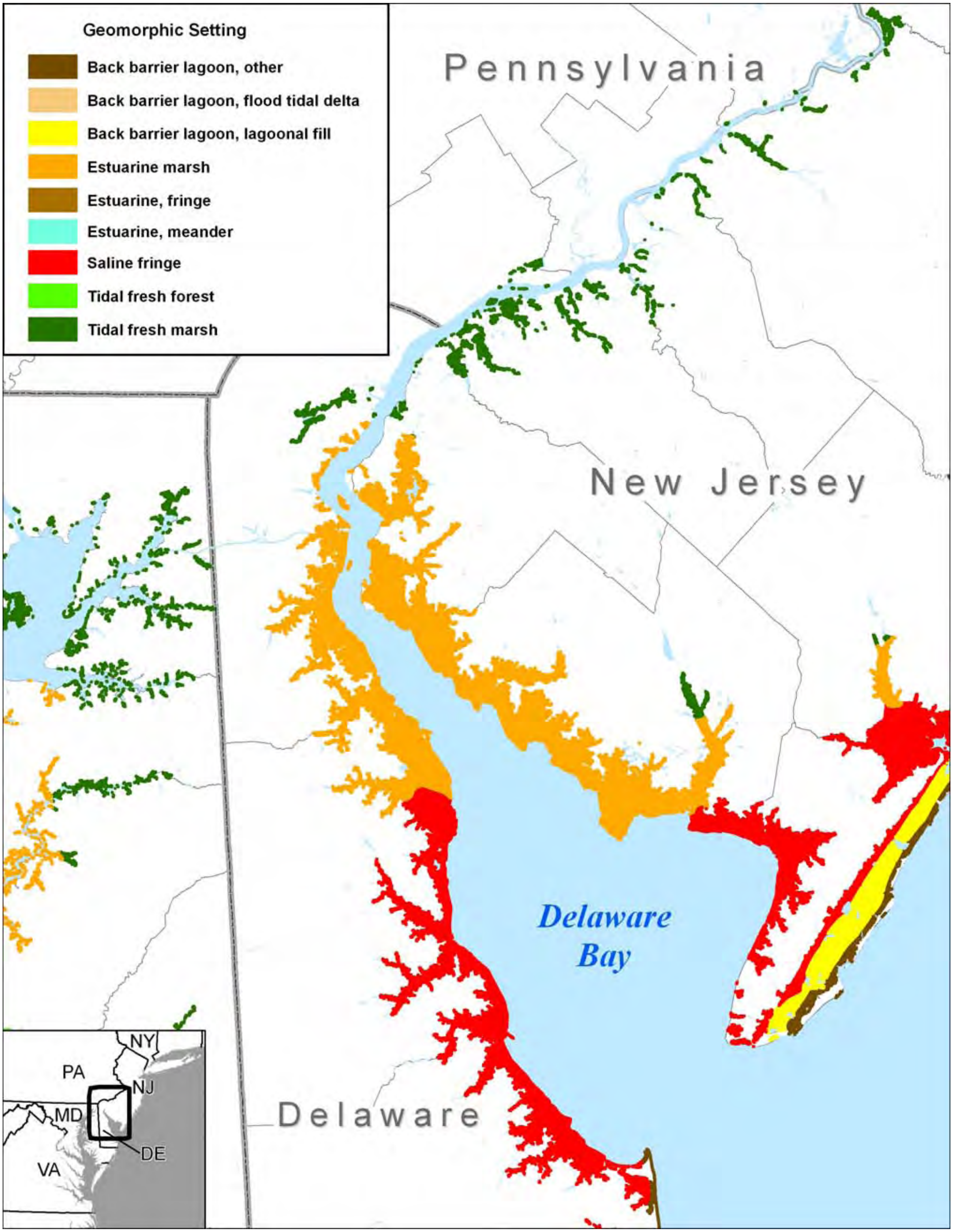
[409] Lathrop, R., M. Allen, and A. Love, 2006, Mapping and Assessing Critical Horseshoe Crab Spawning Habitats in Delaware Bay, Grant F. Walton Center for Remote Sensing and Spatial Analysis, Cook College, Rutgers University, p.15, Table 8, accessed on November 15, 2006 at: http://deathstar.rutgers.edu/projects/delbay/.

[410] See Weinstein, M.P., K.R. Philip, and P. Goodwin, 2000, "Catastrophes, near-catastrophes and the bounds of expectation: Success criteria for macroscale marsh restoration," in *Concepts and Controversies in Tidal Marsh Ecology*, M.P. Weinstein and D.A. Kreeger (eds.), Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 777–804; and Able, K.W., D.M. Nemerson, P.R. Light, and R.O. Bush, 2000, "Initial response of fishes to marsh restoration at a former salt hay farm bordering Delaware Bay," in Weinstein and D.A. Kreeger, pp. 749–776.

[411] Ibid.

[412] Philip, K., 1995, Tidal Wetlands Characterization – Then and Now. Delaware Estuary Program, Final Report to the Delaware River Basin Commission.



Map 3.4. Tidal Wetlands Along the Delaware Estuary. Source: Titus et al. (Section 2.2), using science assessment of Reed et al. (Section 2.1).

Can Marshes Keep Pace with Rising Sea Level?

The sustainability of tidal marshes in response to relative sea level rise depends on the supply of sediment and organic matter to raise the marsh surface, the tide range, and the ability of wetlands to migrate inland, which depends on both the slope of the nearby lowland and whether people allow the wetland migration or block it with shore protection (Section 2.1). The 2 meter daily tide range enables low and high marsh to each subsist over an elevation range of close to 1 meter. Hence it would take a 1 meter rise to submerge all the existing low marsh, or to flood all of the existing high marsh at the frequency that defines 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.[413] Unlike the marshes along the back-barrier bays of Delaware and New Jersey, the tidal marshes of Delaware Bay grow upward primarily through the accretion of organic matter, not sediment.

Evidence of wetland loss can be seen in many areas, such as just inside the mouth of the Maurice River near Port Norris, New Jersey (see Map 3.4). In this location, the effects of sea level rise appear to be acting synergistically with increased erosive energy to lead to significant marsh losses over the past 100 years. One contributing factor here might have been the loss of the oyster reefs near the mouth during the 1950s and 1960s, which might have afforded some protection against storm surge and wave energy. Today, the energy from winter Nor'easters and other storms directly enters the mouth, eroding at the marsh edge across a new embayment and threatening to breach to the river upstream of the town of Bivalve.[414] This idea is attracting some interest as a possible strategy for combating shoreline erosion by restoring nearshore reefs in concert with rehabilitating intertidal mussel and oyster communities along marsh edges as a form of natural armoring. Nevertheless, it is unlikely that such efforts will be widespread enough to ensure that all tidal wetlands accrete vertically at a rate to offset sea level rise, and seaward losses of marsh are certain to continue. In other areas of Delaware Bay, wetlands do not appear to be vanishing as quickly or at all, and so one must consider the possibility that some wetlands will keep pace with rising sea level but others will not.

Considering these factors, Reed et al. (Section 2.1) concluded that with a 2 mm/yr acceleration in sea level rise, most of the Delaware Bay wetlands would be marginal, and that the wetlands will probably convert to open water along Bombay Hook National Wildlife Refuge on the Delaware side, and between Fortescue and the Salem Nuclear Generating Station on the New Jersey side (see Map 3.5).

Can Wetlands Migrate Inland as Sea Level Rises?

As a general rule, where the bay's shoreline is armored, the landward migration of the marsh will be impeded. Along Delaware Bay, most of the shore is undeveloped and unlikely to be armored. Each acre of land submerged, however, would not necessarily correspond to an acre of increased wetland habitat: landward migration of tidal wetlands would 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.

The Partnership for the Delaware Estuary is directing attention to the landward fringe of tidal wetlands, where conversion of nontidal natural lands to tidal natural lands appears imminent and important to safeguard against further losses of tidal wetlands. The Partnership (a National Estuary Program) is currently leading an assessment of land use patterns in the landward buffers adjacent to tidal wetlands to identify locations where landward migration of tidal

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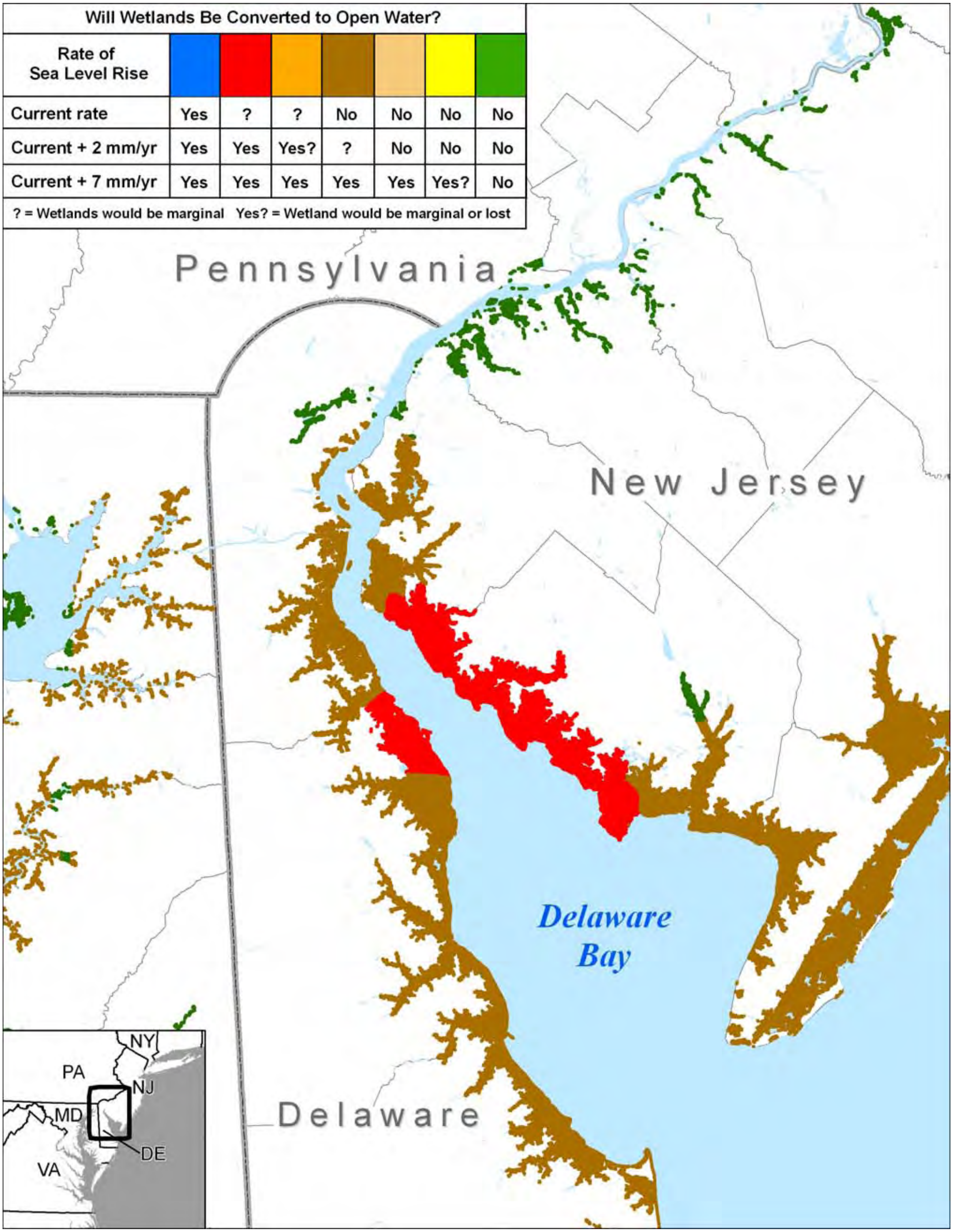
[413]Kearney, M.S., A.S. Rogers, J.R.G. Townsend, E. Rizzo, D. Stutzer, J.C. Stevenson, and K. Sundborg, 2002, "Landsat imagery shows decline of coastal marshes in Chesapeake and Delaware bays," *Eos* 83(16):173.

[414]This case demonstrates how the effects of sea level rise must be considered in a local context that considers multiple physical and ecological factors.



Map 3.5. Potential for Tidal Wetlands along the Delaware Estuary to Keep Pace as Sea Level Rises.
Source: Titus et al. (Section 2.2), using science assessment of Reed et al. (Section 2.1)

marshes might be encouraged, such as undeveloped agricultural lands and natural woodlands.

Implications of Habitat Change

The loss of tidal marsh as sea level rises would harm species that depend on these habitats for food, shelter, or spawning and nursery habitat, including macroinvertebrates, finfish, and wintering waterfowl. Although effects on marsh biota have not been studied directly, current understanding of marsh ecology suggests that changes within the marsh will affect the ecology of not only the marsh itself but also the entire estuary.[415]

Many bird species use or depend on these marshes, including great blue herons, black duck, blue and green-winged teal, northern harrier, osprey, rails, red winged blackbirds, widgeon, and shovelers. Aquatic species such as diamondback terrapin, blue crab, killifish, mummichog, perch, weakfish, flounder, bay anchovy, silverside, herring, and rockfish rely on tidal marshes for a nursery area or for feeding on mussels, fiddler crabs, and other invertebrates.[416]

Research indicates that fishes and birds feeding in the marsh are critical for the export of marsh production to the wider estuarine food web.[417] Any reduction of cordgrass habitat would probably reduce populations of the important macroinvertebrate species. Macroinvertebrates associated with cordgrass stands in the low intertidal include grass shrimp, ribbed mussel, coffee-bean snail, and fiddler crabs.[418] 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.[419] In turn, the depletion of these organisms would reduce the numbers of marsh birds. Wading birds such as the glossy ibis feed on marsh invertebrates.[420] Waterfowl, particularly dabbling ducks, use low marsh areas as a wintering ground. The black duck is already in decline, and is considered a species of special concern by EPA's Delaware Estuary Program.[421] The winter snow goose population in the bay is currently the largest population in the eastern flyway, and a primary source of food for snow geese is the root system of the smooth cordgrass.[422] Diamondback terrapin, listed as a species of conservation concern by the Northeast Regional Technical Committee and as a species of greatest conservation need in Delaware's Wildlife Action Plan, would also be impacted both by loss of wetlands, which are nursery areas for young turtles, and by loss of nesting beaches.

Tidal creeks and shallow water areas of the low marsh provide spawning and nursery areas for finfish that are seasonal residents, year-round residents, and transients from the wider estuary that enter tidal marshes only periodically. The most common fish species of the marsh are mummichog, spot, white perch, Atlantic menhaden, Atlantic silverside, bay anchovy, and sheepshead minnow. [423] The abundance of these species may be affected not only by a loss of habitat but also by reductions in invertebrate food supplies.

High marsh is an important habitat for raptors such as the short-eared owl and for various species of songbirds that breed or pass through the high marsh during their migrations to northern breeding areas.[424] Seaside sparrows are characteristic of cordgrass areas, and sharp-tailed sparrows are more common in upland areas dominated by salt hay.[425] If marsh migration is

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[415]Kneib, R.T., 2000, "Salt marsh ecoscapes and production transfers by estuarine nekton in the southeastern United States," in Weinstein and Kreeger, pp. 267–292 (see note 410).
[416]See Dove and Nyman, 1995 (see note 14).
[417]Deegan, L.A., J.E. Hughes, and R.A. Rountree, 2000, "Salt marsh ecosystem support of marine transients," in Weinstein and Kreeger, pp. 333–368 (see note 410); and Kneib, 2000 (see note 415).
[418]Kreamer, 1995, pp. 81–90 (see note 19); and Kreeger, D. A. and R. I. E. Newell, 2000, "Trophic complexity between primary producers and invertebrate consumers in salt marshes," Chapter 11 in Weinstein and Kreeger, pp. 183–216 (see note 410).
[419]Kreamer, 1995, pp. 81–90 (see note 19).
[420]See Dove and Nyman, 1995 (see note 14).
[421]Ibid.
[422]Ibid.
[423]Rountree and Able, 1992 (see note 22).
[424]See Dove and Nyman, 1995 (see note 14).
[425]Ibid.

impeded by shoreline protection structures and the area of high marsh is reduced, birds of the high marsh will decline and species already in low numbers may be lost.

Beaches

Sandy beaches and foreshores account for 54 percent of the Delaware and New Jersey shores of Delaware Bay, respectively (see Table 3.1). Table 3.1 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 shores are armored or if the land behind the existing beach has too little sand to sustain a beach as the shore retreats.[426] So far, only 4–6 percent of the natural shore had been replaced with shoreline armoring. Another 15 and 4 percent of the shore is developed. However, planners expect that approximately half of (nonwetland) shores will eventually require some sort of shore protection. Although conservation areas encompass 58 percent of Delaware Bay's shores, they include only 32 percent of beaches that are optimal or suitable habitat for horseshoe crabs.

Many Delaware Bay beaches have a relatively thin veneer of sand. Although these small beaches have enough sand to protect the marshes immediately inland from wave action, there is some question about whether some beaches would survive accelerated sea level rise even without shoreline armoring.

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 armored shores. In a few cases, Delaware has nourished beaches with the primary purpose to restore horseshoe crab habitat.[427]

he loss of Delaware Bay's beaches would harm horseshoe crabs, migratory birds, and other wildlife. For example, on their annual migrations from South America to the Arctic, nearly a million shorebirds move through Delaware Bay, where they feed heavily on infaunal benthic invertebrates in tidal mudflats (see subsequent discussion) and particularly on horseshoe crab eggs on the bay's sandy beaches and foreshores.[428] The Delaware Estuary is home to the largest spawning population of horseshoe crabs in the world, and although these animals can lay eggs in tidal marshes, their preferred nesting sites are the mid- and high intertidal zones of sandy beaches. Map 3.6 depicts the suitability of the Delaware Bay shore for horseshoe crab habitat. A sea level rise modeling study estimated that a 2-ft rise in relative sea level over the next century could reduce shorebird foraging areas in Delaware Bay by 57 percent or more by 2100,[429] with likely impacts to horseshoe crabs as well. If these foraging habitats are lost and prey species such as horseshoe crab decline, there could be substantial reductions in the numbers of shorebirds supported by the bay.[430]

Numerous other animals rely on the sandy beaches of Delaware Bay to lay eggs or forage on invertebrates such as amphipods and clams. These include diamondback terrapins, Kemp's and Ridley sea turtles, red fox, raccoons, and opossum. When tides are high, numerous fish also forage along the sandy beaches, such as killifish, mummichogs, rockfish, perch, herring, silversides, and bay anchovy.

Tidal Flats

Areas of exposed tidal flats in Delaware Bay occur between mean sea level (MSL) and mean low water, and extend primarily along the bay's shorelines. Intertidal flats are known to be important foraging areas for finfish as

[426]Cites in Nordstrom, 2005 (see note 153).
[427]See, e.g., Smith et al., 2002 (see note 155).
[428]Smith et al., 2002 (see note 155).
[429]Galbraith et al., 2002 (see note 50).
[430]Ibid.

Table 3.1: The Shores of Delaware Bay: Habitat Type, Likelihood of Shore Protection, and Conservation Status of Shores Suitable for Horseshoe Crabs

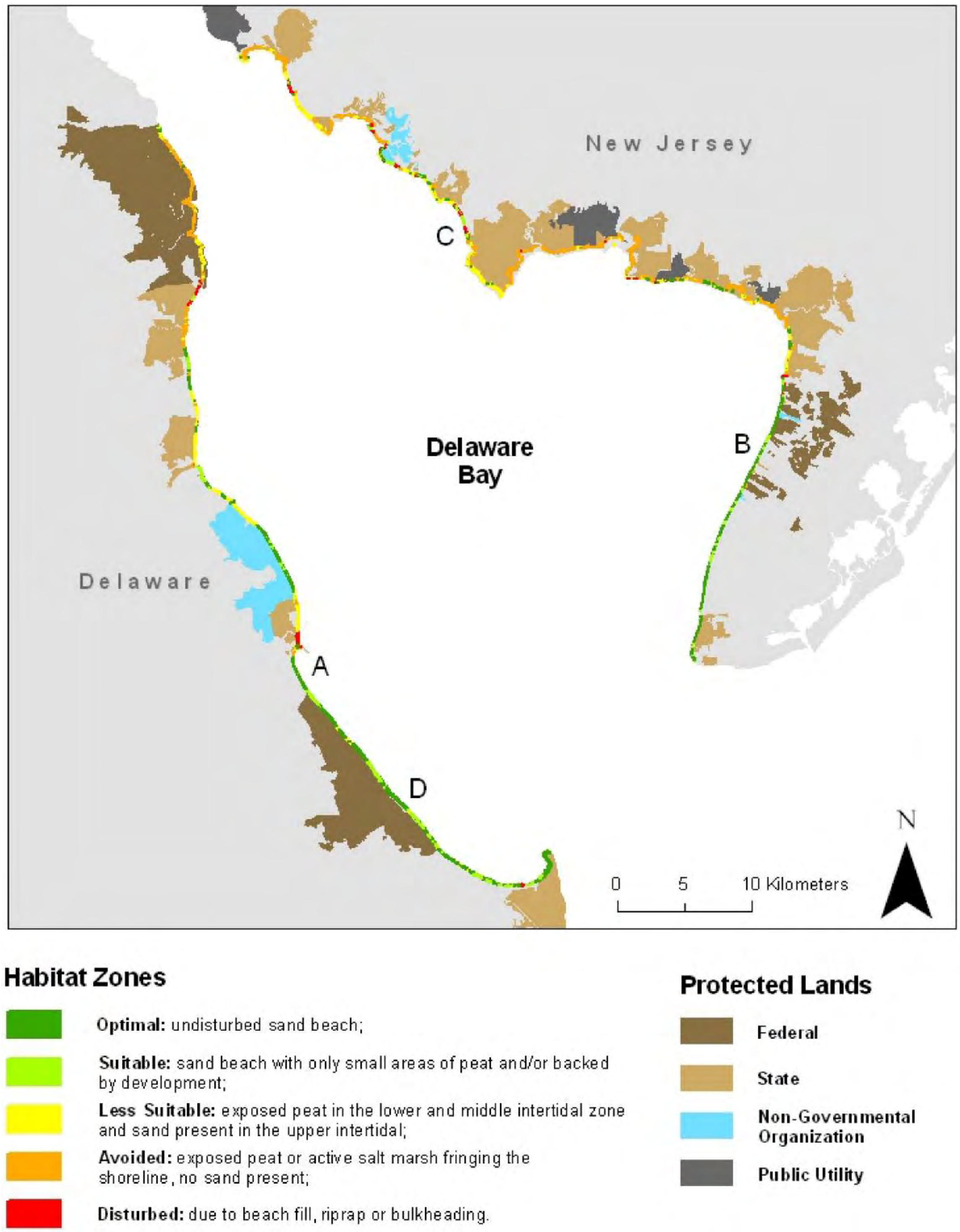
Shoreline Length	**Delaware**		**New Jersey**		**NJ+DE**
…by Habitat Type (percentage of bay shoreline)[a]	km	%	km	%	%
Beach	68	74	62	42	54
Armored Shore	3.7	4	8.3	6	5
Organic	20	22	78	53	41
Total Shoreline	91	100	148	100	100
…by Indicators of Future Shore Protection					
Protection Structures set back from shore[a]	2.7	2.9	5.1	3.4	3
Development[a]	13	15	5.7	3.8	8
...by Likelihood of Shore Protection (percentage of nonwetland shores)					
Shore Protection Almost Certain	35	45	17	29	39
Shore Protection Likely	4	5	3	5	5
Shore Protection Unlikely	17	22	18	31	26
No Shore Protection	21	27	20	34	30
…by Suitability for Horseshoe Crab (percentage of bay shoreline)					
Optimal Habitat[b]	31.3	34	26.0	18	24
Suitable Habitat[b]	10.5	12	5.1	3.5	6.6
Less Suitable Habitat[b]	29.0	32	49.0	33	33
Unsuitable Habitat[b]	20.0	22	67.0	46	37
…Within Conservations Lands by Suitability for Horseshoe Crab (percentage of equally suitable lands)					
Optimal Habitat[c]	12.9	41	9.6	37	39
Optimal and Suitable Habitat[c]	13.6	33	9.8	32	32
Optimal, Suitable, and Less Suitable Habitat[c]	32.2	46	43.3	54	50
All Shores[c]	44.7	49	92.7	63	58

[a] Delaware and New Jersey results from Lathrop et al., Table 8 (see text note 409).
[b] Delaware and New Jersey results from Lathrop et al. (see text note 409) at p.16, Table 9. "Unsuitable" includes both "avoided" and "disturbed."
[c] From Lathrop et al. (see text note 409) at p.18, Table 1. Lathrop et al. report results for the categories separately; we aggregate the categories.

well as migrating shorebirds, including red knot, ruddy turnstone, sanderling, and semipalmated sandpiper.[431] Although the benthic ecology of the system is poorly described, rich mudflat communities of polychaetes and bivalves are thought to sustain blue crabs, grass shrimp, killifish, mummichogs, rockfish, perch, herring, bay anchovy, skates, rays, black ducks, blue and green-winged teal, mallards, northern harriers, rails, and great blue herons. These communities are characteristic of the lower estuary region and Delaware Bay where salinities are greater than about 10 ppt. In the lower salinity areas, polychaetes are replaced with oligochaetes on the mudflats. At low tide, numerous mammals forage on mudflats, such as muskrat, opossum, raccoon, and red fox. Beyond their trophic roles, the ecological importance of these shallow subtidal and intertidal habitats is not well understood in the Delaware Estuary, where little research and assessment has been devoted to aquatic bottom habitats.[432] The greatest loss of mud flats generally occurs where migration is prevented by the presence of shore protection structures. In the Delaware Estuary, extensive mudflats exist in many areas, particularly along sections of the Delaware coastline and within some of the larger marshland tracts in New Jersey.

[431]Dove and Nyman, 1995 (see note 14).

[432]Kreeger, D., R. Tudor, J. Sharp, S. Kilham, D. Soeder, M. Maxwell-Doyle, J. Kraeuter, D. Frizzera, J. Hameedi and C. Collier,. 2006, White Paper on the Status and Needs of Science in the Delaware Estuary, Partnership for the Delaware Estuary Report #06-01, 72 pp. Accessed on November 2, 2006 at http://www.delawareestuary.org/scienceandresearch/datasetsandreports/localandregional.asp.



Map 3.6. Delaware Bay Shore: Conservation Status and Suitability for Horseshoe Crabs
Source: Lathrop et al. (see text note 409).

Shallow Waters

Although the direct effect of sea level rise will be to deepen these waters, shallow water habitat may increase if wetlands convert to open water. Therefore, we cannot currently say whether this type of habitat will increase or decrease.

Even if we knew the direction of change, the resulting impacts on the fish and shellfish of Delaware Bay have not been studied. Nevertheless, many of the finfish and shellfish species of nearshore waters and the shore zone are well known, and habitat changes and loss of habitat area affect species distribution, diversity, and abundance. One of the best known and most popular species of the nearshore waters is the blue crab, *Callinectes sapidus*. Another signature species in the shallow waters of the Delaware Estuary is the eastern oyster, *Crassostrea virginica.* It is not clear how sea level rise might affect these animals, but in the case of oyster reefs there is some concern that natural reef-building is not occurring fast enough to sustain population losses from a variety of other factors.[433]

De Sylva et al. conducted an extensive survey of finfish in the Delaware Estuary, and found that bay anchovy, alewife, Atlantic menhaden, striped bass, hogchoker, and Atlantic croaker use these shallow waters as a nursery area.[434] Other species, including blueback herring, mummichog, banded killifish, silverside, and white perch, spawn in these nearshore areas and move in and out of tidal marshes. Blueback herring spawn in shallow waters of creeks over sand or gravel substrate. The ocean-going bluefish moves into the bay in summer, where the young congregate in nearshore areas. Sand, peat/mud, and mud beaches are also important habitat for some fish species, including alewife, American.

[433]Ibid.

[434]De Sylva, D.P., F.A. Kalber Jr., and C.N. Shuster, 1962, Fishes and Ecological Conditions in the Shore Zone of the Delaware River Estuary, with Notes on Other Species Collected in Deeper Waters. Information series, Publication No. 5, University of Delaware Marine Laboratories, Lewes.

3.8. Maryland and Delaware Coastal Bays

Author: **Elizabeth M. Strange, Stratus Consulting Inc.**

Species and habitats along in the back-barrier bays of Maryland and Delaware (hereafter referred to collectively as the Coastal Bays) are potentially at risk because of sea level rise. 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). The shorelines of the Coastal Bays contain important habitats for a variety of fish, shellfish, and birds, and a great deal is known about their ecology and habitat needs. Based on existing literature and the knowledge of local scientists, this brief literature review discusses the coastal species in the region that could be at risk because of further habitat loss resulting from sea level rise (see Section 3.1, Overview) and shoreline protection (see Map 3.7). Although it is possible to make qualitative statements about the possible impacts if sea level rise causes a total loss of habitat, our ability to discern what the impact might be if only a portion of the habitat is lost is more limited. A total loss of habitat is possible if shores are protected with hard structures and the wetlands are unable to keep pace with sea level rise.

Back-Barrier Salt Marshes

There are an estimated 6,718 ha (16,600 acres) of salt marsh along Maryland's Coastal Bays, mostly along the mainland shorelines of Sinepuxent, Newport, and Chincoteague bays; there are about 1,012 ha (2,500 acres) of salt marsh in the northern bays.[435] There are an estimated 5,510 ha (13,600 acres) of vegetated estuarine wetlands in the Delaware Inland Bays, most of which are tidal salt marshes.[436] These tidal salt marshes are mostly fringing marshes, but there are also large acreages of back-barrier marshes, especially in Rehoboth Bay.[437]

The Delaware's Inland Bays provide one of the few areas in Delaware for colonial nesting waterbirds, including herons, egrets, gulls and terns. The rate of development within the bays' drainage and associated shoreline hardening would likely severely limit marsh migration during sea level rise. Loss of the fringing marshes and islands of the bays would significantly reduce or eliminate nesting habitat for these species in Delaware.[438]

The Maryland Coastal Bays Program considers shoreline erosion due to sea level rise and shoreline hardening major factors contributing to a decline in the amount of natural shoreline habitat available for estuarine species in the

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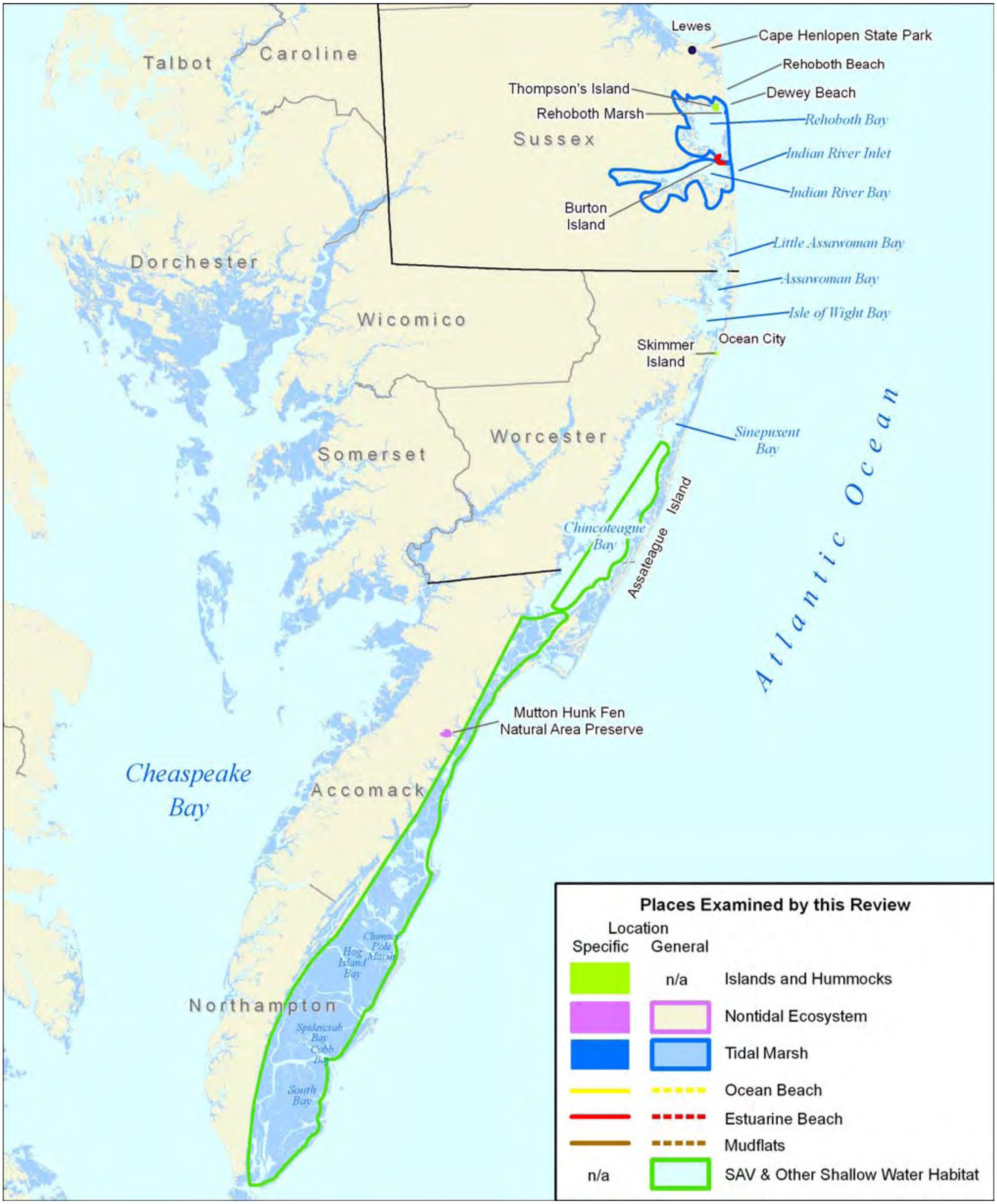
[435] Bleil, D., D. Clearwater, and B. Nichols, 2005, "Status of the wetlands in the Maryland coastal bays," Chapter 6.4 in Wazniak, C.E., and M.R. Hall (eds.), 2005, *Maryland's Coastal Bays: Ecosystem Health Assessment 2004*, DNR-12-1202-0009, Maryland Department of Natural Resources, Tidewater Ecosystem Assessment, Annapolis, MD, p. 6-33.

[436] Tiner, R.W., 2001, Delaware's Wetlands: Status and Trends. U.S. Fish and Wildlife Service, Ecological Services, Region 5, Hadley, MA. Prepared for the Delaware Department of Natural Resources and Environmental Control, Watershed Assessment Section, Division of Water Resources, Dover, DE. Cooperative National Wetlands Inventory Publication, Figure p. 9, text p. 16.

[437] Chris Bason, Center for the Delaware Inland Bays, email communication to Karen Scott, EPA, 5/14/07 (personal visual observation).

[438] Kevin Kalasz, wildlife biologist, Natural Heritage & Endangered Species Program, Delaware Division of Fish and Wildlife, in email entitled Opportunity to comment on U.S. EPA-sponsored papers related to sea level rise and related impacts on habitat and species, to Karen Scott of EPA, 2/16/07 (expert judgment based on official duty).



Map 3.7. Locations and Types of Habitat Discussed in this Report: Atlantic Coast of the Delmarva Peninsula

northern bays.[439] There has been significant shoreline hardening in Maryland's northern coastal bays (Isle of Wight and Assawoman), but little or no hardening in the three southernmost bays (Sinepuxent, Newport, and Chincoteague).[440] Planners expect shores in the southern part of Maryland's coastal bays to remain unprotected. Where natural shorelines remain, marshes in low-lying areas may expand inland as seas rise. 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.[441] Armoring of 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 ha (1,500 acres) of salt marshes have already been lost in the Coastal Bays as a result of shoreline development and stabilization techniques.[442]

Loss of marshes will reduce habitat for many bird species that use the marshes for roosting, nesting, or foraging. Such species include black-bellied plover, dunlin, and horned grebe, wading birds such as herons and egrets, migratory shorebirds, rail species, including Virginia, king, and clapper rails, and many species of waterfowl.[443] Ducks and geese, including mallards, pintails, blue and green winged teals, gadwalls, canvasbacks, loons, buffleheads, mergansers, and golden eyes, overwinter in the bays' marshes.[444] A large colony of American brant winters in Rehoboth and Indian River bays.[445] The Rehoboth marsh is known as an important area for colonies of nesting shorebirds and a food source for young birds.[446] The bays' marshes also provide nesting habitat for many species of concern to federal and state agencies, including northern harrier, 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. There is particular concern for Forster's tern because most of its breeding range is in the salt marshes of the mid-Atlantic.[447]

Marsh loss will also reduce habitat for resident and transient fish and shellfish species. Marsh resident fishes include mummichog, Atlantic silverside, and naked goby. A number of marine transients, including recreationally and commercially important species such as black drum, striped bass, bluefish, Atlantic croaker, sea trout, and summer flounder, depend on the marshes for spawning and nursery habitat. Important forage fish that move into the bays for spawning include spot, menhaden, silver perch, and bay anchovy, which are currently declining all along the Atlantic Coast. Shellfish species found in the bays' marshes include clams, oysters, shrimps, ribbed mussels, and blue crabs.[448]

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[439] Maryland Coastal Bays Program, 1999, *Today's Treasures for Tomorrow: Towards a Brighter Future; The Comprehensive Conservation and Management Plan for Maryland's Coastal Bays*, Maryland's Coastal Bays Program, Berlin, MD, Final Draft, June, p. 45.

[440] Hennessee, L., 2005, Status of the shorelines in the Maryland coastal bays, Chapter 6.5 in Wazniak and Hall (see note 435), p. 6-42.

[441] Maryland Coastal Bays Program, 1999, p. 6 (see note 439).

[442] Maryland Coastal Bays Program, 1999, p. 67 (see note 439).

[443] Dave Wilson, Maryland Coastal Bays Program. In June 13, 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.)

[444] "Discover Delaware's Inland Bays," n.d., fact sheet, Document No. 40-01-01/03/03/01 produced with funding from NOAA by the Delaware Department of Natural Resources and Environmental Control, Delaware Coastal Programs. Available at: www.dnrec.state.de.us/dnrec2000/Library/Misc/InlandBays.pdf; and personal observations of Chris Bason (see note 437).

[445] "Discover Delaware's Inland Bays" (see note 444).

[446] Delaware Inland Bays Comprehensive Conservation and Management Plan, June 1995, Chapter 2: The State of the Inland Bays, p. 86.

[447] Erwin et al., 2006, p.16 (see note 58).

[448] Casey, J., and S. Doctor, 2005, Status of finfish populations in the Maryland Coastal Bays, Chapter 8.4 in Wazniak and Hall (see note 435), p. 8-34.

Forested Wetlands

Forested wetlands occur along both tidal and nontidal creeks. Increasing instances of crown dieback and tree mortality in these wetlands are generally considered a result of sea level rise and an upstream shift in the salinity gradient. Where inland migration is not possible, the understory is being filled in with marsh plants, resulting in loss of tree habitats that are critical for many bird species, including bald eagles and a variety of breeding songbirds.[449]

Sea Level Fen

A rare sea level fen vegetation community grows in the Angola Neck Natural Area along Rehoboth Bay.[450] This extremely rare type of coastal wetland grows only under the unusual circumstances where there is a natural seep from a nearby slope providing nutrient-poor groundwater to support its unique vegetation and where there is protection from nutrient-rich tidal flow (see Section 3.1, Overview, for detailed description of sea level fens).[451] 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.

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 in the Delaware Inland Bays, especially within Assawoman Wildlife Management Area on Little Assawoman Bay.[452]

Back-Barrier Beaches

The back-barrier beaches of the Coastal Bays have a number of important ecological functions. Horseshoe crabs spawn on these beaches,[453] and their eggs are an important food source for migrating shorebirds in spring.[454] *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 limits dune migration and the formation of interdunal swales. Local ecologists favor research to ascertain whether protecting infrastructure from sea level rise might also increase erosion and further limit the formation of new interdunal swales.[455]

Northern diamondback terrapin spend most of their time in the marsh creeks and open waters of the Coastal Bays, but move onto the back-barrier beaches to nest and deposit their eggs along the upper beach.[456] Diamondbacks nest on back-barrier beaches and most types of estuarine beaches. In Delaware, they are known to next on beaches of Burton Island.[457] They also regularly nest in residential areas, which may result from their natal imprint leading them back to former dune habitat that is now developed.[458] A natural instinct to get to the most suitable nesting habitat in the dunes nearer the ocean may be the reason some terrapins cross Route 1.[459] This has become a major management concern because many are killed by traffic.[460]

Loss of additional beach habitat due to sea level rise and erosion below bulkheads and other protective structures could have a number of negative consequences for species that use these beaches for egg-laying, foraging, or other critical

[449] Gary Fleming (personal visual observation) (see note 76).
[450] Delaware Department of Natural Resources and Environmental Control, Inland Bay Report. Accessed December 5, 2007 at: http://www.dnrec.state.de.us/DNREC2000/Admin/WholeBasin/InlandBays/living.pdf.

[451] Westerfelt, K., E. Largay, R. Coxe, W. McAvoy, S. Perles, G. Podniesinski, L. Sneddon, and K. Starkosch Walz, 2006, *A Guide to the Natural Communities of the Delaware Estuary*: *Version 1*, NatureServe, Arlington, VA, p. 258.
[452] Kevin Kalasz (see note 438) (personal visual observation) and Chris Bason (see note 437) (personal visual observation).

[453] Dave Wilson, personal visual observation (see note 443).
[454] Delaware Audubon Society. *Important Bird Areas in the Delaware*. Summary available at: http://www.delawareaudubon.org/birding/globaliba.html.
[455] Kevin Kalasz (see note 438).
[456] Dave Wilson (personal visual observation (see note 443).
[457] "Discover Delaware's Inland Bays" (see note 444).
[458] Chris Bason (personal visual observation) (see note 437).
[459] Ibid.
[460] "Discover Delaware's Inland Bays" (see note 444).

activities. Because terrapins bury their eggs deep within sandy sediment, where the eggs are protected against predators and other dangers, it is unlikely that they could reproduce in alternative habitats where it is more difficult to dig into the sediment to bury their eggs. Horseshoe crabs rarely spawn unless sand is at least deep enough to nearly cover their bodies, about 10 cm (4 in.).[461] 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.[462]

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 amphipod crustaceans such as fleas and beach hoppers that provide food for many species, including migrating shorebirds.[463] In addition, horseshoe crab eggs are sometimes ensnared in the wrack, where they are more accessible to foraging shorebirds.[464] Loss of wrack will decrease these food sources (for a more detailed description, see Section 3.1, Overview).

Tidal Flats

Tidal flats are found at the seaward edge of the shorelines of both the Delaware and Maryland Coastal Bays. The benthic invertebrates of tidal flats typically include bivalves, small crabs, worms, and snails, which are important forage for shorebirds.[465]

The low-lying coastal plain and the fine unconsolidated sediments of the bays makes their tidal flats particularly susceptible to inundation from sea level rise.[466] 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, which will further increase sediment deposition and lead to an increase in low marsh and a reduction in tidal flats.[467] Where sediment deposition is comparatively low, marsh may revert to unvegetated flat, at least in the short term, before the area becomes fully inundated.[468]

Reduction in the area of tidal flats will reduce invertebrate food supplies for wading birds, shorebirds, and dabbling ducks such as mallards and the American black duck. As rising seas cover flats with more and more water, they will become less available to foraging species, particularly short-legged shorebirds.[469] Tidal flats are critical for migrating shorebirds. Some researchers predict that as inundation increases and the area of tidal flats declines, increased crowding in remaining areas will lead to exclusion and mortality of shorebirds.[470]

Shallow Waters and Submerged Aquatic Vegetation (SAV)

There are currently about 4,629 ha (11,438 acres) of SAV in Maryland's coastal bays, mostly eelgrass. Nearly 85 percent of eelgrass beds are found along the bayside of Assateague Island. Eelgrass in Maryland's coastal bays is generally limited to a maximum depth of about 1.5 m (5 feet).[471] Thus, unless conditions change, a 50–100 cm (20–40 in.) rise in sea level could potentially make areas where water depths are greater than 50–100 cm (20–40 in.) inhospitable to SAV.[472]

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[461]Weber, R.G., 2001, Preconstruction horseshoe crab egg density monitoring and habitat availability at Kelly Island, Port Mahon, and Broadkill Beach Study areas, Prepared for the Philadelphia District Corps of Engineers, Philadelphia, PA, p. 4.
[462]Doctor, S., and C.E. Wazniak, 2005, "Status of horseshoe crab, *Limulus polyphemus,* populations in Maryland coastal bays," Chapter 8.7 in Wazniak and Hall (see note 435), p. 8-92.
[463]Dugan et al., 2003, p. 32 (see note 127).
[464]Jackson et al., 2002, p. 418 (see note 139).
[465]Burger, J., L. Niles, and K.E. Clark, 1997, "Importance of beach, mudflat, and marsh habitats to migrant shorebirds in Delaware Bay," *Biological Conservation* 79:283–292, p. 284.
[466]Johnson, Z.P., 2000, *A Sea Level Rise Response Strategy for the State of Maryland*, Maryland Department of Natural Resources, Coastal Zone Management Division, p. 9 and Figure 2.
[467]Redfield, 1972 (see note 132).
[468]Brinson et al., 1995, p. 655 (see note 23).
[469]Erwin, no date (see note 136).
[470]Galbraith et al., 2002 (see note 50).
[471]Wazniak, C., L. Karrh, T. Parham, M. Naylor, M. Hall, T. Carruthers, and R.J. Orth, 2005, Seagrass abundance and habitat criteria in the Maryland Coastal Bays, Chapter 6.1 in Wazniak and Hall (see note 435), p. 6-5.
[472]Short and Neckles, 1999, p. 175 (see note 91).

Researchers are uncertain whether the natural overwash process will keep water depths constant by providing enough sediment for the bay bottoms to rise as fast as the sea rises. Nor does anyone know whether inundated marsh on the mainland would be replaced by SAV. As a result, we are unable to say whether SAV in this area will increase or decrease as sea level rises.

The fate of SAV is very important for secondary productivity in the back-barrier bays of Maryland. Eelgrass beds are considered essential habitat for summer flounder and bay scallop and critical habitat for blue crab, which support substantial recreational and commercial fisheries in the coastal bays.[473] Therefore, the possibility of a net loss of eelgrass as sea level rises implies a risk to the local populations of flounder, scallop, and crab that are harvested in the coastal bays of Maryland. SAV is also important for many nongame species such as sticklebacks, pipefishes, and seahorses.

At present, SAV is almost absent from the Delaware Inland Bays because of eutrophication and turbid conditions in the bays' shallow waters.[474] However, reestablishment of eelgrass beds has been successful near Indian River Inlet, where ocean-influenced water quality supports growth.[475] In the future, poor water quality combined with increasing depth with sea level rise could impede SAV recovery in other parts of the bays.

Marsh and Bay Islands

Islands within the coastal bays are important nesting areas for herons, egrets, black skimmers, gulls and terns. Laughing gulls, herring gulls, and great black-backed gulls nest on the marsh islands of Delaware's Inland Bays. Forster's terns nest on dead marsh grasses on the islands.[476]

Marsh islands within the bays are undergoing rapid erosion. Big Piney Island in Rehoboth Bay experienced erosion rates of 30 ft/yr between 1968 and 1981, and is now gone.[477] Little Piney Island is another historical island in Rehoboth Bay that is completely eroded. Currently, Seal Island in Little Assawoman Bay is eroding rapidly after being nearly totally devegetated by greater snow geese.[478] The erosion of the these island and their potential submergence due to an inability to keep pace with sea level rise are of particular concern because these islands protect other natural and developed shorelines and marshes from increased erosion.

Hundreds of horned grebes stage for migration at the north end of Rehoboth Bay near Thompson's Island. Thompson's Island, part of the Delaware Seashore State Park, is located between Rehoboth and Dewey Beach, and is a significant birding area. Located only a half mile from the beach is the last stand of mature forest of white oak and loblolly pine along the Delaware coast. The island has several other habitat zones, including salt marsh. Resident species include some that are difficult to find along the coast, such as hairy woodpecker and belted kingfisher. The island is especially significant as a "migration trap," where migrating birds are funneled onto the island and "trapped" by 7 miles of inland bays and coast.[479]

Royal tern is a species that nests only on low-lying islands.[480] Although royal terns visit Delaware's Inland Bays in the summer, they do not nest there.[481] In the Maryland bays, royal

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[473]Maryland Coastal Bays Program, 1999, p. 56 (see note 439).
[474]Delaware Department of Natural Resources and Environmental Control, 2001, Inland Bays/Atlantic Ocean Basin Assessment Report, June, p. 39.
[475]Delaware Department of Natural Resources and Environmental Control, n.d., Inland Bays/Atlantic Ocean Environmental Profile. Section on Water Quality: Water Resource Issues. Available at: http://www.dnrec.state.de.us/water2000/Sections/Watershed/ws/ib_atlantic_env_profile.pdf.

[476]"Discover Delaware's Inland Bays" (see note 444).
[477]Swisher, M.L., 1982, The rates and causes of shore erosion around a transgressive coastal lagoon, Rehoboth Bay, Delaware, M.S. Thesis, College of Marine Studies, University of Delaware, Newark.
[478]Chris Bason (personal visual observation) (see note 437).
[479]Ednie, A.P., n.d., *Birding Delaware's Prehistoric Past: Thompson's Island at Delaware Seashore State Park*. Available at: http://www.dvoc.org/DelValBirding/Places/ThompsonsIsland.htm.
[480]Buckley, P.A., and F.G. Buckley, 2002, Royal tern (*Sterna maxima*), in Poole and Gill (see note 370).
[481]"Discover Delaware's Inland Bays" (see note 444).

terns nest only on Skimmer Island, which is currently only about 10 cm (4 in) above sea level.

There are numerous small islands in Maryland's Chincoteague Bay. However, stabilization of the Ocean City inlets and efforts by the U.S. Army Corps of Engineers to prevent formation of new inlets have inhibited the natural formation of new islands. The Corps has created many small dredge spoil islands, but most have disappeared as a result of erosion. These islands typically provide good nesting habitat for gulls, egrets, herons, American oystercatchers, glossy ibis, American black duck, American bald eagle, and osprey.[482]

[482]Erwin, 1996, p. 216 (see note 240).

Many of the small islands in the coastal bays are currently eroding, and may disappear altogether as rising seas inundate low-lying areas. Further loss of these islands because of erosion and sea level rise could result in severe reductions in island bird populations.[483]

The highest number of nesting American oystercatchers in Delaware are found nesting in the Inland Bays. They primarily nest on small sandy beaches and wrack on islands. Loss of nesting habitat for this species would dramatically reduce the population of American oystercatcher in Delaware.[484]

[483]Ibid.
[484]Kevin Kalasz (see note 438) (expert judgment based on official duty).

3.9 The Atlantic Side of the Virginia Eastern Shore

Author: ***Elizabeth M. Strange, Stratus Consulting Inc.***

Species and habitats in the tidal marshes of the Atlantic Coast side of the Virginia Eastern shore are potentially at risk because of sea level rise. This region contains the largest stretch of natural coastline along the U.S. Atlantic Coast, almost all of which is owned by either TNC or the federal government. The region includes extensive back-barrier lagoonal marshes and areas of estuarine beach behind a chain of barrier islands. Fringing salt marshes occur on the mainland side of the lagoons.

Based on existing literature and the knowledge of local scientists, this brief literature review discusses the coastal species in the region that could be at risk because of further habitat loss resulting from sea level rise and shoreline protection (see Section 3.1, Overview) (see Map 3.7). Although it is possible to make qualitative statements about the possible impacts if sea level rise causes a total loss of habitat, our ability to discern what the impact might be if only a portion of the habitat is lost is more limited. A total loss of habitat is possible if shores are protected with hard structures and the wetlands are unable to keep pace with sea level rise.

Back-Barrier Salt Marshes

Salt marsh adaptation to sea level rise. Salt marshes occupy thousands of acres in eastern Accomack and Northampton counties.[485] 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 (see Section 2.1). 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,[486] and the average relative sea level rise along the Eastern Shore is estimated as 2.8–4.2 mm/yr.[487]

The dominant accretion processes in eastern Accomack and Northampton counties are storm sedimentation and overwash from the beaches of the barrier islands. A panel of accretion experts recently suggested that if the rate of sea level rise increases by 2 mm/yr, the survival of marshes in this area will depend on the future frequency of storms supplying sediments (see Section 2.1). Other scientists have suggested that the ability of the marshes of the Eastern Shore to keep pace may be constrained by the generally low sediment supply provided by the small watersheds of the area.[488,489] In 2004, annual losses of 0.2 and 0.67 percent were reported for Curlew Bay and Gull Marsh, respectively, mostly as a result of perimeter erosion to open water.[490] However, in Mockhorn Wildlife Refuge in southern Northampton County, where elevations are lower, sediments have accumulated in shallow waters, and low marsh is encroaching on adjacent tidal flats.[491,492]

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[485]Fleming et al., 2006 (see note 67).

[486]Kastler, J.A., and P.L. Wiberg, 1996, "Sedimentation and boundary changes of Virginia salt marshes," *Estuarine, Coastal and Shelf Science* 42:683–700, p. 691.

[487]May, M.K., 2002, Pattern and Process of Headward Erosion in Salt Marsh Tidal Creeks, Master's Thesis, Department of Biology, Eastern Carolina University, Greenville, NC, p. 4, reviewing the findings of G.F. Oertel, T.F. Wong, and J.D. Conway, 1989, "Sediment accumulation at a fringe marsh during transgression, Oyster, Virginia., *Estuaries* 12:18–26, and B.P. Hayden, D. Dueser, J.T. Callahan, and H.H. Shugart, 1991, "Long-term research at the Virginia Coast Reserve," *BioScience* 41:310–318.

[488]Christiansen, T., P.L. Wiberg, and T.G. Milligan, 2000, "Flow and sediment transport on a tidal salt marsh surface," *Estuarine, Coastal and Shelf Science* 50:315–331, p. 324.

[489]Reed et al., 2008, Section 2.1.

[490]Erwin et al., 2004, p. 891 (see note 16).

[491]Erwin et al., 2006 (see note 58).

Most wetlands are able to keep pace with rising sea level today, become marginal with an acceleration of 2 mm/year, and would be lost with a more substantial acceleration (see Reed et al., Section 2.1). Shore protection is unlikely along much of the mainland opposite the barrier islands and lagoonal marshes. In those unprotected areas, marshes are likely to migrate inland into low-lying areas. Kastler and Wiberg found that from 1938 to 1990 mainland salt marshes on the Eastern Shore increased in area by 8.2 percent, largely as a result of encroachment of salt marsh into upland areas.[493]

Sea level rise may also contribute to invasion by the common reed (*Phragmites*), which provides lower quality habitat. Higher sea levels cause groundwater discharge to migrate upslope with greater volume. Common reed can invade where this discharge flows over the marsh surface, providing lower salinity habitat.[494]

Impacts on fish and wildlife. Sea level rise is considered a major threat to bird species in this area, which is known as the Virginia Barrier Island/Lagoon Important Bird Area (IBA).[495] 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.[496] The USFWS considers black rail and both sparrow species "birds of conservation concern" because populations are already declining in much of their range.[497] A study of Virginia marshes found that the number of bird species was 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).[498]

A diversity of resident and estuarine and marine transient fish species move in and out of marshes with the tides to take advantage of the abundance of decomposing plants in the marsh and refuge from predators.[499] Marine transients include recreationally and commercially important species, including black drum, striped bass, bluefish, and Atlantic croaker. A study in Virginia showed that nekton abundance and diversity is greater in fringing marsh than along intertidal shorelines that are armored.[500]

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. More water on the marsh surface may also provide some benefits. For example, in the salt marshes of the Eastern Shore, resident fishes such as common mummichog and spotfin killifish, and invertebrates such as grass shrimp, forage in shallow waters on the marsh surface to take advantage of an underutilized food source and to avoid predators.[501] However, where marshes drown, the loss of marsh primary production will impair the value of the habitat for fish and shellfish. Virginia's highly valued commercial and recreational fishing industry may be harmed if fish and shellfish production declines in these areas.

Sea Level Fen

A globally rare sea level fen community—one of only four in Virginia—is found in the Mutton Hunk Fen Natural Area Preserve fronting

[492]Erwin et al., 2004, p. 891 (see note 16).
[493]Kastler and Wiberg, 1996 (see note 486).
[494]Barry Truitt (see note 360).
[495]Watts, B.D., 2006, Synthesizing Information Resources for the Virginia Important Bird Area Program: Phase I, Delmarva Peninsula and Tidewater, Center for Conservation Biology Technical Report Series, CCBTR-06-05, College of William and Mary, Williamsburg, VA, p. 6.
[496]Erwin et al., 2004, p. 901 (see note 16).
[497]USFWS, 2002, Birds of Conservation Concern 2002, Division of Migratory Bird Management, Arlington, VA, Table 30. Available at: http://www.fws.gov/migratorybirds/reports/reports.html.
[498]Watts, 1993 (see note 61).
[499]See general discussions in Boesch and Turner, 1984 (see note 318); and Kneib, 1997 (see note 17).
[500]Carroll, R.A., 2002, Nekton utilization of intertidal fringing salt marsh and revetment hardened shorelines, M.S. Thesis, School of Marine Sciences, College of William and Mary, Williamsburg, VA.
[501]Yozzo, D.J., A. Mannino, and D.E. Smith. 1994. "Mid-summer abundance of resident sub-adult marsh nekton at the Virginia Coast Reserve," *Virginia Journal of Science* 45:21–30, as cited by Layman, C.A., 2000, "Fish assemblage structure of the shallow ocean surf zone on the Eastern Shore of Virginia Barrier Islands," *Estuarine, Coastal, and Shelf Science* 51:201.

Gargathy Bay in eastern Accomack County.[502] This extremely rare type of coastal wetland grows only under the unusual circumstances where there is a natural seep from a nearby slope providing nutrient-poor groundwater to support its unique vegetation, and where there is protection from nutrient-rich tidal flow (see Section 3.1 for more description of sea level fens). 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.[503] 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.[504] On the other hand, sea level rise could cause groundwater discharge to increase in volume at some locations, which would benefit fens.[505]

Back-Barrier Beaches

The beaches on the mainland behind the barrier island complex of the Eastern Shore are small strips of beach 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, the many invertebrates that burrow in the sand and species that spawn on beaches will lose critical habitat. Rare species that have sometimes been observed on these beaches include the northern diamondback terrapin and the northeastern tiger beetle.[506]

Tidal Flats

CCSP submissions by the USGS will address the likelihood that sea level rise will reduce the area of tidal flats in areas with naturally low sediment supplies like the Eastern Shore. Loss of tidal flats would eliminate a rich invertebrate food source for migrating birds such as whimbrels, dowitchers, dunlins, black-bellied plovers, and semipalmated sandpipers.[507]

Shallow Waters and Submerged Aquatic Vegetation (SAV)

Natural eelgrass beds occur in a number of areas along the sea side of the Eastern Shore, and are most abundant in Chincoteague Bay. There are also some successful eelgrass restoration projects in South Bay, Cobb Bay, Hog Island Bay, and Spider Crab Bay.[508] The potential effects of sea level rise on eelgrass beds have not been studied directly. However, Short and Neckles 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 percent, resulting in a 30–40 percent reduction in SAV growth.[509] Where this may occur in the nearshore waters of eastern Northampton and Accomack counties would depend on current local conditions such as water depth, the maximum depth of eelgrass growth, and water clarity. A local expert with The Nature Conservancy suggests that because eelgrass is at the southern limit of its range in the Coastal

[502] Fact sheet by Virginia Department of Conservation and Preservation on the Mutton Hunk Fen Natural Area Preserve. Accessed December 5, 2007 at: http://www.dcr.virginia.gov/natural_heritage/natural_area_preserves/muttonhunk.shtml.

[503] Virginia Department of Conservation and Recreation, 2001, The Natural Communities of Virginia, Ecological Classification of Ecological Community Groups, First Approximation, Division of Natural Heritage Natural Heritage Technical Report 01-1, p. 48.

[504] Mutton Hunk Fen Natural Area Preserve Fact Sheet (see note 502).

[505] The authors would like to thank reviewer Barry Truitt for pointing this out (see note 360).

[506] See information on these species and their status in Virginia, provided in Chapter 3: Refuge and Resource Descriptions (specifically pages 3-20 and 3-32) of USFWS, 2004, Eastern Shore of Virginia and Fisherman Island Nation Wildlife Refuges Comprehensive Conservation Plan, Northeast Regional Office, Hadley, MA, available at: http://library.fws.gov/CCPs/eastshoreVA_index.htm.

[507] The Nature Conservancy project profile for the Virginia Coast Reserve, 2006, available by searching on "field guides" at http://www.nature.org/wherewework. See also Watts, B.D., and B.R. Truitt, 2000, "Abundance of shorebirds along the Virginia barrier islands during spring migration," *Raven* 71:33–39.

[508] Information provided in July 12, 2006, email to E. Strange of Stratus Consulting from Scott Lerberg of the Virginia Seaside Heritage Program. Orth, R. J., M. L. Luckenbach, S. R. Marion, K. A. Moore. and D. J. Wilcox, in press, "Recovery of the seagrass *Zostera marina* (eelgrass) in the Delmarva Coastal Bays, USA," *Aquatic Botany*.

[509] Short and Neckles, 1999 (see note 91).

Bays, global warming may be a greater factor in its persistence than light reduction.[510]

Loss of eelgrass beds could harm local populations of birds, fish, and shellfish. Various waterbirds feed on eelgrass beds, including brant, canvas back, and American black duck.[511] Virginia's commercial and recreational fisheries include many estuarine and marine species that rely on eelgrass for nursery habitat.[512] A number of highly valued shellfish species are also found here, including bay scallop, hard clam, and blue crab.

Marsh and Bay Islands

Several bird species of concern in Virginia and elsewhere along the Atlantic Coast, including gull-billed terns, common terns, black skimmers, and American oystercatchers, nest on shellpiles on marsh islands.[513] The advantage of this is that the shellpiles are generally free of mammalian predators. However, marsh islands are also subject to tidal flooding, which is known to reduce the reproductive success of island-nesting birds.[514] Therefore, as islands experience more erosion and flooding as a result of sea level rise, local populations of island-nesting birds may decline.

Island shrinking is already apparent along the Eastern Shore. From 1949 to 1990, Chimney Pole marsh showed a 10 percent loss to open water.[515] Chimney Pole marsh is directly inside Quinby Inlet and subjected to high energy wave action during storms. As early as the mid-1990s, gull-billed tern nests on Chimney Pole Island were only a foot above the June high water mark, indicating its vulnerability to even relatively low increases in rates of sea level rise.[516]

Coastal Habitat for Migrating Neotropical Songbirds

Because of their importance for migrating neotropical songbirds such as indigo buntings and ruby-throated hummingbirds, the coastal areas of southern Northampton County are a designated Important Bird Area (IBA).[517] Not only are these birds valued for their beauty but they also serve important functions of dispersing seeds and controlling insect pests. It is estimated that a pair of warblers can consume thousands of insects as they raise a brood.[518]

Chesapeake Bay is a significant physical barrier that acts as a bottleneck for migrating birds, funneling southbound migrants to lower Northampton County, where they concentrate within the tree canopy and thick understory vegetation found within the lower 9.66 km (6 miles) of the peninsula within 188.82 m (200 yards) 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.[519]

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[510]Barry Truitt (see note 360).
[511] Perry and Deller, 1996 (see note 100).
[512]Wyda et al., 2002 (see note 95).
[513]Rounds et al., 2004 (see note 78).
[514]Eyler et al., 1999 (see note 78).
[515]Kastler and Wiberg, 1996 (see note 486).
[516]Erwin, R.M., J.G. Haig, D.B. Stotts, B. Truitt, and C.R. Carlson, 1995, Will the tide tern? Rising sea levels, invasive species, agricultural pesticides, and nesting gull-billed terns. Available at: http://www.vcrlter.virginia.edu/davedocs/VCRASC95/erwin.html .

[517]Watts, 2006, p. 5 (see note 495).
[518]Mabey, S., B. Watts, and L. McKay, n.d., Migratory Birds of the Lower Delmarva: A Habitat Management Guide for Landowners, The Center for Conservation Biology, College of William and Mary, Willamsburg, VA, p. 7.
[519]Mabey et al., p. 10 (see note 518).

3.10 Chesapeake Bay: Local Area Coastal Habitat and Environmental Implications of Sea Level Rise: Anticipated Effects by Multicounty Region

Author: **Ann Shellenbarger Jones, Industrial Economics Inc.**

The environmental implications of sea level rise vary in extent and certainty for different habitat types. Section 3.1 provides general background on species and their habitats vulnerable to sea level rise for the mid-Atlantic. This collection of short literature reviews describes where impacts to these vulnerable species may occur in Chesapeake Bay by taking a walk along its shoreline, beginning with Norfolk, Virginia, and continuing up the western side of the bay (traversing the Potomac and Patuxent rivers and up to the Susquehanna River), then returning along the eastern shore of the bay, to the southern tip of Northampton County.

We rely on various published sources of data and information on wetlands, shoreline type and condition, erosion, future shore protection, and habitat types and locations to characterize current and potential future shoreline ecology of Chesapeake Bay.[520]

These brief literature reviews discuss species that could be at risk because of further habitat loss resulting from sea level rise and shoreline protection. Existing literature and knowledge of coastal scientists in the area are sufficient in many cases to make qualitative statements about the possible impact if sea level rise causes a total loss of habitat, which might be expected if shores are protected with hard structures or the wetlands are unable to keep pace with sea level rise. Our ability is more limited, however, to say what the impact might be if only a portion of the habitat is lost. The reviews take account of shoreline features, anticipated shore protection, and the potential for wetlands to keep pace with rising sea level. Where possible, they assess the combined implications of those factors, to indicate predicted retention or loss of current primary habitats. Where available, we delineate effects associated with a particular location (e.g. unique shoreline type, endangered and threatened species) (see Section 3.1 for descriptions of generalized potential responses). Map 3.8 illustrates the regions of Chesapeake Bay and the key locations for which we have data on the species that depend on habitat vulnerable to sea level rise. We discuss the following multicounty sections separately.

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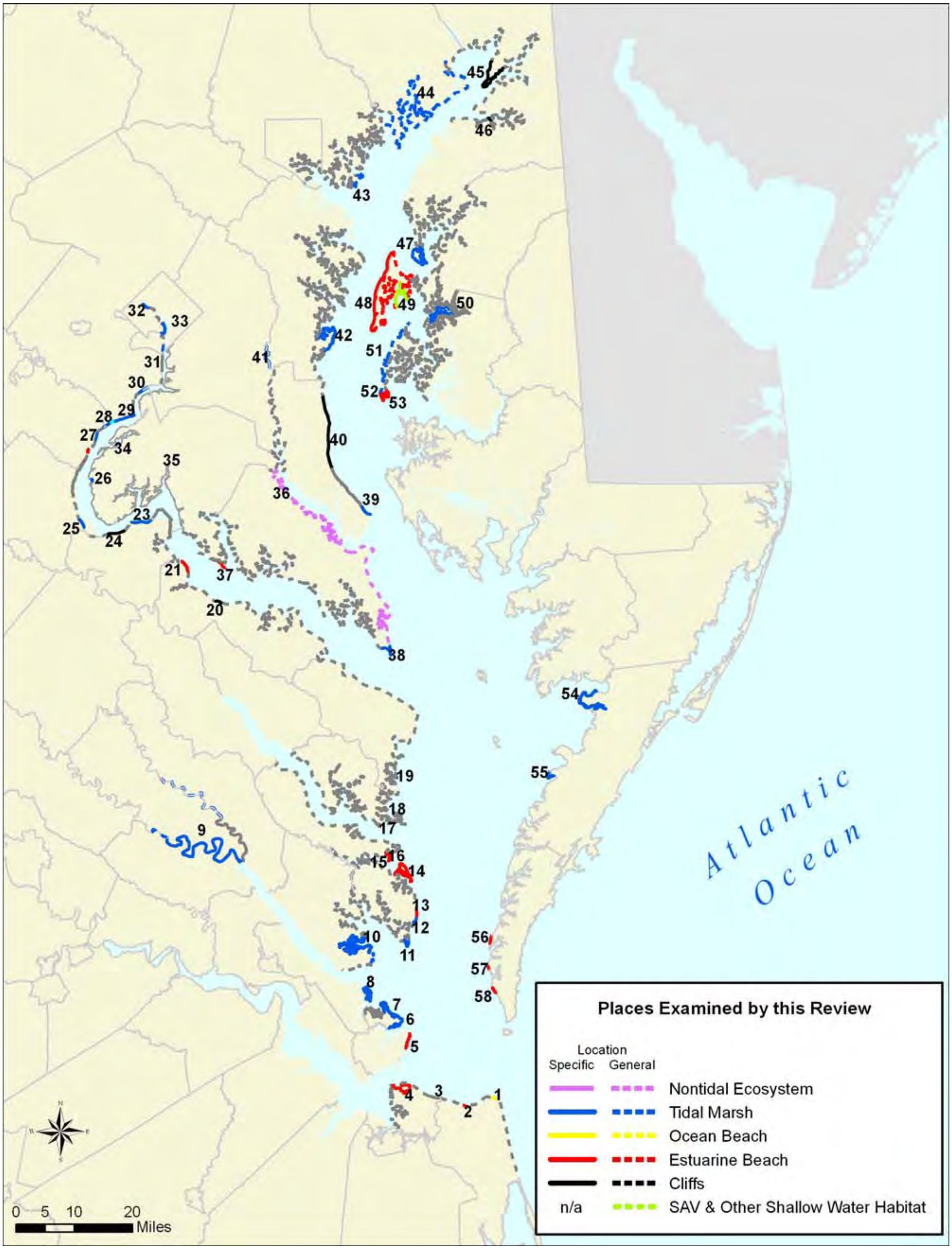
[520]Sources for wetlands information: Tiner and Burke, 1995 (see note 32); and National Wetlands Inventory. Sources for shoreline type and condition: Comprehensive Coastal Inventory Program, 2005, Shoreline Situation Reports, Virginia Institute of Marine Science (VIMS), College of William and Mary, Gloucester Point, VA, available at http://ccrm.vims.edu/gis/gisdata.html. These reports, which will eventually be available for all counties on Chesapeake Bay, include surveys of bank condition (height, erosion extent, vegetative cover, land use), presence and condition of fronting marsh or beach, and the extent and types of shoreline protections.
Source for accretion estimates, unless otherwise noted: Reed et al., Section 2.1.
Source for erosion information in Maryland: Maryland Shoreline Changes Online, from the Maryland Department of Natural Resources. Available at: http://shorelines.dnr.state.md.us/sc_online.asp.

Source for shoreline and habitat types: A set of four maps are available from NOAA's Office of Response and Restoration for all of Chesapeake Bay, showing seasonal changes in the Chesapeake (ESI 1993). Detailed digital maps (GIS format) are available from NOAA's Office of Response and Restoration for the Virginia portion of Chesapeake Bay (ESI 2005). These maps provide detail on shoreline type, nearshore and inshore habitats, and locations of endangered species.



Map 3.8. Environmental Importance of Habitat Vulnerable to Sea Level Rise: Locations Examined in this Report. See legend on next page for location name index and associated habitat.

Legend for Map 3.8

Location Name Index	Habitat (as mentioned in text for this location).	Location Name Index	Habitat (as mentioned in text for this location).
1. Cape Henry	Ocean Beach	30. Accotink Bay	Tidal Marsh
2. Lynnhaven Inlet/River	Estuarine Beach	31. Dyke Marsh	Tidal Marsh
3. City Beach Park	Estuarine Beach	32. Roosevelt Island	Tidal Marsh
4. Willoughby Bay	Estuarine beach - groinfields	33. Anacostia River	Limited tidal marsh, armoring
5. Grandview Beach Nature Preserve	Estuarine Beach	34. Mattawoman Creek	Estuarine Beach
6. Plum Tree Island Marsh	Tidal Marsh	35. Port Tobacco	Tidal Marsh
7. Ware Stick Island	Tidal Marsh	36. Zekiah and Gilbert Swamps	Nontidal marsh
8. Goodwin Islands	Tidal Marsh	37. Cobb Island	Estuarine Beach
9. Pamunkey and Mattaponi Rivers	Tidal Marsh	38. Point Lookout State Park	Tidal Marsh
10. Gloucester Marshes, Guinea Neck	Tidal Marsh	39. Cove Point	Tidal marsh to north of point, beach to south of point
11. New Point Comfort	Tidal Marsh	40. Calvert County Cliffs	Cliffs
12. Winter Harbor	Tidal Marsh	41. Jug Bay and Patuxent River Park	Tidal Marsh
13. Bethel Beach Natural Area Preserve	Tidal Marsh fronted by Estuarine Beach	42. Shady Side	Tidal Marsh
14. Gwynn's Island	Estuarine Beach	43. North Point State Park	Tidal Marsh
15. Fishing Bay	Estuarine Beach	44. Aberdeen Proving Ground	Tidal Marsh
16. Stove Point	Estuarine Beach	45. Elk Neck State Park	Cliffs
17. Mosquito Point	Estuarine Beach	46. Sassafras Natural Resources Management Area	Cliffs
18. North Point	(geographic)	47. Eastern Neck National Wildlife Refuge	Tidal Marsh
19. Hughlett Point Natural Area Preserve	Tidal Marsh	48. Kent Island	Revetments and some estuarine beach
20. Westmoreland State Park	Cliffs	49. Crab Alley Bay	Submerged aquatic vegetation
21. Colonial Beach	Estuarine Beach	50. Wye Island Natural Resources Management Area	Tidal Marsh
22. Intentionally left blank		51. Tilghman Island - western/bay side 51. Tilghman Island - eastern side	Mix of fringing tidal marsh and estuarine beach Tidal marsh shoreline, shallow water/tidal flats
23. Chotank Preserve	Tidal Marsh	52. Poplar Island	Tidal Marsh
24. Caledon Natural Area	Cliffs	53. Walnut Point	Armored estuarine beach
25. Crow's Nest Peninsula	Tidal Marsh	54. Saxis Wildlife Management Area	Tidal Marsh
26. Nanjemoy Peninsula	Tidal Marsh	55. Parkers Marsh Natural Area Preserve	Tidal Marsh
27. Featherstone NWR	Tidal Marsh	56. Savage Neck Dunes Natural Area Preserve	Estuarine Beach
28. Occoquan National Wildlife Refuge	Tidal Marsh	57. Cape Charles Coastal Habitat Natural Area Preserve	Estuarine Beach
29. Mason Neck, Mason Neck State Park, Mason Neck National Wildlife Refuge	Tidal Marsh	58. William B. Trower Bayshore Natural Area Preserve	Estuarine Beach

3.11 The Chesapeake Bay Shoreline near Hampton Roads

Authors: ***Ann Shellenbarger Jones, Industrial Economics Inc.,***
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Overview

The shores of Chesapeake Bay to the south of Hampton Roads[521] are dominated by the north-facing sandy beaches of Virginia Beach and Norfolk. To the north, the shores of Hampton, Poquoson, and York counties are mostly tidal marsh. The marshes and the species that depend on them are potentially vulnerable to sea level rise. The bay beaches, by contrast, appear likely to survive.

Virginia Beach will be greatly affected by continued local anthropogenic actions, which may or may not follow historical patterns that resulted in the current beach configurations. City planners anticipate that the shoreline of the City of Virginia Beach is almost certain to be protected through armoring or beach nourishment. Sandy beaches may be retained in various protected areas owing to nourishment projects, but will otherwise be eroded in front of protective structures. A 2002 beach management plan includes recommendations for long-term replenishment programs at Chesapeake, Ocean Park, and Cape Henry beaches.[522] If beaches are lost in other localities to sea level rise, the few plants that are well adapted to the harsh beach environment in these local areas will be lost. Habitat for invertebrates (e.g., sand diggers, sand fleas, horseshoe crabs, and mole and ghost crabs) will be lost. Shorebirds that rely on beaches for forage and nesting (e.g., turnstones, sanderlings, and plovers) will face more limited resources.[523]

Current rates of sea level rise in the Poquoson marshes and some Hampton areas are converting marsh to open water; these marsh areas will be inundated as sea level rise accelerates, converting marsh areas to tidal flats and then open water (Section 2.1). Inundation will eliminate habitat for many marsh inhabitants such as crustaceans, mollusks, and other invertebrates. Turtles (e.g., diamondback terrapins) and birds (e.g., ducks, rails) that forage on the invertebrates will therefore also lose food sources. Habitat for fish (described subsequently) that spend portions of their lives in wetlands will be lost, as will habitat for birds that nest exclusively in marshes (known as marsh-obligates). In this region, the dozens of bird species that use Plum Tree Island marsh will be impacted by continued marsh loss. The ecosystem functions of flood control, erosion buffering, and nutrient and contaminant filtering will be lost as wetlands are submerged.[524]

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[521]Hampton Roads is the large harbor between the confluence of the James and Elizabeth rivers and Chesapeake Bay. We did not look at the tidal habitat of Hampton Roads or its tributaries. In general, as indicated in ESI 2005, the northern shores of the harbor are hardened with riprap and other artificial structures, while the riparian shores of the Nansemond river are tidal marsh. See Map 3.8 for indication of level of detail provided by location.

[522]Virginia Beach, Beaches and Waterways Advisory Commission, 2002, Virginia Beach Beach Management Plan, accessed on July 25, 2007, at: http://www.vbgov.com/file_source/dept/planning/beach_management_plan.pdf.

[523]Lippson and Lippson, 2006, pp. 26–42 (see note 2).

[524]Lippson and Lippson, 2006, pp.201–239 (see note 2).

Let us now examine the habitat vulnerable to sea level rise and the species that depend on it, from south to north.

City of Virginia Beach

Sandy beaches with dune systems compose the Chesapeake Bay shoreline of the City of Virginia Beach. The sands reach from Cape Henry (CBIM location 1 on Map 3.8) on the northeastern edge of the county to the inlet at the mouth of the Lynnhaven River, past the Chesapeake Bay Bridge and Tunnel and Little Creek to the mouth of the James River.[525] Net longshore transport on Virginia Beach's Bay side is to the west. Overall trends in the last century show the dunes east of the Lynnhaven inlet advancing into Chesapeake Bay (CBIM location 2). 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. Dredging activity for navigation in the Lynnhaven inlet may also be affecting accretion and erosion, temporarily adding sediment to the longshore transport system; some Chesapeake shoreline beaches, such as those at Ocean Park, have required nourishment multiple times to maintain their area. The Virginia Beach resort area on the ocean shore has received beach fill material since the mid-1950s.[526] Given the extensive patterns of nourishment and shoreline protection in place today, minimal additional ecological change from accelerated rates of sea level rise is anticipated.

Studies of beach nourishment indicate that the practice may have minimal biological effects if projects are properly designed, but that projects also have unknown effects related to changing beach slopes, sediment characteristics (e.g., grain size of new material may be different than that of the native material), and potential loss of bay-bottom habitat when beaches are extended waterward.[527] Studies that evaluate long-term effects on biota are not common.[528]

City of Norfolk

The sandy beaches found in the City of Virginia Beach continue westward along the Chesapeake shoreline in the City of Norfolk (CBIM locations 3–4). The rate of erosion is generally low, and beach accretion occurs along much of the shore. However, just west of City Beach Park, erosion potential is higher. Banks up to 10 feet high line the City Beach Park coast, with breakwaters at portions of their bases (CBIM location 3). Groinfields and breakwaters protect the shore going west across Willoughby Bay (CBIM location 4).[529] The areas protected by groinfields and breakwaters have been deemed “relatively stable” by Hardaway et al.[530] As evidenced by the heavily armored status of the shores today, planners anticipate that shoreline protection is almost certain along the entire bay side of Norfolk. Unnourished sandy beaches lacking protection may be eroded, narrowed, and eventually lost,[531] eliminating the habitat they provide today for invertebrates and shore birds.

City of Poquoson and City of Hampton

The City of Poquoson is located at the eastern tip of Virginia's Hampton Roads peninsula (CBIM locations 5–7). Planners indicate that the developed portion of the city is almost certain to be protected, whereas Plum Tree Island Marsh (also known as Big Salt Marsh, CBIM location 6) and adjacent areas east of the city are already experiencing loss to erosion and rising sea levels (Section 2.1). Plum Tree Island Marsh, the largest saline marsh in the Lower Chesapeake, covers 4,100 acres, or 44 percent of Poquoson's 9,395-acre total area, and contains salt marsh and

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[525] Hardaway et al., 2005, Shoreline Evolution, Chesapeake Bay Shoreline, City of Virginia Beach, Virginia. Virginia Institute of Marine Sciences, College of William and Mary, Gloucester Point, VA.
[526] Hardaway et al., 2005, p. 9 (see note 525).
[527] Jackson et al., 2002, p. 420 (see note 139).
[528] Nordstrom, 2005, p. 216 (see note 153).
[529] Berman, M.R., Berquist, H., Killeen, S., Hershner, C.H., Rudnicky, T., Schatt, D.E., Weiss, D., and H. Woods, 2002, City of Norfolk Shoreline Situation Report, Special Report in Applied Marine Science and Ocean Engineering No. 378, Comprehensive Coastal Inventory Program, Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, VA.
[530] Hardaway et al., 2005, p. 9 (see note 525).
[531] Nordstrom, 2005, p. 215 (see note 153).

remnant forested dune hummocks.[532] The Plum Tree Island National Wildlife Refuge has very limited human access because of the quantities of unexploded ordnance on the island from its prior use as a bombing range. The relative isolation of the area has made it a haven for more than 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*). A variety of mammals (muskrats, red fox, white-tailed deer) use the higher ground of the refuge. Endangered sea turtles, primarily the loggerhead, use the nearshore waters. Oyster, clams, and blue crabs use the shallow waters and mudflats, and striped bass, mullet, spot, and white perch, among other fish, have been found in the nearshore waters and marsh.[533] Across from the marsh in Hampton is the Grandview Beach Nature Preserve (CBIM Location 5), which has more than 2 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.[534]

Tidal wetlands with varying degrees of erosion are present throughout the area, and some beaches with low erosion rates line the many small north-facing islands and higher areas such as Ware Stick Island (CBIM location 7) and Cow Island.[535] The highest elevation within the long-established portions of Poquoson is only 10 feet above sea level.[536] Reed et al. in Section 2.1 indicate wetlands loss in Poquoson even with the current rate of sea level rise. The City of Poquoson's Multi-Hazard Mitigation Plan identifies sea level as a threat to the area, noting in particular that over time there is potential for increased storm surges, erosion, and loss of coastal zone land area, including wetlands.[537] Loss of coastal zone areas may lead to loss of the crustaceans, mollusks, and other invertebrates that live in close association with the wetland vegetation. Habitat for fish that use the mudflats and marshes will be lost, as will nesting habitat for marsh-obligate birds and the protection provided by the refuge for the numerous resident and migrating birds (described previously).

York County

Fringing tidal marshes line much of the York County bay shoreline, and the Goodwin Islands (CBIM location 8) at the extreme northeast of the county are made up of extensive marsh areas.[538] The Goodwin Islands are protected as a National Estuarine Research Reserve (NERR). Covering 315 ha (777 acres), they are surrounded by intertidal flats, extensive SAV beds (121 ha; 300 acres of eelgrass and widgeon grass), and shallow open estuarine waters.[539] The salt marshes are dominated by salt marsh cordgrass (*Spartina alterniflora*) and salt meadow hay (*Spartina patens*). Forested wetland ridges are dominated by estuarine scrub/shrub vegetation, with a primarily loblolly pine (*Pinus taeda*) overstory, and wax myrtle (*Morella cerifera*) shrub layer. Mixed oak and pine communities, including red oak (*Quercus rubra*), loblolly pine, black gum (*Nyssa sylvatica*), and cottonwood (*Populus deltoides*), are found on upland ridges located on the largest island.[540] As

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532 City of Poquoson Comprehensive Plan, 1999, Environmental Element, accessed on July 17, 2006, at: http://www.ci.poquoson.va.us/.
533 Profile of the Plum Tree Island National Wildlife Refuge, accessed on July, 20 2006, at http://www.fws.gov/refuges/ profiles/index.cfm?id=51512.
534 USFWS, 1994, p. 6 (see note 158).
535 Berman, M.R., Berquist, H., Dewing, S., Glover, J., Hershner, C.H., Rudnicky, T., Schatt, D.E., and Skunda, K., 2001. City of Poquson Shoreline Situation Report, Special Report in Applied Marine Science and Ocean Engineering No. 369, Comprehensive Coastal Inventory Program, Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, VA.
536 City of Poquoson Comprehensive Plan, 1999 (see note 532).
537 AMEC Earth and Environmental Inc., 2004, City of Poquoson, Virginia, Multi-Hazard Mitigation Plan.
538 NOAA, 2005, Environmental Sensitivity Index digital data for Virginia, obtained from the NOAA Office of Response and Restoration.
539 Chesapeake Bay National Estuarine Research Reserve in Virginia, Goodwin Islands, accessed on November 20, 2006, at http://www.vims.edu/cbnerr/reservesites/goodwin.htm.
540 Chesapeake Bay National Estuarine Research Reserve in Virginia; Virginia Department of Game and Inland Fisheries. Goodwin Islands National Estuarine Research Reserve. Accessed on November 20, 2006, at http://www.dgif.state.va.us/wildlife/vbwt/site.asp?trail=1&site=CLP06&loop=CLP.

of 2002, bald eagles nested on the Goodwin Islands.[541] Presumably, these marsh islands will experience similar effects as those described for other marsh islands, and the surrounding tidal flats and SAV will possibly migrate inland, or eventually be lost (see Section 3.1 for a general description of marsh island, tidal flat, and SAV responses to sea level rise). Reed et al. in Section 2.1 indicate that most lower bay marshes and the fringing marshes along the York River are currently keeping pace with sea level rise through peat accumulation, but would be marginal with a 2 mm per year increase and lost with a 7 mm per year increase.

Wrapup

Continued nourishment and breakwater protection are anticipated for the majority of Hampton Roads beaches, limiting the likelihood of additional ecological change.[542] At the current rate of sea level rise, Plum Tree Island marsh is losing area. With any increase in rates of sea level rise, continued loss of area is expected because of the unprotected status of the majority of the shoreline.[543] The numerous bird species that frequent it will therefore face reduced resources. Vegetation and associated fauna may migrate inland as land is lost, but the developed portions of the city may eventually limit their migration and survival.[544] Though the York County marshes (including Goodwin Islands) are keeping pace with the current rate of sea level rise, it is not known that they will continue to do so with increased rates of sea level rise; they may become marginal under a midrange increase (2 mm per year), and are likely to be lost under a high-range scenario (increase of 7 mm per year).[545]

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[541] Watts, B.D., and C. Markham, 2003, The influence of salinity on diet, prey delivery, and nestling growth in bald eagles in the lower Chesapeake Bay: Progress Report, Center for Conservation Biology Technical Report Series, CCBTR-03-06, College of William and Mary, Williamsburg, VA, p. 1.

[542] Author's analysis from Hardaway et al. 2005 (see note 525), Nordstrom 2005 (see note 153), and Jackson et al. 2002 (see note 139).

[543] Author's analysis based on Section 2.1, and AMEC Earth and Environmental Inc. 2004 (see note 537).

[544] Nordstrom (2005) notes that "fixed human development on eroding shores prevents natural landward migration of coastal landforms" p. 215 (see note 153).

[545] Author's analysis based on Section 2.1.

3.12 The Chesapeake Bay Shoreline of Middle Peninsula

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Overview

The Middle Peninsula region comprises Chesapeake Bay shorelines of Gloucester, Mathews, and Middlesex counties. Additionally, the area includes the Rappahannock and Piankatank River shorelines of these counties and several islands in the rivers.

This brief literature review discusses species that could be at risk because of further habitat loss resulting from sea level rise and shoreline protection (see Section 3.1 for general background). Existing literature and knowledge of coastal scientists in the area appears to be sufficient in many cases to make qualitative statements about the possible impact if sea level rise causes a total loss of habitat, which might be expected if shores are protected with hard structures and the wetlands are unable to keep pace with sea level rise. Our ability is more limited, however, to say what the impact might be if only a portion of the habitat is lost. The overall environmental impact of sea level rise in this multicounty region is likely to include the following:

- The tidal estuarine marshes of Gloucester County are already being submerged, and the Mobjack Bay-facing marshes of Mathews County will be marginal with an increase of 2 mm per year in the rate of sea level rise.[546] Marsh vegetation habitat for a range of species, including crustaceans, mollusks, and other invertebrates, will be lost. Birds and fish that forage on these invertebrates will therefore face a changed or limited food supply. Nesting habitat for birds will also be eliminated.[547] If marsh vegetation is lost, the ecosystem functions of flood control, erosion buffering, and nutrient and contaminant filtering will be lost as wetlands are submerged.

- Unnourished beaches in the Middle Peninsula, such as the natural area preserve of Bethel Beach, are already experiencing erosion, and may be lost to accelerated sea level rise. The few plants that are well adapted to the harsh beach environment, and the rare sea-beach knotweed, will be lost. The population of least terns that nests at Bethel Beach may also lose habitat.[548]

- Marsh islands in the Rappahannock and Piankatank rivers are likely to be lost, eliminating valuable nesting habitat for marsh-obligate birds.

Gloucester County

East of Route 17, Guinea Neck, is vulnerable and already being submerged owing to both erosion and sea level rise (CBIM location 10).[549] The

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[546]Author's read of map in Reed et al., Section 2.1 showing wetlands in this area being converted to open water at the current rate of sea level rise; and Moore, K., 1976, Gloucester County Tidal Marsh Inventory. Special Report No. 64 in Applied Science and Ocean Engineering, Virginia Institute of Marine Science, Gloucester Point, VA. pages 42–44.

[547]Author's analysis based on biological information provided in Lippson and Lippson, 2006, pp. 201–239 (see note 2); and Moore, 1976 (see note 546). For more detail on the impacts of sea level rise to wetland habitat and species, see Section 3.1.

[548]Lippson and Lippson, 2006, pp. 26–42 (see note 2).

[549]Author's read of map in Reed et al., Section 2.1 showing wetlands in this area being converted to open water at the

low-lying area bordering southern Mobjack Bay and Chesapeake Bay is composed of tidal wetlands. It is not likely to be protected and will continue to be lost, decreasing available habitat for the many birds, fish, and other creatures that use the marshes and tidal creeks. Some portions may be able to accrete sufficient sediment or migrate inland, but planners anticipate the construction of shoreline protections, which may preclude migration in protected areas. The 5 to10 foot higher elevation roughly paralleled by Rte. 17 is likely to limit any inland migration that is not outpaced by sea level rise. As early as 1976, though not explicitly linked with sea level rise, it was observed that formerly reclaimed agricultural land was being converted back to marsh and high marsh vegetation species were migrating inland into forested areas.[550] In the upper reaches of the York River's tributaries, such as the Pamunkey and Mattaponi rivers, tidal hardwood marshes show effects of sea level rise (CBIM location 9). Brackish to freshwater marsh plants are encroaching on these forested areas. Tree death is occurring and further inland migration is hindered by the higher upland elevation behind the forested marshes.[551] Tidal hardwood marshes provide nesting sites for piscivorous species such as ospreys, bald eagles, and double-crested cormorants.[552] The freshwater marshes also host a variety of migratory and breeding birds.

A study examining the relationship of birds to vegetation communities in the Lee and Hill marshes in the lower Pamunkey River indicates that bird communities may change if high marsh vegetation is replaced with lower marsh vegetation. The authors posit that brackish marshes, because of their locations at transitions between tidal freshwater and oligohaline marshes, may face greater risk than marshes with more extreme, nontransitional salinities. Outlining a scenario in which sea level rise causes a shift of 100 ha from 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.[553] However, a change to an arrow arum-dominated marsh may increase bird density and diversity during winter, particularly for waterfowl and shorebirds. Arrow arum dies back in winter, creating an open mud flat that provides invertebrate prey to birds.[554]

Mathews County

The Mathews County shoreline, bordered by Mobjack Bay to the south, Chesapeake Bay to the east, and the Piankatank River to the north, has a mix of marshes and beaches. Planners indicate that shore protection is likely or almost certain along Mobjack Bay except for a parcel of public land near the mouth of the East River. On the Chesapeake Bay coast of Mathews County, planners anticipate that the southern third of the coast is likely to be protected, the middle third is unlikely to be protected, and the most northern third, comprising Gwynn's Island (CBIM location 14) and some Piankatank River frontage, is almost certain to be protected. Wetlands and some dunes extend along the county's southern boundary along Mobjack Bay and around New Point Comfort (a Natural Area Preserve) (CBIM location 11). Low elevation woodlands (maritime forest) extend inland from the eroding marshes and dune areas and provide habitat for avian neotropical migrants.[555,556] New

current rate of sea level rise; and Moore, 1976, pp. 42–44 (see note 546).

550 Moore, 1976, pp. 42–44 (see note 546).

551 Gary Fleming, September 11, 2006 email (see note 76) confirming phone call notes, including information regarding his work in the Mattaponi and Pamunkey river freshwater marshes.

552 Robbins, C.S. and E.A.T. Blom, 1996, *Atlas of the Breeding Birds of Maryland and the District of Columbia*, University of Pittsburgh Press, Pittsburgh, PA, pp. 44, 92–94.

553 Paxton, B.J. and B.D. Watts, 2002, Bird Surveys of Lee and Hill Marshes on the Pamunkey River: Possible Affects of Sea-Level Rise on Marsh Bird Communities, Center for Conservation Biology Technical Report Series, CCBTR-03-04, College of William and Mary, Williamsburg, VA, pp. 2, 25–26.

554 Ibid., p. 17.

555 Virginia Department of Game and Inland Fisheries, New Point Comfort Natural Area Preserve, accessed on August 3, 2006, at: http://www.dgif.virginia.gov/wildlife/vbwt/site.asp?trail=1&site=CMT08&loop=CMT.

Point Comfort hosts a population of the northeastern tiger beetle (federally listed as threatened) and nesting least terns (*Sterna antillarum*).[557] Marshes also line tributaries and the landward facing sides of Winter Harbor (CBIM location 12), the mouth of Strutts Creek, just south of Gwynn's Island, and the southern bank of the Piankatank. On the Piankatank, marsh areas frequently front higher elevation areas.[558] Beaches, most showing signs of high erosion rates, front much of the Chesapeake-facing shore (e.g., adjacent to Winter Harbor, along Bethel Beach, Rigby Island, and Gwynn's Island). Marshes and unnourished beaches on the Piankatank are likely to be lost, because migration inland will be limited by the greater than 10 foot elevations. The marsh areas are expected to accrete sufficient sediment to only keep pace marginally with a 2 mm per year increase above current sea level rise rates, and are likely to be lost with a 7 mm per year rate increase (Section 2.1). Loss of marsh area will lead to loss of the species that depend on it, as described above.[559]

Bethel Beach (CBIM location 13), a natural area preserve separating Winter Harbor from Chesapeake Bay, is currently migrating inland over an extensive salt marsh area.[560] The beach is undergoing high erosion,[561] 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.[562] Although the shore is able to continue to migrate, these habitats will remain intact, but eventual overwash and inundation of the marsh will lead to the loss of the sea-beach knotweed and the northeastern beach tiger beetle population, as well as the nesting area for least terns and northern harriers.[563]

Middlesex County

Middlesex County lies on the northern portion of the Middle Peninsula, bordered on the south by the Piankatank River and on the north by the Rappahannock River. The river and bay shorelines are primarily beach, with marsh areas in coves and tributaries such as Broad Creek. As the Rappahannock shore forms a point near Mill Creek, the shoreline becomes predominantly marsh. Stove Point (CBIM location 16) is a defining land feature, an arm of land reaching south into the Piankatank and forming Fishing Bay (CBIM location 15). Its entire eastern shore, approximately 75 percent of which is beach, is protected by bulkheads and riprap as well as a continuous groinfield along its length. Roughly a third of the beach area has high rates of erosion. The peninsula of Middlesex County north and east of Fishing Bay is narrowly connected to the rest of the county between Jackson and Sturgeon creeks. Groinfields, riprap, and bulkheading border the whole peninsula and extend into some of the tributaries, limiting possibilities for shoreline migration.[564]

Apart from the southernmost end of Stove Point, and three small areas on the Rappahannock, planners indicate that shore protection in

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[556]Virginia Department of Conservation and Recreation, New Point Comfort Natural Area Preserve, accessed on August 29, 2006, at: http://www.state.va.us/dcr/dnh/newpoint.htm.
[557]Ibid.
[558]Berman, M.R., Berquist, H., Dewing, S., Glover, J., Hershner, C.H., Rudnicky, T., Schatt, D.E., and Skunda, K., 2000, Mathews County Shoreline Situation Report, Special Report in Applied Marine Science and Ocean Engineering No. 364, Comprehensive Coastal Inventory Program, Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, VA.
[559]Lippson and Lippson, 2006, pp. 201–239 (see note 2).
[560]Gary Fleming email on September 11, 2006 (see note 76), including information regarding Bethel Beach.
[561]Berman et al., 2000 (see note 558).
[562]Virginia DCR Bethel Beach fact sheet, accessed at: http://www.dcr.virginia.gov/dnh/pgbethel.pdf on August 3, 2006.
[563]Author's analysis based on biological information for Bethel Beach (see note 562).
[564]Berman, M.R., Berquist, H., Dewing, S., Glover, J., Hershner, C.H., Rudnicky, T., Schatt, D.E., and Skunda, K., 2000. Middlesex County Shoreline Situation Report, Special Report in Applied Marine Science and Ocean Engineering No. 368, Comprehensive Coastal Inventory Program, Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, VA.

Middlesex County is likely or almost certain. Most of the county along the Rappahannock River is already protected with groinfields extending on both sides of Sturgeon Creek.[565] Without nourishment, beaches in this area are likely to be lost. Off shore from Mill Creek in the Rappahannock River, Parrott Island, composed of tidal marsh, will not be protected. All the marsh areas in Middlesex County may keep pace with a 2 mm per year increase in sea level rise rates through accretion, but not likely with a rate increase of 7 mm per year. Similarly, Berkeley Island in the Piankatank is unlikely to be protected (Section 2.1). This island will potentially be inundated and submerged, presumably leading to loss of habitat for biota that typically inhabit these ecological communities. These may include crustaceans, mollusks, and other invertebrates that feed on and fertilize the marsh vegetation and the turtles (e.g. diamondback terrapins) and birds (e.g. ducks, rails) that forage on them. Habitat for forage and game fish that spend portions of their lives in wetlands will be lost, as will nesting habitat for marsh obligate birds.[566] Islands are also a particularly desirable nesting habitat for birds, owing to the general absence of larger mammalian predators.[567]

Wrapup

The three areas where specific data are available for the Middle Peninsula are vulnerable to sea level rise. First, the Guinea Neck marshes will potentially be converted to open water under an increased rate of sea level rise scenario of 2 mm and most likely will be converted at 7 mm (Section 2.1). Presumably, as in other marsh areas, this will result in impacts to the invertebrates such as crabs and shrimp that use the vegetation, and the birds that feed on them. Likewise, it will eliminate nesting and forage habitat for birds and fish. Second, Bethel Beach may survive with sufficient sediment input, and continued lack of shoreline protections, allowing for survival of the area's northeastern beach tiger beetle and the rare sea-beach knotweed. The beach portion is already experiencing high erosion, and it is estimated that a 7 mm increase in rates of sea level rise might overwhelm the migration processes and lead to marsh inundation in these areas. Third, the tidal marshes in the York River tributaries (the Pamunkey and Mattaponi rivers) are already impacted by sea level rise, and vulnerable to future changes, particularly if changes in salinity drive changes in vegetative cover. In the forested hardwood marshes of the upper reaches, increased salinity is expected to eliminate the forested marsh, which will reduce habitat for eagles and other piscivorous birds.[568] In the brackish marshes in the lower Pamunkey River, inundation may occur if rates of sea level rise increase by 2 mm per year, and is expected with an increase of 7 mm per year. Inundation may increase the percentage of low marsh vegetation (arrow arum), resulting in reduced numbers of red-winged blackbirds and other birds that prefer higher marsh areas, yet habitat for wintering waterfowl would be enhanced because of the likelihood of increased mud flats in winter.[569]

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[565]Berman et al., 2000 (see note 564).
[566]Author's analysis based on biological information in Lippson and Lippson, 2006, pp. 201–239 (see note 2).
[567]Eyler et al., 1999 (see note 78).
[568]Author's analysis based on discussion with Gary Fleming, and on Robbins and Blom, 1996 (see note 552).
[569]Author's analysis based on Paxton and Watts, 2002 (see note 553).

3.13 The Chesapeake Bay Shoreline of Northern Neck

Authors: ***Ann Shellenbarger Jones, Industrial Economics Inc., Christina Bosch, Industrial Economics Inc.***

Overview

The Northern Neck's Chesapeake Bay shoreline comprises Lancaster and Northumberland counties. The Northern Neck has marsh and beach shoreline, with heavily armored areas along developed shores of the Potomac.

This brief literature review discusses species that could be at risk because of further habitat loss resulting from sea level rise and shoreline protection. Existing literature and knowledge of coastal scientists in the area appears to be sufficient in many cases to make qualitative statements about the possible impact if sea level rise causes a total loss of habitat, which might be expected if shores are protected with hard structures and the wetlands are unable to keep pace with sea level rise. Our ability is more limited, however, to say what the impact might be if only a portion of the habitat is lost. The overall environmental impact of sea level rise in this multicounty region is likely to include the following:

- The tidal marshes may be lost with rising sea levels, including the marsh-fringed Mosquito Island. The many rare birds that nest in the Northern Neck marshes, including least bitterns, king rails, and black rails, will lose habitat. In addition, the crustaceans, mollusks, and other invertebrates that live in close association with the wetland vegetation will be lost. Ecological impacts will be similar to those expected for other marsh areas that will be lost. That is, habitat for fish that depend on marshes for nurseries and spawning will be lost, as will nesting habitat for marsh obligate birds. The ecosystem functions of flood control, erosion buffering, and nutrient and contaminant filtering will be lost as wetlands are submerged.[570]
- In Northumberland County, shoreline protections will preserve inland areas, but beach erosion will be likely in unnourished areas. Absent site-specific information for areas other than Hughlett Point, presumably, if beaches are lost to sea level rise, the few plants that are well adapted to the harsh beach environment will be lost, and invertebrates, including the northeastern tiger beetle, sand diggers, sand fleas, and crab species, will be lost. Shorebirds that rely on beaches for forage and nesting (e.g., turnstones, sanderlings, and plovers) will face more limited resources.[571]

Lancaster County

Apart from the peninsular area of North Point (CBIM location 18) in Lancaster County, planners indicate that the county's bay shoreline will almost certainly be protected against rising sea levels. They also indicate that shore protection is unlikely on the county's Rappahannock shore (a primarily agricultural area near the border with Richmond County) and on Mosquito Island (CBIM location 17 in the Rappahannock River). Scrub-shrub, forest, grass and agricultural land cover dominate the shorelines. Although inland migration will not be blocked by protections, the land area is small and as such has limited space in which migrating marshes and forests may establish themselves.[572] Further reducing the likelihood of the area's ability to adapt to rising sea levels, planners anticipate that with a 2 mm per year increase in

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[570]Lippson and Lippson, 2006, pp. 201–239 (see note 2).

[571]Lippson and Lippson, 2006, pp. 26–42 (see note 2).

[572]Berman, M.R., Berquist, H., Dewing, S., Glover, J., Hershner, C.H., Rudnicky, T., Schatt, D.E., and Skunda, K., 2001, Lancaster County Shoreline Situation Report, Special Report in Applied Marine Science and Ocean Engineering No. 371, Comprehensive Coastal Inventory Program, Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, VA.

the rate of sea level rise, marshes will marginally be able to retain current area (Section 2.1).

Lancaster County's bay and river shoreline has interspersed marsh and beach areas, with beaches typically occurring at points, and marshes in coves. Shorelines of Fleet's Bay and Dymer, Tabbs, and Antipoison creeks are covered by marshes with minimal erosion rates. Groinfields stretch from either side of Tabbs Creek in Fleet's Bay, around Clark Point in Little Bay, and west of Rones Bay in Dymer Creek. Similar protections are found at the mouth of Mosquito Creek and at the end of Mosquito Point on the Rappahannock River. Riprap is also present along many discrete portions of the county shoreline.[573] Shoreline marshes will possibly be maintained through accretion with a 2 mm per year acceleration in sea level rise, but most areas will be lost under a 7 mm per year acceleration scenario (Section 2.1). The Virginia brackish marshes are home to a large number of rare birds, including the least bittern, the king rail, and the black rail. The rails eat insects, crustaceans, and seeds, and the least bittern feeds on fish or other small animals.[574] Marsh submersion will lead to loss of these food sources for these rare birds, and for more common marsh birds such as the herons and egrets. Habitat for forage and game fish that spend portions of their lives in wetlands will be lost, as will nesting habitat for marsh obligate birds.[575]

Northumberland County

Northumberland County is densely developed along the Potomac River and on the Chesapeake Bay shoreline. Of 558 miles of Northumberland County shoreline surveyed, approximately 80 percent had marsh coverage, and the remaining 20 had beach.[576] Planners indicate that most of the county will be protected, leading to likely loss of unnourished beaches and marsh areas through erosion and inundation as a result of the inability to retreat inland and lack of sufficient sediment inputs. Hughlett Point Natural Area Preserve, at the midpoint along the Northern Neck's Chesapeake Bay shoreline, has forest areas fronted by estuarine marshes and sandy beaches line most of its shore (CBIM location 19). The preserve hosts a population of northeastern beach tiger beetles and nesting diamondback terrapins and provides a resting point for migratory birds. In addition, gray foxes (*Urocyon cinereoargenteus*) and river otters (*Lontra canadensis*) are present.[577] Presumably, if beaches are lost to sea level rise, the few plants that are well adapted to the harsh beach environment will be lost. Habitat for insects and other invertebrates such as sand diggers, sand fleas, and beach tiger beetles will be lost. Shorebirds that rely on beaches for forage and nesting (e.g., turnstones, sanderlings, and plovers) will face more limited resources.[578] Loss of the marsh areas will lead to ecological effects as described for Lancaster County.

Wrapup

The Northern Neck marshes of Lancaster County will be marginal with an increase of 2 mm per year over current rates of sea level rise and will most likely be lost with an increase of 7 mm, eliminating habitat for rare marsh birds. The beaches of Northumberland County are likely to be eroded in front of the expected shore protections, and lost without nourishment. Hughlett Point Natural Area Preserve may be inundated with an increase of 7 mm in sea level rise rates, eliminating habitat for a variety of species, including the federally listed threatened northeastern beach tiger beetle and migratory birds.

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[573] Berman et al., 2001 (see note 572).

[574] Rare Marsh-Nesting Birds of Virginia's Coastal Plan. Natural Heritage Resources Fact Sheet. Accessed online at http://www.state.va.us/dcr/dnh/mrshfact.htm on June 13, 2006.

[575] Lippson and Lippson, 2006, pp. 201-239 (see note 2).

[576] Berman, M.R., Berquist, H., Killeen, S., Hershner, C.H., Rudnicky, T., Schatt, D.E., Weiss, D., and H. Woods, 2002, Northumberland County Shoreline Situation Report, Special Report in Applied Marine Science and Ocean Engineering No. 379, Comprehensive Coastal Inventory Program, Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, VA.

[577] Virginia Department of Game and Inland Fisheries, n.d., Hughlett Point Natural Area Preserve, accessed on August 3, 2006, at: http://www.dgif.virginia.gov/wildlife/vbwt/site.asp?trail=1&site=CNN12&loop=CNN.

[578] Lippson and Lippson, 2006, pp. 26–42 (see note 2).

3.14 Lower Potomac

Authors: ***Elizabeth M. Strange, Stratus Consulting Inc.***
Ann Shellenbarger Jones, Industrial Economics Inc.

Species and habitats along the lower Potomac River are potentially at risk because of sea level rise. This study region encompasses the estuarine portion of the tidal Potomac downstream of Mattawoman Creek to Chesapeake Bay. The region contains important habitats for a variety of fish, shellfish, and birds, and a great deal is known about the ecology and habitat needs of these species. Based on existing literature and the knowledge of local scientists, this brief literature review discusses those species that could be at risk because of further habitat loss resulting from sea level rise and shoreline protection (see map in Chesapeake Bay review). 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.

The Lower Potomac's shorelines pass through St. Mary's and Charles counties in Maryland and Westmoreland and Northumberland counties in Virginia's Northern Neck. The Maryland side is largely rural and agricultural, but population and development there are growing rapidly. Northumberland County is densely developed along the Potomac River and on the Chesapeake Bay shoreline. Westmoreland County lies entirely along the Potomac, north and west of Northumberland County. The county is highly developed, but also has many conservation areas.

The habitats found in the Lower Potomac and their likely responses to sea level rise include the following:

- Freshwater tidal marshes in the Lower Potomac are found in the headwaters of tidal tributaries. These marshes are currently keeping pace with sea level rise, largely through sediment and peat accumulation, and are expected to continue to do so (and possibly expand in some areas), even if sea level rise rates increase by 2 mm/yr or 7 mm/yr (Section 2.1).

- Brackish tidal marshes border the Lower Potomac River and the downstream portions of the estuary's tributaries. These marshes are keeping pace with sea level rise today, but are considered marginal with a 2 mm/yr increase in the rate of sea level rise, and likely to be lost to open water or replaced by submerged aquatic plants with a 7 mm/yr increase above the current rate (Section 2.1).

- Unnourished beaches and tidal flats of the Lower Potomac are likely to erode as sea levels rise. Where shores are protected with bulkheads and revetments, erosion will also occur.

- The cliffs and bluffs along the Lower Potomac are unlikely to be protected in most areas (e.g., Westmoreland State Park, Caledon Natural Area). Natural erosional processes will continue, helping to maintain the beaches below.

- Where submerged aquatic vegetation (SAV) occurs along coves, shoreline armoring may lead to loss of SAV due to increased wave energy.

Lower Potomac, Maryland Shoreline

The State of Maryland estimates that there are close to 3,440 ha (8,500 acres) of coastal tidal wetlands in the Lower Potomac River watershed, which extends from the mouth of the Potomac in St. Mary's County upstream to Mattawoman Creek in Charles County. This estuarine portion of the tidal Potomac contains mostly brackish marsh along the Potomac shoreline, with freshwater tidal wetlands in the upper reaches of tributaries such as St. Mary's River.[579]

In St. Mary's County, the Potomac River shoreline, as documented in the County Shoreline Situation Report, is a mix of marsh (20 percent) and beach (35 percent); the remainder is armored or low vegetated banks. Approximately 30 percent of the shoreline is currently protected, primarily with riprap. Along both the Potomac and its tributaries, most of the banks are low (< 5 feet), undergoing minimal erosion, and fully vegetated.[580] The narrow tidal wetlands are about equally divided between areas considered likely to be protected and almost certain to be protected. These marshes are not expected to keep pace with a 7 mm/yr increase in the rate of sea level rise, but they might be able to keep pace with a 2 mm/yr increase in the rate of sea level rise, depending on how the wetlands are managed (Section 2.1).

In the Wicomico River, St. Clements Bay, and Breton Bay, shoreline banks are fronted by marsh (40 percent of shoreline) and a small amount of beach (15 percent); under 20 percent of the shoreline is currently protected.[581] Shoreline protections are likely or almost certain at the mouths of the St. Mary's River, Breton Bay, and the Wicomico River.

Areas adjacent to more rural areas on the Maryland side of the Lower Potomac (e.g., inland side of St. George's Creek, Clements Bay) are unlikely to have shore protections, allowing the possibility of shoreline retreat. Tidal freshwater marshes at the upper reaches of the Wicomico River, St. Clement's Bay, and Breton Bay could benefit from more fluvial sediments resulting from increased storms resulting from climate change (Section 2.1).

The seasonally flooded Zekiah Swamp Environmental Area, which feeds the Wicomico River, contains freshwater tidal marsh that should be able to maintain pace with a moderate increase in the rate of sea level rise (Section 2.1). However, salt-water intrusion could lead to crown dieback, tree mortality, and potential infilling of the understory with salt marsh vegetation such as *Spartina*.[582] Nonetheless, given the swamp's relatively large area and water volume, if such detrimental effects occur they are likely to be contained to the Wicomico River end of the swamp.

At the mouth of the Wicomico are the developed areas of Wicomico Beach and Cobb Island. Cobb Island has docks, piers, and sandy beaches along its Potomac side, beaches and marsh along the mainland side, and predominantly beach shorelines along the low (0–5 feet) adjacent mainland areas (Cobb Neck). Cobb Island is almost certain to be protected (most areas already are), which is likely to lead to erosion of beaches and conversion of tidal flats to open water without other actions. On the mainland section, shore protection is likely and armoring is almost certain to protect the homes along Swan Point Neck. Wetlands are likely to be inundated in the western Swan Point section of Cobb Neck because of armoring and insufficient sediment accretion.

Farther up the Potomac toward Port Tobacco and the Nanjemoy Peninsula, the majority of the Potomac shoreline is unlikely to be protected, and brackish marshes along the shore will be able to retreat in response to sea level rise. Despite armoring of Port Tobacco, accretion rates for the tidal freshwater marshes at the head of the Port Tobacco River are most likely sufficient to allow the marshes to keep pace with a 7 mm/yr increase in the current rate of sea level

[579]Clearwater, D., P. Turgeon, C. Noble, and J. LaBranche, 2000, An Overview of Wetlands and Water Resources of Maryland, prepared by the Maryland Department of the Environment for the Maryland Wetland Conservation Plan Work Group, January.
[580]Berman, M.R., Berquist, H., Dewing, S., Hershner, C.H., Rudnicky, T., Barbosa, A., Schatt, D.E., Weiss, D., and H. Woods, 2003, St. Mary's County, Maryland Shoreline Situation Report, Comprehensive Coastal Inventory Program, Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, VA, Tables 6 and 7.
[581]Ibid.

[582]Fleming et al., 2006 (see note 67).

rise. Based on its status as a military site, protection is uncertain at the Blossom Point Proving Ground's highly eroding marshes on the eastern side of the mouth of Nanjemoy Creek.

The Nanjemoy Peninsula is considered an area of great ecological significance and therefore TNC, the Conservation Fund, the Conservancy of Charles County, the Maryland Department of Natural Resources, and the federal Bureau of Land Management have all sought to acquire and carefully manage the area.[583] The TNC-owned rookery along Nanjemoy Creek contains one of the largest great blue heronries on the East Coast. Blue herons nesting within the rookery feed on fish and other aquatic organisms found in the peninsula's wetlands and the shallow waters of the creek and the Potomac River; TNC has also purchased an option for 850 ha (2,100 acres) along Nanjemoy Creek to protect the dwarf wedge mussel, a federally and state-listed freshwater mussel. The creek is one of only four known sites where the mussel is found within Maryland, and is considered the largest and most viable population in the state.[584]

The remaining shoreline along the Lower Potomac in Maryland is characterized by highly eroding beaches up through Mattawoman Creek. These shorelines are unprotected and primarily adjacent to agricultural lands, which should allow for shoreline migration. Two areas of marsh, one at Halfway Creek and one with high erosion at Mallows Bay, break up the beach shorelines in this reach of the Potomac River.

Where brackish tidal marshes are lost, nesting, foraging, roosting, and stopover areas for migrating birds would be lost. Significant concentrations of migrating waterfowl forage and overwinter in the marshes of the Lower Potomac in fall and winter, including black duck, greater and lesser scaup, brant, mallard, Canada goose, northern pintail, oldsquaw, and scoters.

Herons and egrets feed on fish and invertebrates, and ducks feed on seeds and submerged plants. 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, which nest in nearby wooded areas and feed on fish and invertebrates in marshes and tidal creeks, and northern harrier, which nest and forage in marshes.[585]

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.[586] The most visible invertebrates of the brackish marshes are red-jointed fiddler crab, marsh periwinkle, Atlantic ribbed mussel, and common clam worm.[587]

The tidal freshwater marshes support additional species that are rare in brackish environments. Green frog, southern leopard frog, redbelly turtle, Eastern painted turtle, Eastern ribbon snake, and northern water snake are all found in the tidal freshwater marshes of the Chesapeake Bay region. Perching birds such as red-winged blackbirds are common in stands of cattail.[588]

Without nourishment, beaches and tidal flats in front of shoreline protections in this area will erode as seas rise. These habitats often contain a high diversity and abundance of species ranging from microscopic organisms that live between sediment grains and can reach 2 billion individuals per square meter[589] to filter-feeding bivalves and deposit-feeders such as fiddler crabs and mud snails found just below the surface. In turn, numerous predators feed on

[583]U.S. Bureau of Land Management, 2004, Lower Potomac River Proposed Coordinated Management Plan, prepared in cooperation with the State of Maryland Department of Natural Resources, Annapolis. April, p. 72.
[584]Maryland Department of Natural Resources, 2005, Maryland Tributary Strategy, Lower Potomac River Basin Summary Report for 1985–2003 data, Maryland Department of Natural Resources, Annapolis, p. 2.

[585]White, 1989, pp. 107–123 (see note 25).
[586]White, 1989, p. 85 (see note 25).
[587]White, 1989, p. 124 (see note 25).
[588]White, 1989, pp. 107–109 (see note 25).
[589]Bertness, 1999, p. 256 (see note 133).

these invertebrates, including snails, blue crab, and a variety of fishes and birds.[590]

Lower Potomac, Virginia Shoreline

On the Virginia side of the Lower Potomac, shoreline protection is almost certain throughout Northumberland County, with shoreline protection already in place for much of the developed land (see Section 3.14). Beaches and tidal flats line the Potomac shore of Northumberland County, and low vegetated banks and brackish marsh edge the many coves and inlets.[591] Most of the county is almost certain to be protected, leading to erosion of unnourished beaches and preventing marsh migration.

In Westmoreland County, from the Yecomico River to Currioman Bay, most areas are likely or almost certain to be protected. Much of the likely protected areas of the Potomac shoreline are bordered by brackish marshes, which may be inundated under most sea level rise acceleration scenarios due to insufficient accretion and the inability to migrate. In these areas, wetlands may be replaced by SAV beds.

Farther upstream, Westmoreland State Park has undeveloped bluffs up to 45.7 m (150 ft) high with narrow sandy beaches along the shore. With shoreline protection unlikely, continued cliff erosion is presumed, which will provide sediment to maintain the beach toe against increasing sea level rise.

The highly developed areas near Colonial Beach are almost certain to be protected. Although some brackish marshes may be lost along the Potomac shore, tributaries on either side of the area are unlikely to be protected, which should preserve wetland habitats in these areas. However, unless nourished, the rocky, sandy shoreline at Colonial Beach may be lost due to the close proximity of residential development to the water.

In King George County, the Mathias Point Neck area is almost certain to be protected, The shoreline is a mix of narrow sand beaches, wooded banks, and marsh areas, with jetties and docks extending into the water. There is a large fringing bed of SAV, dominated by milfoil, wild celery, and hydrilla,[592] from the Upper Machodoc Creek to Mathias Point, with smaller beds between Mathias Point and Quantico.[593]

Farther upstream are the Caledon Natural Area and the adjoining Chotank Creek Natural Area Preserve, which is part of the Cedar Grove Farm conservation easements. At the eastern edge of the Caledon Natural Area, shoreline protection is likely on the northern side of Chotank Creek. Protection is unlikely, however, on the southern side of the creek, which may allow sufficient area for wetland migration.

The Caledon Natural Area and the Chotank Preserve provide a diversity of habitats that are potentially vulnerable to sea level rise and shoreline protection. Along the shoreline at Caledon is a narrow strip of sand-gravel beach backed by freshwater tidal marsh dominated by cattails and *Phragmites*. In shallow areas, the marshes are dominated by pickerelweed and arrow arum. Marsh areas are backed by swamp forest of sweet gum and oak. Some of the swamp trees that have died because of excess standing water now provide nesting sites for bald eagles. Red headed woodpeckers are also seen nesting in these areas.

Even if the rate of sea level rise increases by 7 mm per year, these marshes are likely to be able to migrate inland. The marshes provide habitat for catfish, perch, sunfish, and carp, and support numerous turtles, including the red-eared palm slider and its close relative the yellow-belly palm slider, painted turtles, and snapping turtles. Green heron, great blue heron, and the

[590]For general information on the fauna of soft-sediment habitats, see Bertness, 1999 (see note 133).

[591]Berman et al., 2002, Northumberland, Table 4 (see note 576).

[592]Species of SAV are provided as examples; in reality, species vary annually. Long-term trends in SAV from DC to Maryland Point are described in Rybicki, N.B. and J. M. Landwehr, 2007, "Long-term changes in abundance and diversity of macrophyte and waterfowl populations in an estuary with exotic macrophytes and improving water quality," *Limnology and Oceanography* 52:1195–1207.

[593]Maryland Department of Natural Resources, 2005, Maryland Tributary Strategy, p. 15 (see note 584).

occasional egret feed on fish and invertebrates in the marshes. Jones Pond within the marsh was breached by Hurricane Ernesto and is now tidal. The pond attracts numerous waterfowl, including Canada geese, tundra swan, and many duck species, including mallards, canvasback, and black ducks. Upstream of Caledon, residential developments line the shore, which is primarily composed of sandy beaches along the Potomac, with freshwater tidal marshes in the upper reaches of tributaries.[594] In the more densely developed areas, shoreline protection is almost certain. Similarly, even in the less dense areas, shore protection is likely. Shoreline protections will inhibit any inland migration of these shoreline habitats.

With the exception of the southern edge of the headwaters of Potomac and Accokeek creeks, protection is likely or almost certain throughout this region. Between these creeks lies the 1,619 ha (4,000 acre) Crow's Nest Peninsula, an area of substantial conservation interest as well as a target for potential development. The peninsula is ecologically noteworthy for its 1,416 ha (3,500 acre) of unfragmented mature hardwood forest, considered the finest remaining example in the Mid-Atlantic coastal plain, and 283 ha (700 acre) of undisturbed tidal freshwater marsh. The marshes include three vegetation zones, defined according to elevation in relation to mean low water. Below mean low water is a zone of yellow pond lily with clusters of American lotus. Next are mixed stands of pickerelweed, arrow arum, spatterdock, and wild rice. At the highest elevation is a zone of marsh hibiscus, smartweed, cardinal flower, big cordgrass, jewelweed, and beggar-ticks.[595]

In addition to their value as a rare example of pristine freshwater tidal marsh, the marshes of Crow's Nest Peninsula provide habitat for numerous bird species, including some 26 species of waterfowl that use the freshwater tidal marshes and wooded swamps for nesting, migration, and overwintering habitat. These include 10 of 13 North American Wildlife Conservation Association Priority Wildlife Species. There is also a large great blue heron rookery along upper Potomac creek that supports more than 600 nests. The marshes also provide valuable spawning and nursery habitat for a number of economically important recreational and commercial fish species, including striped bass, alewife, blueback herring, white perch, hickory shad, and yellow perch.[596]

Although currently not developed, the potential for future development makes shore protection along Crow's Nest Peninsula likely. The fringing wetlands would be unable to migrate in these areas if shore protections were implemented (and potentially unable to migrate in the absence of protections, given the bank heights in many areas). However, sediment accretion is likely to be sufficient to maintain wetlands in place even if the rate of sea level rise increases by 7 mm per year above the current rate.

In Aquia Creek, to the north of Crow's Nest Peninsula, shoreline protection is almost certain. Several areas already have breakwaters (e.g., eastern shore of Aquia Landing) that might disrupt sediment transport, potentially preventing sufficient marsh accretion (e.g., in the freshwater tidal marshes on the western side of Aquia Landing). Sandy beach occurs near the mouth of Aquia Creek. The remainder of the county shoreline north of Aquia Creek is also primarily sandy beach, about two-thirds considered by planners as likely to be protected and one-third almost certain. Without nourishment, these beaches are likely to be eliminated in areas where armoring restricts shoreline retreat.

[594]NOAA, 2005 (see note 538).
[595]USFWS, 2000, Final Environmental Assessment: Proposed Accokeek National Wildlife Refuge, USFWS Region 5, October, pp. 11–12.
[596]USFWS, 2000, pp. 12–18 (see note 595).

3.15 Upper Potomac

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Species and habitats along the Upper Potomac River are potentially at risk because of sea level rise. The Upper Potomac extends from Mattawoman Creek upstream to the head of tide of the Potomac River near Georgetown in the District of Columbia (DC) and to the head of tide of the Anacostia River near Bladensburg, Maryland. The region contains important habitats for a variety of fish, shellfish, and birds, and a great deal is known about the ecology and habitat needs of these species. Based on existing literature and the knowledge of local scientists, this brief literature review discusses those species that could be at risk because of further habitat loss resulting from sea level rise and shoreline protection (see map in Chesapeake Bay review). 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.

The Upper Potomac is the tidal freshwater portion of the river (salinity less than 0.5 ppt). In this area, the Potomac's eastern shore passes through Charles and Prince George's counties, Maryland, and DC; the western shore passes through King George, Stafford, Prince William, Fairfax, Alexandria, and Arlington counties in Virginia.

With accelerated sea level rise, the habitat effects in this study region may include the following:

- Tidal freshwater marshes are unlikely to be lost, at least not in their entirety. A panel of accretion experts convened for this report concluded that tidal freshwater marshes in the Chesapeake Bay region can keep pace with sea level rise, possibly even in the face of a 7 mm/yr increase in the current rate of sea level rise (Section 2.1). Thus, it is likely that the tidal freshwater marshes of Mason Neck, Dyke Marsh, Roosevelt Island, and the Anacostia estuary could all keep pace with sea level rise, even if the rate of sea level rise increases by 7 mm/yr. However, erosion may contribute to reductions in the area of marshes, and migration potential is limited because of inland development.

- Small pockets of estuarine beach and mudflat are found at many sites along the shorelines of the Upper Potomac, and in the DC area these habitats are backed by coastal wooded swamps. Some locations (e.g., Indian Head) have more prominent stretches of sandy beach, but for the most part unconsolidated soft-sediment habitats are only a minor component of the shoreline in the study region. These shorelines will erode as sea levels rise, and beaches will be lost except where there is nourishment.

- Where cliffs and bluffs along the Upper Potomac are protected to preserve property, erosional processes may no longer supply adequate sediment to maintain the beaches below.

- Where SAV occurs along coves, shoreline armoring may lead to loss of SAV due to increased wave energy. Where wetlands recede, SAV could spread landward via vegetative spread or if propagules or seeds reach sites with suitable growing conditions.

Upper Potomac, Maryland shoreline

On the Maryland side of the Upper Potomac River, we do not know whether the Department of Defense will choose to protect the shoreline at the Indian Head Naval Surface Warfare Center to the north of Mattawoman Creek. There is currently minimal shoreline protection, and if there is no beach nourishment as seas continue to rise, sand and mud shorelines will erode. The town of Indian Head has a developed shoreline with narrow beaches and piers, and local planners expect that the town is almost certain to be protected. Above Fort Washington shoreline protection is also almost certain; some areas are already protected with riprap.[597] These shorelines will erode in front of hard structures. Not only will this eliminate habitat for beach invertebrates, but increased sedimentation of nearshore waters will also impair SAV and other habitat for popular recreational fish species such as striped bass, largemouth bass, and yellow perch.

Because of the presence of several large parks and undeveloped areas, shoreline protection is unlikely from Indian Head north into Prince George's County, and the high banks in this area will prevent migration. However, the tall cliffs on the Potomac north of the Indian Head facility are likely to be protected to preserve property at the top of the cliffs.

Along the natural shorelines of Roosevelt Island in DC, shore protection is unlikely. The island consists of both upland and swamp forest as well as tidal marsh. Fish in the marsh provide food for herons, egrets, and other marsh birds. Snapping and painted turtles use the nearshore waters and shoreline for forage and resting.[598] The ability of the tidal marshes of the island to keep pace with sea level rise will depend in part on the supply of sediment. Increased inundation of the swamp forest with rising seas could result in crown dieback and tree mortality.[599]

[597]Berman, M.R., Berquist, H., Killeen, S., Nunez, K., Rudnicky, T., Schatt, D.E., Weiss, D. and K. Reay, 2006, Prince George's County, Maryland—Shoreline Situation Report, Comprehensive Coastal Inventory Program, Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, VA.
[598]National Park Service, Description of Roosevelt Island, accessed at http://www.nps.gov/gwmp/pac/tri/backgrnd.html on July 20 2006.
[599]Lippson and Lippson, 2006, p. 218 (see note 2).

Elsewhere in Washington, D.C., the Potomac shoreline is already largely hardened, and therefore minimal additional habitat change is expected as a result of sea level rise. Because it is a major population center, some form of shore protection is almost certain throughout the area. Currently, the District is most likely to use environmentally sensitive means of shore protection rather than allowing inland migration.

Some shores of the Anacostia River may prove an exception to the general approach of preventing migration. Historically, the Anacostia included extensive freshwater wetlands. As human development proceeded, the river was dredged from its mouth at the Potomac in DC to Bladensburg, Maryland, and a stone seawall was built along the shoreline, eliminating virtually all historical wetlands.[600] The tidal Kingman and Kenilworth lakes were dredged, but over time they filled with sediment. In recent decades local organizations have been working to restore some of the former wetlands on the sediments in these lakes. Restoration of the 13 ha (32 acre) Kenilworth Marsh was completed in 1993; restoration of the Kingman Lake marshes began in 2000.[601] Other efforts to restore the river include converting of some seawalls and bulkheads to woodland buffers. As seas rise, local planners expect that some marsh migration may be allowed on Kingman Island, although parts of the island may also be armored to continue to protect some dryland uses, resulting in marsh erosion. Loss of any marsh along the Anacostia would have a notable impact because so little of this habitat is left. Monitoring of the restored habitats demonstrates that these marshes can be very productive. For example, a recent bird survey identified 177 species of birds in the marshes comprising 14 taxonomic orders and 16 families,[602] including shorebirds, gulls, terns, passerines, and raptors as well as marsh nesting

[600]See website describing wetland restoration in the Anacostia by Dr. Dick Hammerschlag of the Patuxent Wildlife Research Center, the lead scientist monitoring recovery of wetland habitats and biota: http://www.pwrc.usgs.gov/resshow/hammerschlag/anacostia.cfm.
[601]Ibid.
[602]Paul, M., C. Krafft, and D. Hammerschlag, 2004, Avian Comparisons between Kingman and Kenilworth Marshes, Final Report 2001–2004, p. 4. USGS publication available online at: http://www.pwrc.usgs.gov/resshow/hammerschlag/anacostia.cfm.

species such as marsh wren and swamp sparrow.[603]

Upper Potomac, Virginia shoreline

On the Virginia side, much of the Prince William County shoreline of the Potomac is sandy beach, and almost certain to be protected.[604] In the few areas where shoreline protection is unlikely, marshes will have little opportunity to migrate because most shores are developed. However, accretion rates in the Upper Potomac are likely to be sufficient to meet most sea level rise acceleration scenarios, including a 7 mm/yr accelerated rate.

Several state parks and federal wildlife refuges in Prince William County adjoin the Potomac shoreline. The Potomac River National Wildlife Refuge Complex includes the Featherstone National Wildlife Refuge across from Leesylvania State Park, the Occoquan National Wildlife Refuge at the confluence of the Potomac and Occoquan rivers on Occoquan-Belmont Bay, and the Mason Neck National Wildlife Refuge across the Bay on the Mason Neck Peninsula (Mason Neck).

The parklands on Mason Neck Peninsula are unlikely to be protected, particularly Mason Neck National Wildlife Refuge and Mason Neck State Park. However, adjacent sites on the eastern end of Mason Neck are almost certain to be protected, which could potentially affect sediment transport in the area and thus affect the ability of the Mason Neck marshes to keep pace with sea level rise.

Wetland loss will reduce habitat for species that are particular conservation targets in the refuge. The Mason Neck National Wildlife Refuge was originally established to protect the federally endangered bald eagle. Today, the 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, with an estimated 1,600 nests. In addition to serving as a major heron rookery and a nesting site for bald eagles, the marsh also provides nesting areas for hawks and waterfowl and a stopover for migratory birds.[605] Herons feed on fish and other aquatic species in the marsh, and teals, mallards, and black ducks feed on marsh plants and seeds.[606] Six bird species, classified as "high priority" by the Atlantic Coast Joint Venture, use the Mason Neck area as overwintering and migration habitat. These include black duck, mallard, pintail, greater and lesser scaup, and the Southern James Bay population of Canada goose. The ducks and Canada goose feed on invertebrates, plant material, and seeds in the flooded marshes and adjacent rivers and lakes. Other priority species such as wood duck, American widgeon, redhead, canvasback, and ring-necked duck use these habitats for foraging and resting. Wood duck and green- and blue-winged teal use the emergent marshes for brood rearing and staging in fall.[607] 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.[608]

Upriver is Fort Belvoir, where protection is uncertain given the military nature of the site. Accotink Bay, adjacent to the fort, has significant areas of tidal marshes, which may be threatened by shore protections at Fort Belvoir. Among the species using the bay are shorebirds, waterfowl, and ospreys.[609]

Beyond Accotink Bay, the Virginia shoreline of the Upper Potomac is almost certain to be

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[603]Paul et al., 2004, p. 11 (see note 602).
[604]NOAA, 2005 (see note 538).

[605]The Mason Neck NWR was established in 1969 as the first federally protected refuge for the bald eagle. A profile of the refuge is available at http://www.fws.gov/Refuges/profiles/index.cfm?id=51610.
[606]Personal observations of J. Bucknam, interpreter, Mason Neck State Park and USFWS fact sheet "Mason Neck National Wildlife Refuge, Potomac River National Wildlife River Refuge Complex," available at: http://www.fws.gov/northeast/facts/MasonNeck06.pdf.
[607]Atlantic Coast Joint Venture, 2005, Revised Waterfowl Implementation Plan—Focus Area Report, Lower Potomac River, Virginia, pp. 485–486.
[608]Watts, 1993 (see note 61).
[609] Virginia Department of Game and Inland Fisheries, Accotink Bay Wildlife Refuge, Army Garrison Fort Belvoir. Accessed December 5, 2007 at: http://www.dgif.state.va.us/wildlife/vbwt/site.asp?trail=1&site=CMN05&loop=CMN.

protected up through Washington D.C., with the possible exception of habitats within National Park Service holdings. The freshwater tidal marsh within the Dyke Marsh Preserve is one of the last major remnants of the original freshwater tidal marshes of the Upper Potomac River,[610] making it particularly valuable for local populations of fish, birds, and other wildlife.

The marsh proper is dominated by cattails, along with several other common freshwater tidal marsh plants, including arrow arum, sweetflag, and spatterdock.[611] Adjacent to the marsh, the Hunting Creek embayment contains one of the largest mudflats along the Upper Potomac River, providing forage areas for both migratory and resident birds.[612] A survey of the marsh in 2000 found 62 species of fish, 9 species of amphibians, 7 species of turtles, 2 species of lizards, 3 species of snakes, 34 species of mammals, and 76 species of birds in Dyke Marsh.[613] The rare least bittern and the federally listed bald eagle breed in the marsh, and scientists at the University of Maryland believe that other rare species such as black rail and American bittern could also breed there.[614] The marsh also contains the only known breeding population of marsh wrens in the upper tidal Potomac.[615] A fish survey between 2001 and 2004 collected longnose gar, a species on Virginia's candidate list. There was substantial evidence of the marsh's importance as juvenile fish habitat, with large numbers of juveniles collected, including juveniles of striped bass, American shad, yellow perch, blueback herring, and alewife. All of these are species that are important for commercial and recreational fisheries in the area. Typical marsh residents such as killifishes, which provide food for these estuarine species, were also collected.[616]

Erosion and subsidence are problems in the marsh today.[617] Previous dredging and marsh removal may be contributing factors, in part because these activities eliminated the tidal creeks that drained the marsh.[618] Much of the current emergent marsh is on a shelf of shallow water about 0.91–1.22 m (3–4 ft) above mean low tide and is therefore not inundated during the marsh's typical 3 ft tidal cycle.[619]

Scientists analyzing current marsh conditions to make recommendations to the National Park Service about restoration of the marsh concluded that responses of the marsh's vegetation communities to inundation will require additional study to predict the effects of sea level rise on the existing marsh or any new marsh that is created.[620]

[610]Johnston, D.W., 2000, "The Dyke Marsh preserve ecosystem," *Virginia Journal of Marine Science* 51:223–273, p. 242.
[611]Ibid.
[612]Ibid., p. 228.
[613]Engelhardt, K.A. M., S. Seagle, and K.N. Hopfensperger, 2005, Should We Restore Dyke Marsh? A Management Dilemma Facing George Washington Memorial Parkway, Final Report, submitted to the George Washington Memorial Parkway, National Park Service, National Capital Region, McLean, VA, p. 4.
[614]Gates, J.E., and R. Peet, 2005, Birds of Dyke Marsh Wildlife Preserve Virginia: A Ten-Year Analysis of Transect Count Data. Unpublished manuscript submitted to Melissa Kangas of the National Park Service, National Capital Region National Parks, McLean, VA. September 5. pp. 25–26.
[615]Johnston, 2000, p. 248 (see note 610).
[616]Mangold, M. F., R.C. Tipton, S.M. Eyler, and T.M. McCrobie, 2004, Inventory of Fish Species within Dyke Marsh, Potomac River (2001–2004), U.S. Fish and Wildlife Service in conjunction with Maryland Fishery Resources Office, Annapolis, MD, October 22.
[617]Johnston, 2000, pp. 229 and 242 (see note 610).
[618]Engelhardt et al., 2005, p. 2 (see note 613).
[619]Engelhardt et al., 2005, p. 3 (see note 613).
[620]Engelhardt et al., 2005, p. 7 (see note 613).

3.16 Western Shore Chesapeake Bay Shoreline

Authors: ***Ann Shellenbarger Jones and Christina Bosch***

Overview

The western shore region of Chesapeake Bay includes St. Mary's, Calvert, and Anne Arundel counties and Baltimore City and County.[621] Land types in these counties vary from major urban areas such as Baltimore and Annapolis to largely rural areas in Calvert County. The region, particularly Calvert County, is characterized by smoothed shorelines, indicating sufficient sediment supply and longshore transport as compared to the more jagged eastern shore's coves, inlets, and islands.[622]

This brief literature review discusses species that could be at risk because of further habitat loss resulting from sea level rise and shoreline protection. Existing literature and knowledge of coastal scientists in the area appears to be sufficient in many cases to make qualitative statements about the possible impact if sea level rise causes a total loss of habitat, which might be expected if shores are protected with hard structures and the wetlands are unable to keep pace with sea level rise. Our ability is more limited, however, to say what the impact might be if only a portion of the habitat is lost. The major tributaries to Chesapeake Bay on the western shore are the Patuxent River, a major Bay tributary bordering Calvert, St. Mary's, Charles, and Prince George's counties; the South River and the Severn River in Anne Arundel County; the Patapsco River on the southern side of Baltimore; and the Gunpowder River, straddling the border of Baltimore and Harford counties. Western shore tidal wetlands are primarily located in these tributaries, in particular, at the mouth of the Gunpowder, at Jug Bay in the Patuxent, and in Sullivan's Cove Marsh and Round Bay Bog on the Severn. Some of these tributaries have been dramatically modified with shoreline protections, yet others have remained largely unchanged. For example, the Patapsco formerly supported populations of anadromous fish, but urbanization along its banks and installation of dams along its course have since prevented their migration.[623] In contrast, the Severn's steep cliffs and deep ravines earned it a designation of Scenic River by the Maryland General Assembly.

The western shore will see a range of impacts from sea level rise in the future. Despite large areas of conservation or parkland and restricted development (e.g. upper Patuxent River, Calvert Cliffs), loss of key habitats may occur. The large degree of shoreline armoring from northern Calvert County through Baltimore will also affect shoreline retreat. The overall environmental impact of sea level rise in this multicounty region are likely to include the following:

- Partial or complete marsh loss is expected in many areas. In the upper Patuxent River, marsh areas have experienced minimal migration despite inundation. 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 foraging and nesting for the large bird population, including many sensitive species.
- *Beach* loss, particularly in St. Mary's, Calvert, and Anne Arundel counties along

[621]This review looks at ecological implications of sea level rise from Baltimore County through the northern half of St. Mary's County, including its Patuxent River shoreline.
[622]Stevenson and Kearney, 1996, p. 234 (see note 38).

[623]Alliance for the Chesapeake Bay, n.d., River Summaries, accessed on May 3, 2006, at http://www.acb-online.org/about.cfm.

Chesapeake Bay, may occur in areas without nourishment. The widespread presence of shoreline protection can interfere with longshore transport. Beach loss or reduction may occur even in areas where shoreline retreat is possible. Many invertebrates will lose their habitat, including the northeastern beach tiger beetle (federally listed as threatened).

- The *cliffs* of Calvert County will not be lost, but effects from increased rates of sea level rise and impediments to longshore sediment transport may increase erosion rates above sustainable levels for the resident populations. The Puritan tiger beetle (federally listed as threatened) may lose essential habitat.
- Effects on *nearshore* communities may be observed. In the upper Patuxent River, the spread of SAV more tolerant of deeper depths and higher turbidity (*Hydrilla*) may be accompanied by a decrease in larger fish, though its spread may be tempered by changes in salinity.[624]

Sediment deposition is fairly high along the western shore of Chesapeake Bay, both from land runoff and erosion. Along the bay shorelines, marsh areas are expected to be marginal with a 2 mm per year rate increase in sea level rise and to be lost with a 7 mm per year increase. The ability to migrate will most likely determine their survival. In upper reaches of tributaries, marsh accretion should be sufficient to meet a 7 mm per year increase in the rate of sea level rise (Section 2.1). However, localized areas may have differing rates of accretion, subsidence, and erosion, and some wetlands on the western shore are being inundated (e.g., in Jug Bay on the upper Patuxent). Planners indicate that shoreline protections are almost certain throughout much of Anne Arundel and Baltimore City/County, which will most likely lead to the loss of both intertidal areas and wetlands with sea level rise rate increases of 2 mm per year.

St. Mary's County, Chesapeake shoreline

Beginning at the southern tip of St. Mary's County, the bay-front shoreline between the Potomac and the Patuxent rivers is primarily narrow sandy beaches with low bank heights (less than 5 feet). Erosion is a significant problem: more than half the beach is eroding, although a large portion of the remaining shoreline is already stabilized with bulkheads or riprap.[625] Erosion is likely to be a problem on the beaches fronting shoreline protections and may be so in other areas as well. In general, beach loss will lead to habitat loss for resident insects and other invertebrates and forage loss for larger predators such as shorebirds.[626] Estuarine marshes line the many small coves. Given existing erosion, these marshes are unlikely to accrete or migrate sufficiently to retain their current size, even in unprotected areas. Wetlands loss harms the crustaceans, mollusks, and other invertebrates that live in close association with the wetland vegetation and the turtles (e.g. diamondback terrapins) and birds (e.g. ducks, rails) that forage on them.[627] At Point Lookout State Park (CBIM location 38), a loblolly pine tidal woodland is already being lost to relative sea level rise. Saltwater intrusion across the fronting estuarine marsh is killing trees as a result of salt stress and increased inundation.[628,629] Tidal hardwoods such as loblolly pines provide nesting sites for piscivorous species such as ospreys, bald eagles, and double-crested cormorants.[630]

Patuxent River

Erosion is also an issue in the lower Patuxent River. The St. Mary's County shoreline is a mix of low to high banks, mostly with trees and shrubs or residential development, with

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[624]See Section 3.1 for general background on species and habitats vulnerable to sea level rise for the mid-Atlantic. It includes overview information on salinity and other factors not discussed in detail here.

[625]Berman et al., 2003, St. Mary's County (see note 580).
[626]Lippson and Lippson, 2006, pp. 26–42 (see note 2).
[627]Lippson and Lippson, 2006, pp. 201–239 (see note 2).
[628]Tiner and Burke, 1995, Plate 7 (see note 32).
[629]Harrison, J.W., P. Stango III, and M.C. Aguirre, 2004, Forested tidal wetland communities of Maryland's Eastern Shore: Identification, assessment, and monitoring, Maryland Department of Natural Resources, Natural Heritage Program, Annapolis, MD, unpublished report submitted to U.S. EPA.
[630]Robbins and Blom, 1996, pp. 44 and 92–94 (see note 552).

significant erosion rates in the higher banks.[631] The immediate shores are primarily vegetated bank with a minimal intertidal area; roughly 15 percent are fronted by sandy beaches and 25 percent by marshes.[632] Erosion is prevalent through all shoreline types. The Calvert County shoreline is assumed to be similar in this region. Planners indicate that shoreline protections are almost certain for the first few miles of the river, but further up are unlikely. Given current erosion rates and low rates of accretion near Chesapeake Bay, marsh areas are likely to be inundated in the protected areas. Some marsh migration may occur at the northern end of St. Mary's County, but the high banks in many locations will inhibit migration, resulting in net loss of marsh areas.

North from the Prince George's and Charles County border, large areas of tidal estuarine marsh line the Patuxent River, changing to tidal freshwater above the Anne Arundel County line.[633] Shoreline protection is unlikely in this area. Sediment inputs are predicted to be high enough to retain marsh area, but naturalists at Jug Bay in the upper Patuxent River (CBIM location 41) have observed inundation and minimal migration of low marsh, with direct conversion of wooded or high marsh areas to open water.[634] The marsh has decreased visibly in size over the last 25 years, with the appearance of more emergent vegetation (e.g., spatterdock, *Nuphar luteum*) as water depth increases. In the Jug Bay Sanctuary, as erosion continues and water levels rise, spatterdock is becoming submerged and is being displaced by the highly invasive *Hydrilla verticillata*, which can tolerate deeper waters and reduced light, and higher suspended sediment loads is filling in open water and unvegetated mudflat areas. Spatterdock, a perennial, grows before *Hydrilla* in the spring, and has not been affected by the increase in *Hydrilla*.[635] Although *Hydrilla* may displace other native vegetation or become sufficiently dense to prohibit movement of larger fish, the species does improve water quality (as compared to the absence of vegetation) by trapping sediments, contributing oxygen, and increasing carbon dioxide uptake, and may provide sheltering habitat for smaller fish.[636] The increasing water depth has also compounded stress on local vegetation and on the birds that feed on the plants. Migrating populations of Sora rails (*Porzana carolina*), a marsh-dependent species that feed primarily on seed and green plant matter, declined in Jug Bay throughout the 1990s because of overgrazing of one of their primary food sources (wild rice, *Z. aquatica*) by resident Canada geese (*Branta canadensis*).[637,638] Wild rice restoration efforts have been affected by the increasing water depths. The rice survives regular tidal inundation of up to 2 feet, and usually stands in roughly 6 to 12 inches of water, but under additional stresses such as the foraging of resident Canada geese is less resilient. Unusually cold and wet weather in the spring of 2005 and 2006, with associated higher water levels in the marsh, hindered wild rice growth in the lower marsh. Wild rice in the upper marsh areas was not adversely affected, and even

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[631]The St. Mary's County Patuxent River shoreline is more than 40 percent low bank (0–5 feet), 10 percent medium (5–10 feet), more than 25 percent high (10–30 feet), and more than 10 percent above 30 feet. Berman et al., 2003 (see note 580).
[632]Berman et al., 2003 (see note 580).
[633]Tiner and Burke, 1995 (see note 32).
[634]Phone conversations on April 27 and December 1, 2006, and email confirmation "Re: Final review of Patuxent section of report," of discussions about Jug Bay, and 25 years of observations there, between IEc and Greg Kearns, naturalist, Jug Bay Natural Area.

[635]Phone conversation, including description of *Hydrilla* and its current presence, characteristics, and relation to spatterdock in the Patuxent marshes. Greg Kearns, naturalist, Jug Bay Natural Area, December 1, 2006.
[636]Nonindigenous aquatic species: *Hydrilla verticillata*, accessed on May 30, 2006, at http://nas.er.usgs.gov/taxgroup/plants/docs/hy_verti.html; Plant Invaders of Mid-Atlantic Natural Areas, accessed on May 30, 2006, at http://www.nps.gov/plants/alien/pubs/midatlantic/hyve.htm; and phone conversation with Greg Kearns (see note 636).
[637]Gough, G.A., J.R. Sauer, and M. Iliff, 1998, *Patuxent Bird Identification Infocenter,* version 97.1, Patuxent Wildlife Research Center, Laurel, MD, available at: http://www.mbr-pwrc.usgs.gov/id/framlst/infocenter.html.
[638]Phone conversation, including discussion of sora rail populations, dependence on wild rice, and efforts to monitor and restore wild rice. Greg Kearns, April 27, 2006. Confirmed by email "Re: Final review of Patuxent section of report," on December 1, 2006. Note: smartweeds (*Polygonum* spp.) are also important in diets of sora rails.

increased its coverage dramatically in some areas.[639,640]

Calvert County/Chesapeake shoreline

Returning to Chesapeake Bay at the mouth of the Patuxent River, Cove Point (CBIM location 39) has a unique shoreline formation, the cuspate foreland. The foreland results when sand is moved along a shoreline predominantly in one direction, and then hits a geologic formation that traps the sand. A point forms with sands accreting on the downshore side of the cusp. Cove Point Marsh is a 150-acre freshwater, barrier-beach marsh on the upshore side of the cusp. Numerous state-defined rare plant species, including American frog's-bit (*Limnobium spongia*), silver plumegrass (*Erianthus alopecuroides*), various ferns, and unique wetland communities,[641] as well as populations of the northeastern beach tiger beetle, and the Puritan tiger beetle (both federally listed as threatened), and the rare leaf beetle *Glyptina maritima*, are present there. The marsh side is threatened by storm-driven overwash, sea level rise, and residential development on the south side, which has disrupted the migration of the foreland in recent decades. The marsh is continuing to migrate, but will soon hit the northern edge of the development. Shoreline protections to the north may limit sediment inputs to the marsh that would otherwise allow accretion to keep up with sea level rise.[642] The marsh area will slowly be lost as the outer edge is eroded and inundated, endangering the many rare plants in the marsh. The upstream protections may be leading to significant erosion and coincidental loss of northeastern beach tiger beetle larval habitat areas north and south of the Cove Point pier, the likely causes of decline in the local population.[643]

North of Cove Point are the Calvert Cliffs (CBIM location 40), which formed during the Miocene epoch when Chesapeake Bay was a shallow sea. The cliffs are the remnants of the sea floor, now standing up to 115 feet above the water. Fossilized remains are exposed as wind and water erode the cliffs at a rate up to 2.75 feet per year.[644] The area inland of the cliffs in southern Calvert County is largely undeveloped (primarily because of the presence of the Calvert Cliffs Nuclear Power Station), but more development is present along the northern shoreline. The northeastern beach tiger beetle and the Puritan tiger beetle both depend on the naturally eroding cliffs and the sandy fronting beaches of the Calvert Cliffs for habitat, both as larvae and as adults. Puritan tiger beetle populations at Calvert Cliffs have been declining in recent years, in part owing to habitat loss.[645] The larvae require a moderate amount of cliff face erosion, although exact rates are unknown. Continuous erosion prevents vegetation from establishing on the beaches or cliffs, maintaining the necessary bare substrate for the beetles. In areas where cliff erosion is slowed by increased toe elevation or armoring, the cliff face subsides into a more modest slope, and vegetation then stabilizes it. At Calvert Beach, larvae and adults were absent from the areas stabilized by vegetation, but were present on sandy bluff faces.[646] According to a beetle expert, in areas where beach is entirely submerged at high to mid-tides, few to no Puritan tiger beetles are present.[647] In contrast to areas stabilized by

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[639] Phone conversation, including description of observations of vegetation dynamics by Greg Kearns, April, 27, 2006, and confirmed by email "Re: Final review of Patuxent section of report," on December 1, 2006. Aerial photographs described by Kearns have captured these changes in wild rice coverage.

[640] Wild rice also occurs in the freshwater portions of the York, Potomac, and Choptank rivers (Lippson and Lippson, 2006, p. 208, see note 2).

[641] Steury, B., 2002, "The vascular flora of Cove Point, Calvert County, Maryland," *The Maryland Naturalist* 45(2):1–28, pp. 16, 21.

[642] Email communication from Katharine McCarthy, Southern Regional Ecologist, Natural Heritage Program, Wildlife and Heritage Service, Maryland DNR, to Ann Shellenbarger Jones and Christina Bosch, Industrial Economics. "RE: Calvert Cliffs State Park" including confirmation of prior emails, and text in draft report. Sent September 11, 2006.

[643] Knisley, C.B., 2000, Population decline of the northeastern beach tiger beetle in Calvert County, MD. Final Report, submitted to Cove Point Natural Heritage Trust, January 18.

[644] Calvert Cliffs State Park, accessed on May 9, 2006, at http://www.dnr.state.md.us/baylinks/15.html.

[645] Knisley, 2000 (see note 643).

[646] USFWS, 1993 (see note 166).

[647] Peer review comment by Barry Knisely on this section on the Western Shore Chesapeake Bay Shoreline, received July 20, 2007.

vegetation, as cliff erosion increases because of loss of toe elevation, winter storm waves shear off large portions of cliff and may kill larvae in localized areas.[648] If erosion occurred at rates high enough to shear of areas to a depth below larvae burrows, Puritan tiger beetles could be eliminated. Impacts to adult Puritan tiger beetles may also occur if sea level rise or increased erosion diminishes the beach habitats used for foraging.[649]

Although 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 affecting the Calvert Cliffs shoreline. Effects on longshore sediment transport from upstream shoreline protections are an identified cause of increased erosion rates.[650] In addition, there is increasing pressure for shoreline stabilization along the more southern shoreline (in particular near Little Cove Point), and revetments and other shoreline stabilization projects have been recently constructed or are proposed.[651] Unfortunately, overly rapid erosion is also a threat to the Puritan tiger beetle, owing to shearing of cliff habitat. Shoreline protections are almost certain along much of the developed northern coast of Calvert County, which may increase erosion rates in the unprotected southern cliff areas beyond the range required by the tiger beetles. In the more northern areas where the cliffs are stabilized, the rocky and sandy toes to the cliffs will be lost to inundation with sea level rise, along with the invertebrate community (e.g., burrowing amphipods and hermit crabs) that resides there.

Anne Arundel County

Anne Arundel County has dense residential development near its primarily sandy bay shoreline. Shady Side (CBIM location 42), at the southern end, is located on a peninsula surrounded on two sides by the West River, and on a third by Chesapeake Bay. The area is generally at low elevation above the water level and highly developed.[652] Given the already severely limited state of tidal wetlands, the primary effect of sea level rise in Shady Side will most likely be more frequent upland flood events. Large portions of the shoreline are already protected, with future protection almost certain along most of the shoreline.[653] The interior areas of the Shady Side peninsula are marked by nontidal wetlands. The myriad creeks and streams that cross the Shady Side wetlands provide spawning and nursery areas for freshwater, estuarine, and anadromous fish such as striped bass, white perch, spot, croaker, and a variety of forage fish.[654] Increased inundation events in the nontidal freshwater areas with higher salinity water could cause significant habitat decline in freshwater species.[655] Farther north in the county, higher elevations limit the wetlands close to the coastline. However, Anne Arundel County does have a policy of encouraging and supporting nonstructural or hybrid shoreline protection projects. The County provides free technical support, site evaluation, and plant plugs (*S. alterniflora* and *S. patens*) for residents.[656] With the likelihood of almost certain shoreline protections throughout, the current

[648]U.S. FWS, 1993 (see note 166).
[649]Barry Knisely (see note 647).
[650]Wilcock et al., 1998 (see note 161).
[651]Barry Knisely (see note 647); and USFWS, 2006, Pre-decisional draft biological opinion on "Chesapeake Ranch Estates/Phase V/Breakwater," Accessed on July 26, 2007, at: http://www.fws.gov/northeast/Endangered/tebo/PDFs/CHES.RANCH.BO.revised%20project6.pdf.

[652]The elevation ranges from 3 to 10 feet, with an average of 7. Anne Arundel County Small Planning Area Plan for Deale/Shady Side, Section X. Land Use and Zoning, p. 71, accessed on May 5, 2006, at http://www.aacounty.org/PlanZone/SAP/DealeSS.cfm.
[653]More than 75 percent (1,609 out of 2,120) of parcels studied had shoreline improvements in place. Michael, J.A., D.A. Sides, and T.E. Sullivan, 2003, The economic cost of sea level rise to three Chesapeake Bay communities. NOAA, Maryland DNR, and Center for Geographic Information Sciences at Towson University.
[654]Anne Arundel County Small Planning Area Plan (see note 652).
[655]Bay waters at Shady Side average between 5–10 ppt salinity in spring and summer and 10–15 ppt in fall. Average Surface Salinities Map, accessed on May 30, 2006, at: http://mddnr.chesapeakebay.net/eyesonthebay/images/bay_salinity.jpg.
[656]Anne Arundel County, Maryland, Office of Environmental and Cultural Resources, 2006, Emergent Marsh Grass Re-Vegetation Program, available at: http://www.aacounty.org/LandUse/OECR/EmergentGrasses.cfm. Program discussed in phone conversation with Jim Johnson, May 30, 2006.

intertidal areas will be inundated by sea level rise. The fringing marshes created through Anne Arundel County's shoreline projects may provide key habitat for marsh invertebrates in addition to protecting upland areas. Several rare birds, including the black rail (*Laterallus jamaicensis*), which is listed by the DNR as in need of conservation, breed in the Anne Arundel County marshes.[657]

Baltimore City and County

Planners in both Baltimore City and County anticipate that shore protection is almost certain throughout the area. Almost half of the shoreline already has bulkheads or riprap, particularly along the Patapsco River.[658] The remaining narrow muddy shores and mudflats, particularly in the currently less developed sections of the Patapsco, may be lost because of sea level rise if shorelines are protected. In the upper portion of the Back River north of Baltimore, small areas of wetlands may be able to accrete sufficient sediment to retain function, but migration will be prevented by shoreline protection. Directly on Chesapeake Bay, the large marshes at Edgemere (North Point State Park, CBIM location 43) and Hart-Miller Island may be lost to inundation if the sea level rise rate increases by 2 mm per year, and most will likely be lost with a 7 mm per year increase. Hart-Miller Island, created from dredge material and a haven for migrating shorebirds, has extensive mudflats that will are likely to be lost to sea level rise. During spring and fall migrations, daily numbers of shorebirds range from 1,000 to 10,000. The most numerous shorebird species are sandpipers and plovers. The mudflats are also used as a roost site for significant numbers of migrating Caspian terns (*Sterna caspia*). In 2004, small numbers of three high conservation priority species nested and bred on Hart-Miller Island: the coastal plain subspecies of swamp sparrow (*Melospiza georgiana*), listed by the Maryland Department of Natural Resources as "In Need of Conservation in Maryland," the spotted sandpiper (*Actitis macularia*), a rare species in the state, and the willow flycatcher (*Empidonax traillii*), an Audubon WatchList species.[659] These mudflat areas are all susceptible to inundation from sea level rise. Low-elevation islands such as Hart-Miller have limited habitat migration options and will be dependent on accretion rates (or additional dredged sediment inputs) for maintenance of habitats. Loss of these islands and mudflat areas would eliminate the nesting and foraging opportunities currently provided for the shorebirds.

Wrapup

The Western Shore will see a range of ecological impacts from sea level rise in the future. Most marsh areas near Chesapeake Bay are expected to be marginal with midrange increase in the rate of sea level rise (2 mm per year) and to be lost with a high-range increase (7 mm per year). In upper tributaries, sediment accretion is likely to be sufficient to retain current area under a high-range increase scenario. The extensive shoreline armoring from northern Calvert County through Baltimore City and County will limit shoreline retreat, and eliminate sand and mudflats in front of the protections. Loss of mudflats will eliminate a key stopover for migratory birds (i.e., Hart-Miller Island). With tree death in high marsh and higher water levels already visible in the Patuxent River marshes, sea level rise may induce changes in vegetation types even at current rates and therefore impact the species that rely on them, causing changes similar to those expected in other Bay tributaries such as the Pamunkey in Virginia. In contrast to these potential losses, the protected portions of the Calvert Cliffs will be allowed to continue eroding inland, providing the habitat needed by tiger beetles. Nevertheless, both larval and adult forms of the beetles may suffer impacts of reduced habitat caused by increased erosion and subsequent loss of beach or cliff-face shearing.

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[657]Robbins and Blom, 1996, p. 122 (see note 552).

[658]Maryland Coastal Zone Management Program, Department of Natural Resources, 2004, Development of the Maryland Shoreline Inventory Methods and Guidelines for Baltimore County and the City of Baltimore, prepared by the Comprehensive Coastal Inventory Program, Center for Coastal Resources Management, Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, VA. NOAA Award No. 14-03-889 CZM049.

[659]Audubon Important Bird Areas, Hart-Miller site profile, accessed on May 5, 2006, at http://iba.audubon.org/iba/view SiteProfile.do?siteId=371&navSite=state.

3.17 Upper Chesapeake Bay Shoreline

Author: ***Ann Shellenbarger Jones, Industrial Economics Inc.***

Overview

The “Upper Bay” region encompasses Harford, Cecil and Kent counties, from the Gunpowder River to the Chester River. The region is primarily rural, with several small cities (Aberdeen, Havre de Grace, Perryville, and Elkton) along the coast and tributaries.

This brief literature review discusses species that could be at risk because of further habitat loss resulting from sea level rise and shoreline protection. Existing literature and knowledge of coastal scientists in the area appears to be sufficient in many cases to make qualitative statements about the possible impact if sea level rise causes a total loss of habitat, which might be expected if shores are protected with hard structures and the wetlands are unable to keep pace with sea level rise. Our ability is more limited, however, to say what the impact might be if only a portion of the habitat is lost. Overall effects of sea level rise may include the following:

- Most marsh areas will be retained through accretion. On Eastern Neck, some areas are being lost, but efforts are under way to restore the shoreline using protected *S. alterniflora* marshes. Upper Chesapeake Bay will continue to provide spawning and nursery habitat for crabs and fish, as well as provide nesting and foraging habitat for migratory and residential birds, including bald eagles and large numbers of waterfowl.

- The cliff areas at Elk Neck State Park and the Sassafras River NRMA will be left to erode naturally. The cliff swallows and Puritan tiger beetle (federally listed as threatened) will continue to use the unique habitat. Cliff areas surrounding Grove Point and the Puritan tiger beetle population inhabiting them may be impacted because without nourishment shoreline stabilization may result in loss of beach areas.

- Although some of the beaches may require nourishment for retention, the general lack of shoreline protections will minimize interferences with longshore sediment transport. Beaches are likely to remain intact throughout much of the region.

The Susquehanna, located on the border between Harford and Cecil counties, provides a large (though variable) influx of sediment to upper Chesapeake Bay, as well as almost half of Chesapeake Bay's freshwater input.[660] Much of this sediment is retained above the mixing zone (the estuarine turbidity maximum or ETM), generally above the Chesapeake Bay Bridge.[661] This sediment source provides material for accretion in the tidal wetlands of the region. 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.

Freshwater tidal wetlands are spread throughout upper Chesapeake Bay, particularly in the upper reaches of the tributaries. Key rivers in the areas include the Susquehanna, the Elk, the Sassafras, and the Chester. With the exception of the Susquehanna, with headwaters in New York that are not considered in this report, all of the rivers

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[660] Bay Trends and Indicators, Chesapeake Bay Program, accessed at: http://www.chesapeakebay.net/status/status_dev.cfm?SID=201&SUBJECTAREA=INDICATORS.

[661] Chesapeake Bay Program, 2002, The Impact of Susquehanna Sediments on the Chesapeake Bay, Scientific and Technical Advisory Committee Workshop Report, May 2000.

in upper Chesapeake Bay have tidal wetlands at their head. The high eroding cliffs characteristic of Chesapeake Bay are also found in the region, particularly at the mouths of the Susquehanna, Elk, and Sassafras rivers. The remaining shorelines are primarily a mix of narrow muddy and sandy beaches and low vegetated banks.

Harford County

The Harford County shoreline is predominantly marsh. Aberdeen Proving Ground (CBIM location 44) is its defining feature, constituting approximately a quarter of the county's area and the majority of its Bay shoreline, from the Gunpowder River north almost to the Susquehanna River.[662] The proving ground is primarily within 5 meters of sea level and contains a large concentration of tidal wetlands (20,000 acres). The extent of shoreline protections is uncertain given the military nature of the site.[663] Structural shoreline protections throughout the proving ground shoreline would eliminate the potential for wetland migration. The wetlands may accrete sufficient sediment to meet a 2 mm per year increase in sea level rise rates, but a 7 mm per year increase would result in loss of the tidal marshes and associated ecological functions. In particular, the large bird populations (bald eagles, great blue herons, double-crested cormorants) that migrate through and nest in these marshes would be affected.[664] If structural shoreline protections are minimal, a combination of sediment accretion and inland migration may occur, and wetlands function are likely to be retained at approximately current levels. The headwaters of the Bush River, inland of the Proving Ground, are tidal and nontidal wetlands. Large portions of the associated shoreline are almost certain to be protected, which will prevent migration of the wetlands. Accretion in the upper parts of the tributaries may be sufficient to meet an accelerated sea level rise (high range estimate of 7 mm per year above current rates). At the mouth of the Susquehanna, the shoreline of Havre de Grace is mostly developed and armored, with minimal beach or marsh area.

Cecil County

Across the Susquehanna, in Cecil County, the city of Perryville also has an armored shoreline. Cecil County comprises minimal low-lying land, with most areas above the 20-ft elevation. The majority of the shoreline is not protected, particularly along the Sassafras and Elk rivers, and planners indicate that undeveloped areas are unlikely to be protected in the future. Cliffs line the mouth of the Elk River at Elk Neck State Park (CBIM location 45); despite continuing erosion, planners indicate shore protection is unlikely.[665] The headwaters of the Northeast and Elk rivers are tidal freshwater wetlands, with shore protection considered likely because of the developments on adjacent land. Tidal flats in the Northeast River's upper reaches and adjacent wetlands become important fish spawning areas in the spring.[666] Accretion is expected to be sufficient to meet an accelerated sea level rise because of the large sediment inputs in the Upper Bay, but significant armoring in the developed headwaters could interfere with sediment transport. If accretion rates are not sufficient, wetland migration would be difficult in Cecil County owing to the upland elevation adjacent to the shorelines; consequently, loss of the large tidal fresh marshes could occur. The marshes of the upper reaches of the Elk River are a spawning and nursery area for striped bass and a nursery area for alewife (*Alosa pseudoharengus*), blueback herring (*Alosa aestivalis*), hickory shad

[662] A portion of the Aberdeen Proving Ground is located within Baltimore County.

[663] "Aberdeen Proving Ground Pioneers Approach to Wetland Mitigation," available at: http://aec.army.mil/usaec/publicaffairs/update/win04/win0420.html. Although some protections are required at the site under CERCLA actions to prevent migration of contaminated sediments, the majority of the shoreline is extensive wetlands. National Priorities List Fact sheet for Aberdeen–Edgewood available at: http://www.epa.gov/reg3hwmd/npl/MD2210020036.htm, and http://www.apg.army.mil/apghome/sites/directorates/restor/PDF_ Files/carrolis.pdf.

[664] Maryland DNR Bald Eagle Fact Sheet, accessed on May 23, 2006, at http://www.dnr.state.md.us/wildlife/baldeagle.html.

[665] Maryland Shoreline Changes Online, from the Maryland Department of Natural Resources, Available at http://shorelines.dnr.state.md.us/sc_online.asp.

[666] NOAA, 1994, Environmental Sensitivity Index Maps.

(*Alosa mediocris*), and white perch, as well as a wintering and breeding area for waterfowl.[667]

Kent County

At the southern border of Cecil County is the Sassafras River, shared with Kent County. Near the mouth of the river are narrow sandy beaches, backed by low bluffs to high cliffs. Because of high sediment input and limited shoreline armoring, beach loss caused by sea level rise is likely to be minimal. Shore protection is unlikely throughout most of the river. Portions of beach and cliff habitat supporting a population of the Puritan tiger beetle (federally listed as threatened) at and around Grove Point, however, may be stabilized resulting in loss of habitat.[668] In contrast, on the southern shore, one section of cliffs at the Sassafras Natural Resource Management Area (Sassafras NRMA, CBIM location 46) has a population of the Puritan tiger beetle. For this reason, the cliffs in the Sassafras NRMA are allowed to retreat naturally. On the bay shore south of the Sassafras River, Kent County has a higher energy shoreline, with agricultural areas leading down to more generally developed shorelines. Groins, jetties, and bulkheads are all in use along portions of the county's Chesapeake shoreline, but the majority of the shoreline is unlikely to be protected. Sandy and rocky shorelines predominate (e.g., Gratitude, Rock Hall) along with forested riparian buffers. Tidal wetlands are rare along the coast, except in sheltered coves. Shoreline migration can readily occur in the unprotected agricultural areas, minimizing ecological losses. In the sheltered areas near Rock Hall, tidal wetlands may be lost because of the almost certain armoring along the developed areas. Loss of wetlands diminishes habitat for the crustaceans, mollusks, and other invertebrates that feed on and provide nutrients for marsh vegetation and the turtles (e.g., diamondback terrapins) and birds (e.g., ducks, rails) that forage on them. Spawning and nursery areas in marshes for fish will be lost, as will nesting habitat for marsh obligate birds.[669]

At the southern tip of Kent County is the Eastern Neck National Wildlife Refuge (CBIM location 47). Currently, the greatest rates of erosion in the county are found here, on the western shore of the neck and the southeastern tip on the Chester River.[670] Because of its status as a national wildlife refuge, some shoreline protections are being introduced, with the goal of preserving shoreline habitats for the many migratory 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 *Phragmites australis* are the only areas retaining sediment.[671] Practices of removing invasive *P. australis* stands and revegetating with native, noninvasive species have been curtailed in some areas of the refuge, in recognition of the desirable role that *P. australis* plays in retaining soil.[672] Higher levels of substrate accumulation, both below ground and above ground, have been documented in stands of *P. australis* relative to *Spartina* spp.[673] At Eastern Neck, 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.[674]

Thousands of waterfowl winter at Eastern Neck, including Canada geese, tundra swans (*Cygnus columbianus*), and a variety of dabbling and diving ducks, such as mallards, buffleheads (*Bucephala albeola*), red-breasted and hooded mergansers (*Mergus serrator,* and *Lophodytes cucullatus*), scaup, and pintails.[675] Migrating and

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[667]USFWS, 1980, Atlantic coast ecological inventory: Wilmington, No. 39074-A1-EI-250, USFWS, Washington, D.C. As referenced for the Elk River in the Sealand Limited Site description of NOAA trust resources, available at: http://response.restoration.noaa.gov/book_shelf/207_Sealand.pdf (Table 2).
[668]Barry Knisely (see note 647); USFWS, 1993 (see note 166).
[669]Lippson and Lippson, 2006, pp. 201–239 (see note 2).
[670]Maryland Shoreline Changes Online (see note 665).
[671]Written communication, Tom Eagle, Eastern Neck National Wildlife Refuge, to Christina Bosch, Industrial Economics. "Re: Sea level rise report wrap-up - please respond" confirming text citing Tom Eagle in draft report, including this sentence, sent September 11, 2006.
[672]Ibid.
[673]Rooth and Stevenson, 2000, p. 173 (see note 45).
[674]Tom Eagle (see note 671).
[675]January 2005 waterfowl survey results for Eastern Neck National Wildlife Refuge. Accessed online at

residential birds are a primary component of the Eastern Neck ecosystem. Bald eagles nest at Eastern Neck, usually occupying five to seven active nests at the forested riparian edge.[676] Loss of upland to open water will decrease eagle habitat. Historically, Eastern Neck was a site for black duck (*Anas rubripes*) nesting, along with Smith Island, Barren Island, and other locations in the lower Eastern Shore. However, 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, a likely cause of reductions in black duck counts.[677] Loss of tidal marsh at Eastern Neck will reduce suitable habitat for resident and migratory shorebirds. The decreasing size of the upland forested areas will also diminish critical habitat for the Delmarva Peninsula fox squirrel, which resides in forests adjacent to marsh.

Wrapup

Generally, sediment input to upper Chesapeake Bay is expected to maintain shoreline areas at current rates of sea level rise; marshes will be marginal with a 2 mm per year increase in rates, and lost with a 7 mm per year increase. The Eastern Neck National Wildlife Refuge and the Cecil County marshes in the Elk River are the only areas identified in the Upper Bay as likely to be negatively impacted because of sea level rise. Eastern Neck has already lost marsh areas to open water, and continued loss will limit habitat for bald eagles, the Delmarva Peninsula fox squirrel, and marsh birds. Armoring of the shoreline for developments in Cecil County may limit sediment transport and accretion to marsh areas, thus limiting their extent and suitable spawning habitat for some game fish.

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http://www.fws.gov/ northeast/easternneck/ on 8 June 2006.

[676]Tom Eagle (see note 671).

[677]Ibid.

3.18 The Chesapeake Bay Shoreline of the Central Eastern Shore

Author: **Ann Shellenbarger Jones, Industrial Economics Inc.**

Overview

The central eastern shore region covers the area between the Chester and Choptank rivers. The shore is jagged and sediment-poor, characterized by multiple coves and inlets.[678] On the northern end of Kent Island and the Chester River, marshes are expected to be marginal with an increase of 2 mm per year in the rate of sea level rise and to be lost with an increase of 7 mm per year. South of Kent Island, tidal marshes are marginally keeping pace with current rates of sea level rise, and inundation is likely to occur with an increase in sea level rise rate of 2 mm per year (Section 2.1). Erosion is also a significant issue. Planners expect that shorefront development, particularly on Kent Island and in the Easton-St. Michaels area, will lead to widespread shore protection along Chesapeake Bay and the lower tributaries.

This brief literature review discusses species that could be at risk because of further habitat loss resulting from sea level rise and shoreline protection. Existing literature and knowledge of coastal scientists in the area appear to be sufficient in many cases to make qualitative statements about the possible impact if sea level rise causes a total loss of habitat, which might be expected if shores are protected with hard structures and the wetlands are unable to keep pace with sea level rise. Our ability is more limited, however, to say what the impact might be if only a portion of the habitat is lost. The overall environmental impact of sea level rise seems likely to be the following:

- Large areas of marshes and tidal flats, particularly near the mouth of the Chester and Choptank rivers and around the Eastern Bay, will be lost. Crabs, juvenile fish, and the larger fish and waterfowl that feed on them will all be affected. The area lies in the Atlantic Flyway, and will affect the ability of migratory birds to feed on the route south in the winter.

- Assuming that shores are protected with structures rather than beach nourishment, many of the remaining beaches will erode up to the shore protection structure. This will reduce the invertebrate population (e.g., mudsnails, tiger beetles, crabs) and therefore stress shorebirds that prey on these species.

- Various marsh areas are likely to be retained. The upper reaches of tributaries, including the Chester and Choptank rivers as well as areas with minimal shoreline protection and low erosion, such as the Wye Island area, are likely to retain current marshes. These areas provide critical spawning and nursery habitat for anadromous fish. Poplar Island will provide a large, isolated marsh and tidal flat area. These regions will continue to support the fish, crustaceans, birds, and reptiles that rely on them today.

Chester River and Kent Island

The Chester River forms the northern border of Queen Anne's County. Planners expect that its shores are unlikely to be protected from Chestertown in the upper river down to Queenstown. Accretion estimates indicate that marshes along the river will be marginal with an increase in sea level rise rates of 2 mm per year (Section 2.1). Fringing tidal marshes are present throughout this portion of the river, with minimal large marshes. Migration may be possible, but in

[678]Stevenson and Kearney, 1996 (see note 38).

some areas inshore elevation quickly rises (e.g., elevation rises to 20 feet high within 500 feet of the shoreline along Wilmer Neck) and will impede migration. Birds that breed in the Chester River marshes (e.g., Virginia rail, American black duck) or breed near and feed in the marshes (e.g., great blue and green herons, osprey) will be negatively affected by the habitat and prey loss.[679] Along the river southeast of Eastern Neck, near Queenstown, are large tidal flats.[680] Local planners view shore protection as almost certain along the developed areas between Queenstown and Kent Island, at the mouth of the Chester River. Therefore, unless sedimentation increases significantly, these tidal flats are likely to be inundated if sea level rise accelerates. The Chester River also provides essential spawning habitat for king and Spanish mackerel, cobia, and red drum, as well as forage habitat for flounder and bluefish that feed in marsh and shallow water areas near the mouth of the river.[681] 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).[682]

Kent Island is highly developed, with shore protection almost certain along the Chesapeake Bay side (CBIM location 48). Historically, the shore along Chesapeake Bay had mostly narrow sandy beaches with some pebbles along low bluffs, with some wider beaches with small dunes. Terrapin Park, north of the Bay Bridge, still has an extensive dune system. The privately owned shores, however, 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.[683] The Eastern Bay side, by contrast, has several tidal creeks, extensive tidal flats, and wetlands. Planners expect that only two-thirds of the these shores are likely or certain to be protected, because Maryland’s Critical Areas Act will prevent intense development along one-third of the shore. Given the low accretion rates, the current marshes and tidal flats in these areas are likely to be lost, although some marsh may convert to tidal flat. Extensive SAV beds once grew in the nearshore areas of Eastern Bay, but little remains except in Crab Alley Bay (CBIM location 49), where shore protection is likely or almost certain.[684] Increasing water depths are likely to reduce—and eventually eliminate—the existing 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 (see discussion of SAV in Section 3.1). The loss of tidal wetlands and probable loss of SAV would cause losses to fish and birds as discussed above for the Chester River. Additionally, large shellfish beds in Eastern Bay may be affected by the habitat changes, with uncertain consequences.

Talbot County/Wye River

East of Kent Island across Eastern Bay is the Wye River, Wye East River, and Wye Narrows. In the Wye River, recreationally important fish include striped and largemouth bass, several catfish and perch species, blue gill, and black crappie. Many smaller fish inhabit the marshes and SAV, including mummichog, striped killifish, menhaden, bay anchovy, hogchoker, and Atlantic silverside. The Wye River also produces an abundant blue crab harvest, as well as oysters and soft-shell clams.[685] The Wye East River and Wye Narrows contain extensive

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[679]Robbins and Blom, 1996, pp. 76–77, 92–93, 128–129 (see note 552).
[680]Tiner and Burke, 1995 (see note 32).
[681]NOAA's Guide to Essential Fish Habitat Designations in the Northeastern United States, Summary of Essential Fish Habitat for the Chester River, accessed on July 20, 2006, at http://www.nero.noaa.gov/hcd/md2.html.
[682]Author's analysis based on Robbins and Blom, 1996, pp. 50 and 63 (see note 552).
[683]Lippson and Lippson, 2006, pp. 26–42 (see note 2).
[684]Orth, R. J., D. J. Wilcox, L. S. Nagey, A. L. Owens, J. R. Whiting, and A. K. Kenne, 2005, 2004 Distribution of Submerged Aquatic Vegetation in the Chesapeake Bay and Coastal Bays, VIMS Special Scientific Report No. 146, Final report to U.S. EPA, Chesapeake Bay Program, Annapolis, MD, Grant No.CB973013-01-0, available at: http://www.vims.edu/bio/sav/sav04.
[685]Wye Island NRMA Land Unit Plan, 2004, Prepared by the Maryland DNR Land and Water Conservation Service. p. 19.

freshwater marsh. Planners view shore protection as unlikely along the eastern side of the Wye River and in the Wye Narrows, but almost certain along the western side (e.g., the Bennett Point region) and likely along parts of the Wye East River. If the marshes and tidal flats in these areas are lost, the juvenile fish nurseries will be lost and species that feed in the marshes and SAV (e.g., wading birds, striped bass, blue gill, blue crabs) will lose an important food source.

Farther upstream on the Wye East River is the Wye Island Natural Resource Management Area (Wye Island NRMA, CBIM location 50). Steep vegetated banks, 1 to 20 feet in height with some areas eroded to bluffs, are the primary border around the island, with some areas of estuarine marsh forming more gradual slopes to upland areas.[686] The marshes of Wye Island support a large waterfowl population, with a wintering waterfowl count of 20,000 birds such as mallard, canvasback, and ruddy ducks and Canada geese.[687] Local planners indicate that adjacent areas are unlikely to be protected, with the exception of the area south of Wye Island. Current erosion rates in the area are low (approximately 2 feet per year); however, accretion rates are also low and migration is impeded in areas by the upland height and by dense vegetation, which shades the shorelines and inhibits growth of emergent vegetation.[688] Nonstructural and hybrid shoreline protections have been implemented at the Wye Island NRMA site to protect the various habitats.[689] 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.[690]

[686]Ibid., p. 13.
[687]Ibid., p. 18.
[688]Ibid., pp. 33–34.
[689]Burke, D., E.W. Koch, and J.C. Stevenson, 2005, Assessment of Hybrid Type Shore Erosion Control Projects in Maryland's Chesapeake Bay, Phases I and II, Final Report submitted to the Chesapeake Bay Trust, Annapolis, MD, p. 9, and further discussions throughout document.
[690]Wye Island, 2004, p. 12 (see note 685).

Easton–St. Michaels–Tilghman Island

Planners expect continued development and shore protection in the general area of Easton and St. Michaels, including both sides of the Miles and Tred Avon rivers and most of the land in between. On the bay side of Tilghman Island (CBIM location 51), the high erosion rates will tend to encourage construction of shoreline protection measures, particularly following construction of waterfront homes.[691] Walnut Point (CBIM location 53), at the southern end of Tilghman Island, has been riprapped and bulkheaded multiple times after continuing losses of protective measures from storms and high-energy waves. The multiple waterways (e.g., Harris Creek, Broad Creek, Avon River) east of Tilghman Island that flow into the Choptank are also all highly developed. The bay side of Tilghman Island has fringing marsh, nearshore SAV beds, and beaches. On the east side of Tilghman Island, marshes and tidal flats are found extensively along the multiple waterways particularly on the eastern edge of Harris Creek and the borders of Broad Creek.[692] Sea level rise will eliminate most of these marsh and shallow water areas owing to the inability to migrate and their marginal ability to migrate with current sea level rise rates. The loss of beaches and shallow water habitat 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). Shallow water habitats, with their resident community of bivalves, worms and other invertebrates, provide a high-density feeding ground for many predators, including fish and wading birds. Loss of shallow water habitat will decrease the SAV that is distributed throughout the coves. Today the SAV provides habitat for many fish as well as forage for waterfowl. Extensive soft-shell clam (*Mya arenaria*) beds are also found in shallow water west of Tilghman Island opposite areas almost certain to be protected.[693] The impact of the

[691]Maryland Shoreline Changes Online (see note 665).
[692]Tiner and Burke, 1995 (see note 32).
[693]NOAA, 1993, Environmental Sensitivity Index summary maps for Chesapeake Bay, obtained from the NOAA Office of Response and Restoration.

armoring and sea level rise on these beds is unknown.

West of Tilghman Island, Poplar Island (CBIM location 52) eroded from more than 1,000 acres during the mid-19th century to less than 10 acres today. It is now being restored to the footprint of 1847 through the beneficial use of dredge material, which is creating shallow water, low marsh, high marsh, and vegetated upland areas.[694] During the creation process, the island has attracted a variety of wildlife, including great blue herons, double-breasted cormorants, and diamondback terrapins.[695,696] The final upland elevations will be 20 feet above mean lower low water, more than high enough to retain its functions as sea level rises for the foreseeable future.

Wrapup

Large areas of marshes and tidal flats, particularly near the mouth of the Choptank River and around the Eastern Bay, are likely to be lost. These marshes are only marginally meeting current rates of sea level rise, and are predicted to be lost with a 2 mm/yr increase in rate. Crabs, juvenile fish, and the larger fish and waterfowl that feed on them will all be affected. The central eastern shore lies in the Atlantic Flyway and marsh loss will affect the ability of migratory birds to feed on the route south in the winter. Although the northern side of Kent Island and the marshes on the Chester River are keeping pace today, they are expected to be marginal with a 2 mm/yr increase in sea level rise and to be lost with a 7 mm/yr increase. Armoring of developed areas on Kent Island and south to Queenstown is likely to cause inundation of tidal flats and some marsh areas up to the protection structures.

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[694] Poplar Island Environmental Restoration Site, U.S. Army Corps of Engineers, accessed on July 17, 2006, at: http://www.nab.usace.army.mil/projects/Maryland/PoplarIsland/index.html.

[695] Ibid.

[696] Robbins and Blom, 1996, double-crested cormorants, pp. 44—45 (see note 552).

3.19 Virginia Eastern Shore of Chesapeake Bay

Author: ***Elizabeth M. Strange, Stratus Consulting Inc.***

Species and habitats of the Virginia Eastern Shore along Chesapeake Bay are potentially at risk because of sea level rise. This study region includes the bay side of Northampton and Accomack counties. Shorelines of the region contain important habitats for a variety of species, and a great deal is known about their ecology and habitat needs. Based on existing literature and the knowledge of local scientists, this brief literature review discusses those species that could be at risk because of further habitat loss resulting from sea level rise and shoreline protection (see Map 3.8). 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 wetland habitat could occur if shores are protected with hard structures and the wetlands are unable to keep pace with sea level rise.

Northampton and Accomack counties have the greatest area of wetlands and dry land in Virginia that are vulnerable to sea level rise, estimated at 47,863 ha (184.8 mi^2) and 53,923.6 ha (208.2 mi^2) for Northampton and Accomack counties, respectively. Because most of the land in the two counties is undeveloped or agricultural land, they also have the greatest potential for wetland creation than other Virginia shorelines.

Bay Side of Northampton County

The bay side of Northampton County is characterized by relatively high lands, including substantial cliffs near the mouth of the bay. This shoreline has some small areas of salt marsh within coves, but is most notable for its beach/dune systems, including some wide sandy beaches near the Town of Cape Charles.[697]

Estuarine beach/dune systems occur in areas of stability and sand accretion, such as the mouths of tidal creeks, embayments, in front of older dune features such as washovers or spits, and against structures like jetties and groins. An estimated 16.42 km (10.2 miles) of dune shore occur along the bay side of Northampton County, mostly fronting headlands.[698]

Shore protection is likely along most of Northampton's bay side shoreline, with the exception of the heads of some tidal creeks. Shore protection often is required on upland banks and interfluves experiencing erosion.[699] Regardless of any shoreline hardening, the high upland elevation of this area would make marsh migration difficult. The lack of lowlands, with the exception of the shoreline near the Town of Cape Charles, means that the primary impact of sea level rise on these shorelines will be erosion. Beach nourishment to protect public beaches is likely, and recently the Board on Conservation and Development of Public Beaches provided $300,000 for a breakwater and beach nourishment project in the Town of Cape Charles. The dunes themselves are important for erosion control of adjoining lands, and therefore the Commonwealth of Virginia seeks to preserve them under the Coastal Primary Sand Dune Protection Act of 1980.[700]

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[697] Varnell, L.M., and C.S. Hardaway Jr., 2005, "A risk assessment approach to management of estuarine dunefields," *Ocean & Coastal Management* 48:767–781.

[698] Hardaway, C.S., Jr., D.A. Milligan, L.M. Varnell, G.R. Thomas, W.I. Priest, L.M. Menghini, T.A. Barnard, and C. Wilcox, 2004, Northampton County Dune Inventory, Technical Report, Virginia Institute of Marine Science, College of William & Mary, Gloucester Point, VA, p. 5.

[699] Lyle Varnell and Scott Hardaway, Virginia Institute of Marine Sciences, written communication, 2/15/07.

[700] Milligan, D.W., C.S. Hardaway, Jr., G.R. Thomas, L.M. Varnell, T. Barnard, W. Reay, T.R. Comer, and C.A. Wilcox, 2005, Chesapeake Bay Dune Systems: Monitoring, Technical Report, Virginia Institute of Marine Science, College of William & Mary, Gloucester Point, VA.

[701] Varnell and Hardaway, 2005, p. 768 (see note 697).

The beaches and maritime forests on the bay side of Northampton County provide habitat for a variety of species, most notably neotropical songbirds and the federally listed threatened northeastern beach tiger beetle.[701] Evidence for the presence of these species comes from surveys in area nature preserves. The Cape Charles Coastal Habitat Natural Area Preserve (Cape Charles Preserve)[702] and the Savage Neck Dunes Natural Area Preserve (Savage Neck Preserve)[703] both provide what preserve staff consider "outstanding" beach/dune and maritime forest habitat for migratory songbirds. Tiger beetles are also found on the beaches of both preserves, as well as the William B. Trower Bayshore Natural Area Preserve.[704]

Bay Side of Accomack County

The bay side of rural 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 high water (MHW), and therefore these marshes are among the most vulnerable in the state.

Local planners expect that most of the bay side shoreline of Accomack County will remain unprotected, with the exception of Onancock Creek, the town of Saxis and the Saxis Wildlife Management Area near the Maryland border, and part of the southern shore of Pungoteague Creek. These unprotected marshes are already migrating inland in response to sea level rise, creating new wetlands in agricultural areas at a rate of 16.2 ha (40 acres) per year (see Section 2.1). Given the anticipated lack of shoreline protection, and the marginal likelihood of sufficient sediment input to meet an acceleration in sea level rise of more than 2 mm/yr, the seaward boundaries of these tidal wetlands are likely to continue retreating.

The upland elevations are higher in southern than northern Accomack County, which will make migration more difficult. Marshes in the Hackensack area in northern Accomack County cannot keep pace even with the current rate of sea level rise (Section 2.1). The likelihood of armoring along the inland portions of the tidal creeks south of Onancock could also lead to greater relative wetlands loss along this shoreline compared to the northern part of the county.

The salt marshes of Accomack County support a variety of species, including rare bird species such as the seaside and sharp-tailed sparrow. According to a fact sheet by the State of Virginia, Parkers Marsh Natural Area Preserve in Accomack County provides excellent habitat for sharp-tailed sparrow and Peregrine falcon.[705] Growth and survival of these species could be reduced where shores are hardened, unless alternative suitable habitat is available nearby.

A study in the Eastern Shore indicated that bird communities in large marshes cannot persist in habitat patches of less than 5 ha (12.4 acres)[706] Declines in birds where marsh loss is substantial could have a dramatic effect on local estuarine food webs. Dr. Michael Erwin of the Patuxent Wildlife Research Center has noted that waterbirds and shorebirds are top-level consumers in marshes and an important link in energy and nutrient transport among nearshore, marsh, and upland habitats as well as the surrounding estuary.[707] Loss of these birds could remove a significant amount of biomass from nearshore habitats (e.g., the total biomass of just

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[702] Virginia Department of Conservation and Recreation, Cape Charles Coastal Habitat Natural Area Preserve Fact Sheet. Accessed December 5, 2007 at: http://www.dcr.virginia.gov/natural_heritage/natural_area_preserves/capecharles.shtml.

[703] Virginia Department of Conservation and Recreation, Savage Neck Dunes Natural Area Preserve Fact Sheet. Accessed December 5, 2007 at: http://www.dcr.virginia.gov/natural_heritage/natural_area_preserves/savage.shtml.

[704] Virginia Department of Conservation and Recreation, William B. Trower Bayshore Natural Area Preserve Fact Sheet. Accessed December 5, 2007 at: http://www.dcr.virginia.gov/natural_heritage/natural_area_preserves/wmtrower.shtml.

[705] Virginia Department of Conservation and Recreation, Parkers Marsh Natural Area Preserve Fact Sheet. Accessed December 5, 2007 at: http://www.dcr.virginia.gov/natural_heritage/natural_area_preserves/parkers.shtml.

[706] Watts, 1993, p. 35 (see note 61).

[707] Erwin, 1996, p. 214 (see note 240).

one species of wintering waterfowl exceeded 50,000 kg).[708]

Although gradual inundation in the near term could increase tidal creeks and channels, making the marsh surface more accessible for nekton (i.e., free-swimming finfish and decapod crustaceans such as shrimps and crabs), as tidal flooding increases and the accessible area declines, a decrease in nekton production could occur. For example, Weisburg and Lotrich demonstrated experimentally that growth rates of mummichogs can decrease significantly when they have no access to tidal marsh.[709] As marsh habitats drown, populations of immobile species that cannot survive when permanently inundated could be lost. Mobile species will need to find other suitable habitats, but if these alternative sites provide lower quality habitat, the growth and survival of these populations could decline.

Accomack County lacks the dune/beach shorelines found on the bay side of Northampton County. Nonetheless, the small patches of beach that do occur provide important species habitat. For example, the rare tiger beetle is found in sandy beach habitat in the Parker's Marsh Natural Area Preserve.[710]

There are four major island complexes on the bay side of Accomack County, including Tangier, Smith, Great Fox, and Watts islands. These islands provide nearly predator-free nesting for numerous island-nesting bird species. Erosion and flooding on these islands due to sea level rise could reduce critical habitat and the local populations of these species.[711]

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[708]Ibid.

[709]Weisburg, S.B., and V.A. Lotrich, 1982, "The importance of an infrequently flooded intertidal marsh surface as an energy source for the mummichog *Fundulus heteroclitus*: An experimental approach," *Marine Biology* 66:307–310.

[710]Virginia Department of Conservation and Recreation, Parkers Marsh Natural Area Preserve Fact Sheet. Accessed December 5, 2007 at: http://www.state.va.us/dcr/dnh/parkers.htm.

[711]Watts, 2006, p. 32 (see note 495).

3.20 Sea Level Rise Modeling Study

Authors: **Russell Jones, Stratus Consulting Inc., Elizabeth M. Strange, Stratus Consulting Inc.**

Introduction

Over the past century, the rate of sea level rise has increased more than twice the average historical rate.[712] The U.S. EPA estimates that by 2100, sea level will increase nearly 2 feet in many coastal areas of the United States, with half of this increase directly attributable to global warming.[713,714] Rising sea level, often associated with land subsidence, coupled with human habitation of the shore zone and shoreline armoring with seawalls and similar structures, places shoreline property and coastal habitats and biota at risk.[715,716,717]

As the sea rises, beaches are eroded and tidal wetlands are gradually converted to open water. Seawalls and other armoring structures are often used to protect shoreline property. However, such structures also prevent the landward migration of wetlands that would otherwise follow sea level rise. In addition, waves scour away sand seaward of armoring structures, preventing natural replenishment of sand. The combination of increased sea level rise and shoreline armoring can result in the loss of wetlands, beaches, and other nearshore areas that are highly valued by humans and are necessary for the survival of fish, birds, and wildlife.

Unfortunately, potential impacts on shoreline property are often the sole focus of strategies for responding to anticipated sea level rise. However, planning must also consider responses that will protect natural ecological processes and coastal resources. Otherwise, there may be substantial and irreversible losses of coastal habitats and biota with unintended ecological and economic consequences.

We conducted a pilot study of coastal Ocean County, New Jersey, in which we developed and applied methods for evaluating risks to coastal ecosystems under alternative sea level rise and armoring scenarios. The study is one of the first attempts to quantify not just habitat changes but also changes in biota in response to sea level rise.[718]

The analysis focused on impacts to tidal marshes, SAV, sandy beaches, and open water. Maintaining tidal marshes in response to sea level rise depends on the availability of adjacent low gradient uplands to allow landward development of coastal marshes. As sea level rises, armoring structures will preclude the

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[712]Huybrechts et al., 2001 (see note 1).
[713]Barth, M.C. and J.G. Titus, 1984, *Greenhouse Effect and Sea Level Rise: A Challenge for This Generation*, Van Nostrand Reinhold, New York.
[714]Titus and Narayanan, 1995 (see note 3).
[715]Titus, J.G., R.A. Park, S.P. Leatherman, J.R. Weggel, M.S. Greene, P.W. Mausel, S. Brown, G. Gaunt, M. Trehan, and G. Yohe, 1991, "Greenhouse effect and sea level rise: The cost of holding back the sea," *Coastal Management* 19:171–204.
[716]Douglas, B., M. Kearney, and S. Leatherman (eds.), 2001, *Sea Level Rise: History and Consequences*, Academic Press, San Francisco, CA.
[717]Wu, S-Y., B. Yarnal, and A. Fisher, 2002, "Vulnerability of coastal communities to sea-level rise: A case study of Cape May County, New Jersey," *Climate Research* 22:255–270.

[718]The technical work that forms the basis for this report was funded by EPA's Office of Atmospheric Programs under Contract No. 68-W02-027. The report itself was prepared by Stratus Consulting with corporate development funds. James G. Titus, the EPA work assignment manager, developed the sea level rise and armoring scenarios that were evaluated as well as the habitat-elevation relationships used in the inundation model. Dr. Michael P. Weinstein of the New Jersey Marine Sciences Consortium, Sandy Hook Field Station provided valuable assistance with the analysis of effects on fish production of changes in marsh habitat. Dr. Michael Kearney of the University of Maryland developed accretion rates. ICF Consulting Inc. provided elevation data, and Industrial Economics developed the armoring scenarios in consultation with local planners. The conclusions presented in this report are those of the authors and do not represent the opinions of subcontractors or the official position of the EPA.

inland movement of most tidal wetlands, and will influence the exchange of nutrients, other allochthonous materials, and organisms from watersheds to estuaries.

Most critically, without the ability of intertidal habitats to migrate or accrete sediments seaward of a structure at an accelerated rate, they will ultimately "drown" and be eliminated as sea level rise inundates the shoreline seaward of the armored structures.

This study considered potential impacts of sea level rise and shoreline armoring on:

- finfish and shrimp with varying dependency on SAV and *Spartina* marshes; and
- birds that depend on coastal habitats for feeding, resting, or nesting.

The following key questions were addressed:

- What habitat changes are likely to occur?
- What species are associated with these vulnerable habitats?
- To what extent can habitat and species changes be quantified?

We first present an overview of the study area and the habitats and species evaluated. Next we describe the inundation model developed to evaluate habitat changes under various sea level rise and armoring scenarios and defines the scenarios that were evaluated. We present methods used to evaluate potential changes in biota in response to predicted habitat changes, and then discuss results of the analysis and directions for future research. The appendix presents GIS maps of modeled habitat changes.

Study Habitats and Biota

Study Area

The study area included all of coastal Ocean County, New Jersey, including Barnegat Bay, inland to the boundary of the zone defined by New Jersey's Coastal Areas Facilities Review Act (CAFRA) (Plate 1 in the appendix). The CAFRA zone includes the area considered by CAFRA to be vulnerable to sea level rise.

The study area includes a system of barrier beaches, tidal wetlands, and productive, shallow, backwater lagoons that are important for estuarine fish and shellfish, migratory and wintering waterfowl, migratory shorebirds, colonial nesting waterbirds, migratory passerines and raptors, and resident terrapin sea turtles.[719] Important habitats include barrier beach and dune, open water, SAV, intertidal sand and mudflats, salt marsh islands, and fringing tidal salt marshes. While recognizing the importance of all of these habitats, this study examined potential changes only in the areal extent of tidal marshes, SAV, sandy beaches, and open water.

Habitat Classification Scheme

Based on review of a number of habitat classification schemes amenable to analysis using a geographic information system (GIS), we selected a classification scheme that was developed by the Grant F. Walton Center for Remote Sensing and Spatial Analysis (CRSSA) at Rutgers University. We selected this scheme because it links well with National Wetlands Inventory (NWI) data[720] and has many classes that coincide well with other classification schemes. It also incorporates some finer scale data that were developed for use in a study of habitat loss and alteration in the Barnegat Bay watershed (Figure 3.1).[721]

Submerged aquatic vegetation. The SAV of Barnegat Bay is dominated by eelgrass (*Zostera*

[719] USFWS, 1997 (see note 172).
[720] Cowardin, L.M., V. Carter, F.C. Golet, and E.T. LaRoe, 1979, Classification of Wetlands and Deepwater Habitats of the United States, FWS/OBS-79/31. USFWS, Washington, DC.
[721] CRSSA, 2000, Rutgers University, 20000731, New Jersey 1995, Level III Land Cover Classification. Digital GIS data. Center for Remote Sensing and Spatial Analysis.

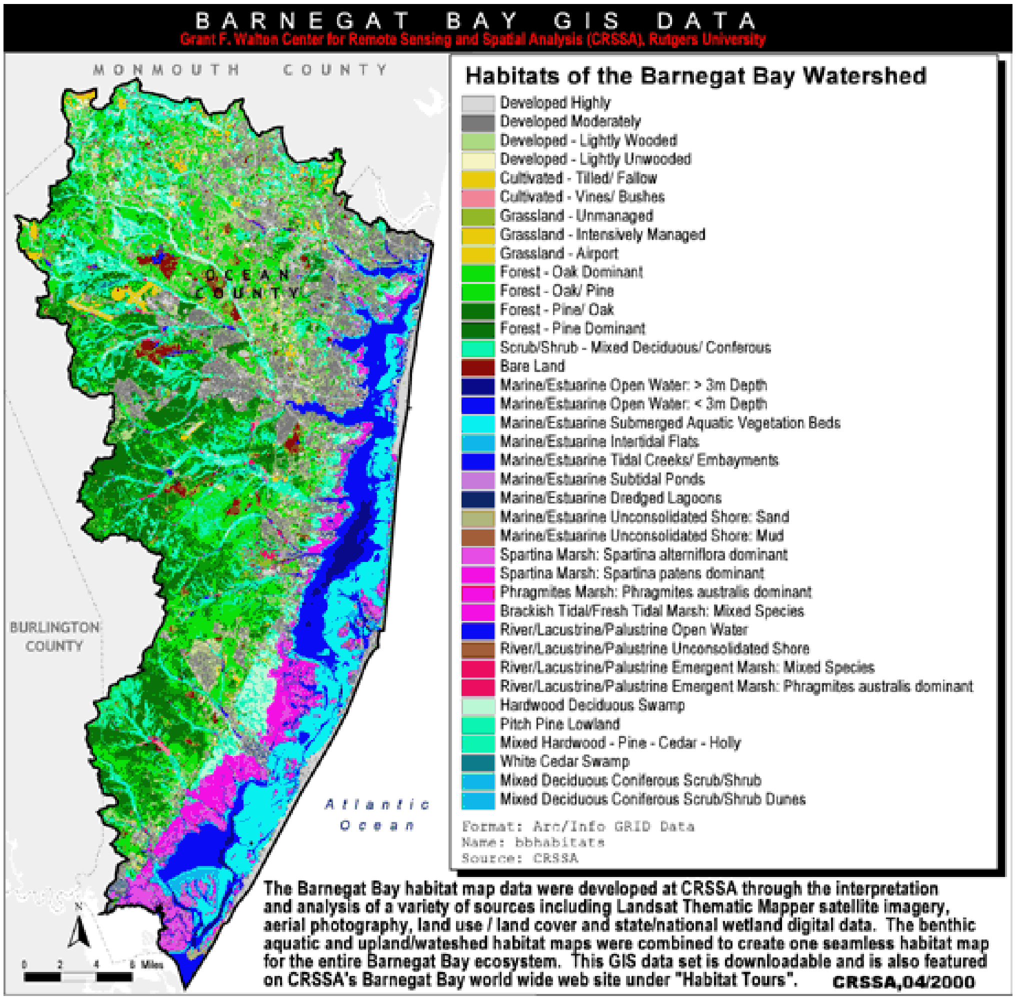

Figure 3.1. Habitats of the Barnegat Bay Watershed. Source: Grant F. Walton Center for Remote Sensing and Spatial Analysis, Rutgers University.

marina), occurring in dense beds at water depths of 1 meter or less.[722] SAV beds provide spawning and nursery areas for epibenthic fishes such as fourspine stickleback (*Apeltes quadracus*), naked goby (*Gobiosoma bosci*), northern pipefish (*Syngnathus fuscus*), and rainwater killifish (*Lucania parva*), and refuge for decapod crustaceans such as blue crab (*Callinectes sapidus*), grass shrimp (*Hippolyte pleuracanthus*), and sand shrimp (*Crangon septemspinosa*).[723]

SAV beds are also important feeding grounds for waterfowl. Midwinter aerial waterfowl counts in Barnegat Bay average 50,000 birds, mostly brant (*Branta bernicla*), American black duck (*Anas rubripes*), scaup (*Aythya* spp.), mallard (*Anas platyrhynchos*), bufflehead (*Bucephala albeola*), Canada goose (*Branta danadensis*), and mergansers (*Mergus* spp.).[724]

Tidal marshes. Marsh vegetation type is largely controlled by salinity and tidal regime (BBNEP, 2001). Low marsh, which is regularly inundated by the tide, is dominated by smooth cordgrass (*Spartina alterniflora*). Low marsh occurs in intertidal areas, especially along tidal creeks and channels.[725]

The high marsh, which is only irregularly flooded by saline waters, is dominated by salt meadow cordgrass (*S. patens*). The extensive salt

[722]USFWS, 1997 (see note 172).
[723]Sogard and Able, 1991 (see note 94).

[724]USFWS, 1997 (see note 172).
[725]Ibid.

marshes along the mainland shoreline and salt marsh islands of Barnegat Bay are mostly high marsh.[726]

The invasive common reed (*Phragmites australis*) occurs in a narrow fringe along the upland edge of marshes where salinities are low because of less tidal flooding and greater freshwater runoff.[727]

Extensive networks of creeks ranging from small tidal rivulets to major subtidal tributaries occur throughout the *Spartina* marshes of New Jersey.[728] Marsh creeks support significantly higher densities of finfish than do SAV beds, whereas densities of decapod crustaceans such as blue crab tend to be higher in SAV.[729] The fish fauna of marsh creeks is dominated by small schooling species such as Atlantic silverside (*Menidia menidia*), mummichog (*Fundulus heteroclitus*), and bay anchovy (*Anchoa mitchilli*).

S. alterniflora marsh provides habitat for songbirds such as seaside sparrow (*Ammodramus maritimus*) and long-billed marsh wren (*Telmatodytes palustris*), and *S. patens* marsh provides habitat for sharp-tailed sparrow (*A. caudacutus*) and red-winged blackbird (*Agelaius phoeniceus*).[730]

Phragmites marshes support significantly fewer larval and small juvenile fish[731] and macroinvertebrates[732] than do *Spartina* marshes. *Spartina* marshes appear to have more standing water on the marsh surface and a more complex topography than do the generally drier and flatter *Phragmites* marshes.[733]

Sandy beaches. Beach nesting birds include black skimmer (*Rynchops niger)* and least tern (*Sterna antillarum*), both of which are state-listed endangered species, and piping plover (*Charadrius melodus*), a federally listed threatened species. According to surveys by the USFWS,[734] Holgate Beach within Barnegat Bay supported an average of 13 nesting pairs of piping plover from 1985 to 1995 and 1,500 black skimmers in 1993. In 1995, 570 nesting black skimmers were counted in Barnegat Bay. Holgate Beach and Barnegat Inlet had 400 and 307 adult least tern, respectively.

Beaches are also important spawning habitat for horseshoe crabs (*Limulus polyphemus*).[735] Horseshoe crab eggs are an important component of the diet for migratory shorebirds that use beaches as a feeding area.

Inundation Model

Model Algorithms

To predict habitat changes under various sea level rise and armoring scenarios, Stratus Consulting developed a GIS-based inundation model. The inundation model includes three integrated algorithms written in Arc Macro Language (AML) and run in the GRID module of ArcInfo software (v. 8.3).

The main algorithm predicts how current tidal wetland habitats (*S. alterniflora*, *S. patens*, and *Phragmites*) will change on an annual basis over 200 years based on the relationship of the habitat to the spring tide range and on estimated elevation changes relative to mean tide level (MTL) resulting from net sea level rise. Based on the available literature, net sea level rise is defined as the historical sea level rise rate plus the accelerated rate due to global warming minus

[726] Ibid.
[727] Ibid.
[728] Sogard and Able, 1991 (see note 94).
[729] Ibid.; Rountree and Able, 1992 (see note 22).
[730] BBNEP, 2001, *The Barnegat Bay Estuary Program Characterization Report*, available from the Barnegat Bay National Estuary Program at: http://www.bbep.org/char_rep.htm.
[731] Able, K.W. and S.M. Hagan, 2000, "Effects of common reed (*Phragmites australis*) invasion on marsh surface macrofauna: Response of fishes and decapod crustaceans," *Estuaries* 23:633–646.
[732] Angradi, T.R., S.M. Hagan, and K.W. Able, 2004, "Vegetation type and the intertidal macroinvertebrate fauna of a brackish marsh: *Phragmites* vs. *Spartina*," *Wetlands* 21:75–92.
[733] Able and Hagan, 2000 (see note 731).
[734] USFWS, 1997 (see note 172).
[735] Smith, D.R., P.S. Pooler, B.L. Swan, S.F. Michels, W.R. Hall, P.J. Minchak, and M.J. Millard, 2002, "Spatial and temporal distribution of horseshoe crab (*Limulus polyphemus*) spawning in Delaware Bay: Implications for monitoring," *Estuaries* 25:115–125.

the estimated accretion rate for each type of tidal wetland,[736] calculated annually over the 200 year time period.

Accretion rate estimates were developed for the project by Dr. Michael Kearney of the University of Maryland. He considered data from the literature and his own studies on vertical accretion rates in barrier lagoonal marshes with a similar tidal and physiographic setting. Accretion rates for *S. alterniflora* in the Virginia Barrier Islands determined by Pb-210 dating were about 2 mm/yr. Accretion rates of *S. patens* are expected to be somewhat less because *S. patens* is a planophile species (flatter and closer to the ground), and therefore less capable of trapping sediments. By contrast, *Phragmites australis* is a large plant with high biomass and effective sediment trapping, and therefore has a comparatively high accretion rate. On this basis, we modeled rates specific to each wetland type as follows:

- *Phragmites australis*: 10 mm/yr
- *S. patens*: 1.5 mm/yr
- *S. alterniflora*: 2 mm/yr

We recognize that accretion is a very complex process and that specific rates may vary significantly over space and time, but for modeling purposes these habitat-specific accretion rates were applied uniformly across the study area.

A second algorithm determines if non-nourished beach habitat will migrate inland or if migration will be impeded by an armoring structure, resulting in inundation. In this algorithm, the distance the beach would be expected to migrate inland is calculated using the Bruhn rule, which states that for each vertical unit of sea level rise, the beach will migrate 100 units inland.[737]

The third algorithm predicts the types and areal extent of tidal wetland habitat that would have existed in the study area if development had not occurred. This algorithm does not take sea level rise into account.

Data Layers

Several GIS layers were required as inputs to the inundation model. All data layers were in ArcInfo grid format (raster) with a resolution of 30 × 30 m pixel size. By working at a high spatial resolution, the model is able to address the spatial heterogeneity of the spring tide as well as the historical sea level rise rate.

The primary input layers included the following: current habitat (as of 1995), elevation relative to MTL (as of 1995), a layer delineating the historical rate of sea level rise, a layer delineating the spring tide range, and a separate layer for each of five armoring scenarios.

Two additional layers were created to delineate areas where no change in habitat was allowed to occur. The first of these "masks" covered two tidal deltas: Beach Haven Inlet and Barnegat Inlet (see Plate 21 in the appendix). The assumption was made that river- and tidal-borne sediments would replenish these areas. The second mask prevented any alteration of beaches on the eastern shore of the barrier island, because the assumption was made that beaches would be protected from inundation by nourishment with imported sand.

The "current" habitat layer was created by combining data from several source layers. The primary source was 1995 Landsat TM satellite data created by the Grant F. Walton Center for Remote Sensing and Spatial Analysis at Rutgers University.[738] The Landsat data were then combined with another layer from Rutgers of SAV that showed the extent of this vegetation as of 1999.[739] Data showing the extent of intertidal flats and subtidal pools, from NWI data,[740] were combined with the other two layers to produce a

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[736]Titus and Narayanan, 1995 (see note 3); Huybrechts et al., 2001 (see note 1).
[737]Bruhn, P., 1962, "Sea level rise as a cause of shore erosion," American Society of Civil Engineers, *Journal of Waterways and Harbor Division* 88:117–130.

[738]CRSSA, 2000 (see note 721).
[739]CRSSA, 1999, Rutgers University, 19991118, Submerged Aquatic Vegetation in Barnegat Bay — 1999. Digital GIS data, Center for Remote Sensing and Spatial Analysis.
[740]USFWS, n.d., National Wetlands Inventory, accessed on December 28, 2001, at http://www.nwi.fws.gov.

Table 3.2. Habitat classifications and elevation ranges

Modeled habitat description	Elevation range[a]
Beach	na
Marine/estuarine unconsolidated shore: mud/organic	< = MTL
S. alterniflora	> MTL to LM
S. patens	> LM to HM
Phragmites australis[b]	> LM
Upland	> HM
Open water	MTL to –1 m
Upland	> HM
SAV beds	< = MTL
Marine/estuarine intertidal flats	< = MTL
Marine/estuarine subtidal pools	< = MTL
Intertidal mixed wetlands	na

[a] Upper elevations calculations:
HM = [MTL + (Spring tide range/2) + 0.3048 m]
LM = [0.666 * (Spring tide range/2)]
[b] *Phragmites* occurs both within the HM range and above HM range.

final composite habitat layer. One final modification was made to add a strip of wetlands where unarmored wetland abuts open water (intertidal mixed wetlands) to more realistically estimate the current habitat.

The elevation layer was created through interpolation of USGS DLG contours, U.S. Army Corps of Engineers point spot elevation data, and wetland boundaries created by the New Jersey Department of Environmental Quality. Elevations were relative to MTL and were adjusted from the 1969 tidal epoch to 1995 using the historical rate of sea level rise. Spring tide range and historical sea level rise rate layers were generated by interpolation of tide gauge data.

Modeled Habitats

The model evaluated potential changes in the areal extent of tidal wetland habitats (*Phragmites*, *S. alterniflora*, and *S. patens*), sandy beaches, SAV, and open water habitat. All upland habitats were modeled as a single "upland" category, intertidal habitats were not modeled, and it was assumed that beach loss would be minimal because of beach nourishment of the majority of beaches in the study area.

Using the set of input layers, the program determines for each 30 × 30 m pixel of habitat, elevation relative to MTL, spring tide range, and historical sea level rise rate. The elevation ranges for specific habitats are shown in Table 3.2. Changes in habitat type were based on elevation changes relative to MTL resulting from net sea level rise (historical sea level rise rate, plus acceleration rate, minus estimated accretion rate) over 200 years and the relation of each habitat to the spring tide range (see Figure 3.2).

Because the habitat and elevation data sets were derived independently, the initial 1995 habitat layer does not always correspond to the elevation range outlined in Table 3.2. These elevation/habitat "mismatches" are preprocessed by the model before any further processing by adjusting the elevation at that location to the elevation appropriate to the habitat found there.

Scenarios Evaluated

We used the model to examine habitat changes on an annual basis over a period of 200 years under various sea level rise rates and armoring scenarios. In addition, a historical scenario was developed to predict what type of wetland habitat would have existed in currently developed areas in the absence of development. Sea level rise was not taken into account for this scenario. For all scenarios, it was assumed that local communities would replenish beaches as needed.

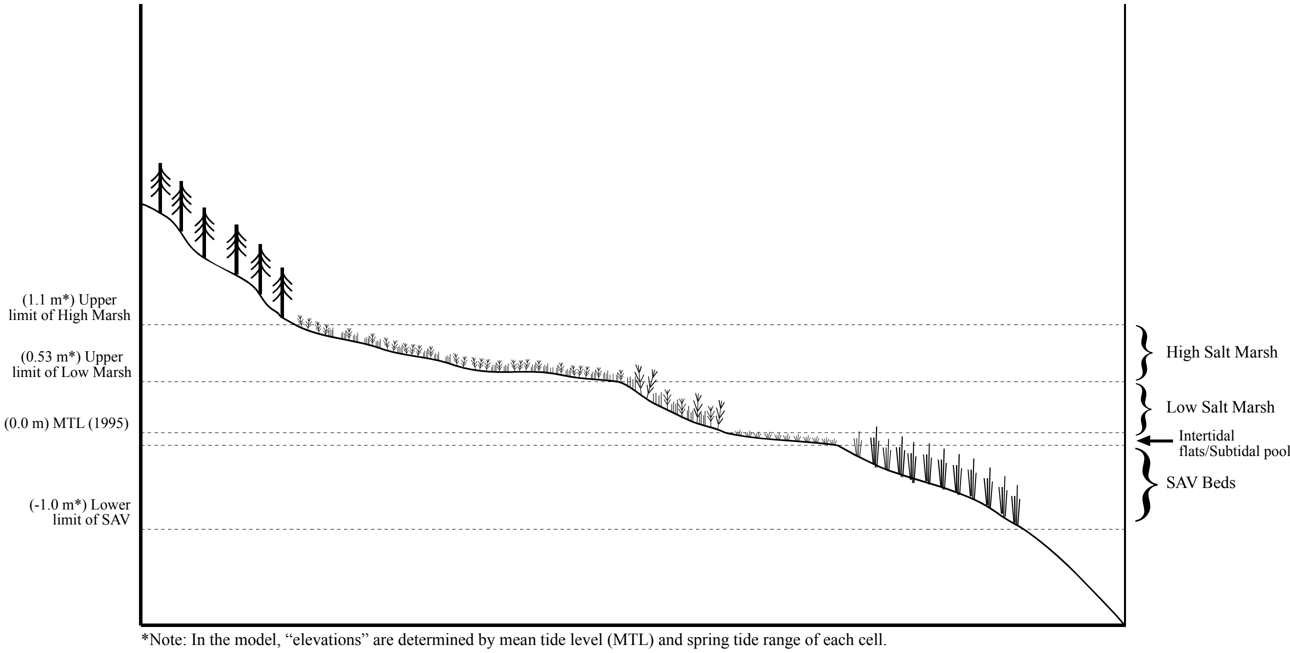

Figure 3.2. Hypothetical shoreline profile showing relationship between habitat type and elevation range relative to 1995 mean tide level (MTL).

The sea level rise and armoring scenarios were digitally mapped, and changes in the areal extent of various habitat classes under different scenarios were quantified. Two accelerated sea level rise rates were evaluated, 3 and 9 mm annual increases above the historical rate. For each sea level rise rate, six levels of response to sea level rise were evaluated: no armoring; current level of armoring; armoring scenario 1 (areas where there is a legal right to hold back the sea); armoring scenario 2 (areas that will probably be armored based on the best judgment of local planners); armoring scenario 3 (the same as scenario 2 except that no armoring is assumed in areas identified by planners where wetland migration might occur, because of increased environmental concerns or doubts about the cost-effectiveness of shore protection); and armoring scenario 4 (areas that should not be armored based on environmental considerations). The armoring scenarios were developed in consultation with local planners.

Armoring scenarios assumed placement of armored structures such as bulkheads on the landward side of mean high water (MHW)[741] or mean higher high water (MHHW).[742]

Methods for Quantifying Changes in Biota

Because the focus of our habitat analysis was on tidal marshes, SAV, and open water, estimates of changes in biota focused on species in these habitats, with a focus on avifauna, finfish, and nekton. Because of a general lack of data on the production of such species in these habitats, this version of the model makes the simplifying assumption that in most cases species losses will be proportional to habitat losses. This assumption can be modified as more data become available.

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[741]The average height of high waters (maximum height reached by a rising tide) over a 19 year period.
[742]The average height of the higher high waters (the higher of two high waters of a tidal day) over a 19 year period.

Table 3.3. Modeling assumptions for bird species

Species	Habitat	Modeling assumptions
Migrating waterfowl — dabbling ducks	SAV	Stable population until habitat loss exceeds 33%, then 1:1 decrease in abundance with loss of SAV
Migrating waterfowl — diving ducks	Open water	Increase in wintering habitat, but no increase in population, because limiting factors are probably not winter habitat
Loons, grebes	Open water	Increase in wintering habitat, but no increase in population, because limiting factors are probably not winter habitat
Mergansers, buffleheads	Open water	25% increase in abundance with increase in area of open water
Songbirds — marsh wrens	*Phragmites* marsh	1:1 decrease in abundance with loss of *Phragmites*
Songbirds — seaside sparrows	*S. alterniflora* marsh	1:1 decrease in abundance with loss of *S. alterniflora*
Songbirds — sharp-tailed sparrows	*S. patens* marsh	1:1 decrease in abundance with loss of *S. patens*

Table 3.4. Modeling assumptions for finfish in SAV and *Spartina* marshes

Species	Habitat	Modeling assumptions
Finfish: fourspine stickleback (*Apeltes quadracus*) naked goby (*Gobiosoma bosci*) northern pipefish (*Syngnathus fuscus*) rainwater killifish (*Lucania parva*)	SAV	1:1 decrease with loss of SAV
Finfish: Atlantic silverside (*Menidia menidia*) mummichog (*Fundulus heteroclitus*) bay anchovy (*Anchoa mitchilli*)	*Spartina* marsh	1:1 decrease with loss of *Spartina* marsh

Birds

Table 3.3 summarizes our assumptions about how the relative abundances of representative bird species in the study area will change with changes in the areal extent of different habitats. These assumptions are based on best professional judgment. The inundation model does not consider salt marsh islands or intertidal sand and mudflats, and assumes that there will be beach nourishment on the ocean side of the barrier island, which represents the majority of the beach habitat. Therefore, our analysis does not consider potential changes in migratory shorebirds, nesting shorebirds, or colonial nesting birds that depend on these habitats.

Estimations of changes in dabbling duck abundance in SAV are based on the assumption that current SAV can accommodate a 50 percent annual variation in bird abundance, but that loss of greater than 33 percent of SAV habitat will result in a 1:1 decrease in dabbling duck abundance. For birds using open water habitats in winter, increases in open water will provide increased habitat, but will not result in population increases, because the limiting factors on diving duck, loon, grebe, and merganser populations are not likely to be wintering habitat. For birds breeding in marsh habitats, the long-term percent change in bird abundance is assumed to be the same as the long-term habitat change.

Relative Abundances of Finfish in Spartina Marshes and SAV

Relative abundances of fish in SAV and tidal marsh were modeled on the basis of data from Great Bay-Little Egg Harbor, adjacent to the Barnegat Bay study area.[743] As indicated in Table 3.4, we assumed that there will be declines in the growth, survival, or reproduction of the

[743] Sogard and Able, 1991 (see note 94).

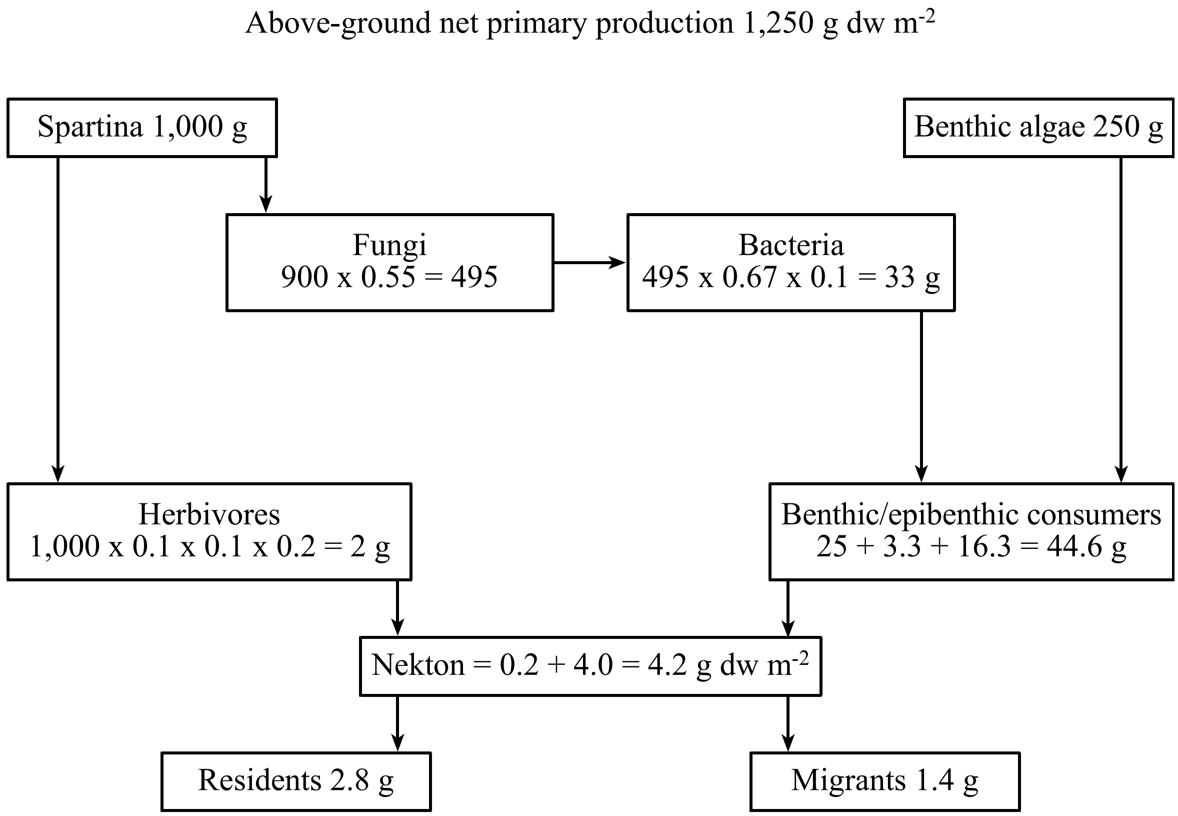

Figure 3.3. Production flows to nekton from net annual marsh primary production.
Source: After Figure 1 in Kneib (see text note 276).

dominant species in each habitat, resulting in declines in abundance proportional to habitat losses.

Annual Production of Nekton in Spartina Marshes

We estimated annual production of nekton (actively swimming fish and shrimp) in *Spartina* marshes based on consultation with a local expert (Dr. Michael Weinstein, Director, New Jersey Sea Marine Sciences Consortium) and data and methods in Kneib.[744] Kneib used two alternative methods to estimate the annual production of nekton in tidal wetlands. First, Kneib developed an estimate of annual nekton production by multiplying estimated mean annual standing stock biomass by a production:biomass (P:B) ratio. Based on a review of the scientific literature, Kneib used a P:B ratio of 2 for marsh fishes, 3 for penaeid shrimp, and 5 for caridean shrimp. On this basis, Kneib estimated that annual nekton production in *Spartina* marshes averages 1.5 g dry weight (g dw) m^{-2}.

Kneib also developed a simple trophic transfer model to estimate the annual production of nekton resulting from the annual above-ground production of *Spartina alterniflora*. The model is based on the premise that the primary production of salt marshes is linked to the secondary production of both resident and transient nekton.[745] Kneib's model is summarized in Figure 3.3.

[744]Kneib, 1997 (see note 17).

[745]Weinstein, 1979 (see note 361); Weinstein, M.P., 1983, "Population dynamics of an estuarine-dependent fish, the spot (*Leisotomus xanthurus*) along a tidal creek-seagrass meadow coenocline," *Canadian Journal of Fisheries and Aquatic Sciences* 40:1633–1638; Weigert, R.G. and L.R. Pomeroy, 1981, "The salt-marsh ecosystem: A synthesis," in *The Ecology of a Salt Marsh,* L.R. Pomeroy and R.G. Weigert (eds.), Springer Verlag, New York, pp. 219–230; Boesch and Turner (see note 318); Deegan, L.A., 1993, "Nutrient and

The model estimates that a total of 4.2 g dw m^{-2} of nekton is supported by the original 1,250 g dw m^{-2} of above-ground plant production. Of this total, Kneib assumed that two-thirds (2.8 g) are resident species (e.g., killifishes such as *Fundulus* spp.) and one-third (1.4 g) are estuarine migrants (e.g., juvenile white shrimp *Litopenoeus setiferus*).[746] Estimates in other studies of annual productivity of fish and shrimp in tidal marshes range from 9 to 16 g dw m^{-2} yr^{-1} for shrimp, from 10.2 to 16 g dw m^{-2} yr^{-1} for mummichog (*Fundulus heteroclitus*), and from 22.1 to 48.5 g dw m^{-2} yr^{-1} for total fish (review in Strange et al.[747]). Many of these studies estimate secondary productivity based on the total regional fisheries yield per unit area of supporting marsh. These results suggest that Kneib's estimate of 4.2 g dw m^{-2} may represent a lower bound estimate of marsh secondary productivity.

Results and Discussion

Results of the pilot study make clear that as armoring increases in response to anticipated sea level rise, there are likely to be substantial adverse impacts to certain coastal habitats and the species supported by those habitats. Even minimal armoring is predicted to substantially reduce the abundance and production of finfish and birds in coastal areas as critical habitats are lost or converted.

Habitat Changes

The appendix (map plates) and Table 3.5 show predicted changes in the distribution of the modeled coastal habitat types after 200 years under the different sea level rise and armoring scenarios. The predicted change in the areal extent of *S. alterniflora* is shown in Figure 3.4, *S. patens* in Figure 3.5, *Phragmites* in Figure 3.6, SAV in Figure 3.7, and open water in Figure 3.8.

Under all sea level rise and armoring scenarios, there are substantial declines in *Spartina* marshes, with more *S. patens* marsh lost compared to *S. alterniflora* marsh. This is to be expected given the lower accretion rate of *S. patens* marsh. The greatest declines in both *S. alterniflora* and *S. patens* occur under armoring scenario 1 for both 3 and 9 mm accelerated sea level rise rates.

Phragmites marsh, which is assumed to accrete at a rate that is five times higher than *S. alterniflora*, persists under a 3 mm accelerated sea level rise rate, but declines under a 9 mm increase.

SAV increases under armoring scenario 4, assuming a 3 mm accelerated rate of sea level rise. In contrast, SAV declines substantially under all 9 mm scenarios. The greatest decline in SAV occurs under the assumption of a 9 mm rate of sea level rise and armoring scenario 1.

Open water habitat increases under all sea level rise scenarios. The greatest increase occurs under the unarmored scenario and a 9 mm accelerated sea level rise rate. Note that because the model assumes that there will be beach nourishment for the majority of beaches in the study area, the extent of sandy beach habitat is relatively unchanged.

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energy transport between estuaries and coastal marine ecosystems by fish migration," *Canadian Journal of Fisheries and Aquatic Science* 50:74–79; Weinstein, M.P. and S.Y. Litvin, 2000, "The role of tidal salt marsh as an energy source for marine transient and resident finfishes: A stable isotope approach," *Transactions of the American Fisheries Society* 129:797–810; Kneib, 1997 (see note 17); Kneib, 2003 (see note 276); Deegan et al., 2000 (see note 428), in Weinstein and Kreeger, pp. 333–368 (see note 410).

[746] Kneib, 2003 (see note 276).

[747] Strange, E., H. Galbraith, S. Bickel, D. Mills, D. Beltman, and J. Lipton, 2002, "Determining ecological equivalence in service-to-service scaling of salt marsh restoration," *Environmental Management* 20:290–300.

Table 3.5. Area comparison of current (1995) coastal habitat (in hectares) to estimates modeled under six shoreline protection (armoring) scenarios and two accelerated sea level rise rates above the historical rate

Scenario	3 mm[a] accelerated sea level rise					9 mm[a] accelerated sea level rise				
	Low salt marsh *S. alterniflora* dominant	High salt marsh *S. patens* dominant	High salt marsh *Phragmites australis* dominant	Marine/ estuarine open water	Sub-aquatic vegetation	Low salt marsh *S. alterniflora* dominant	High salt marsh *S. patens* dominant	High salt marsh *Phragmites australis* dominant	Marine/ estuarine open water	Sub-aquatic vegetation
Current (1995)	5,036	3,875	1,507	42,903	5,591	5,036	3,875	1,507	42,903	5,591
Unarmored	3,206	966	1,507	52,744	7,433	2,893	739	95	63,077	4,492
Current armoring	1,996	366	1,507	52,740	5,054	2,160	463	95	59,357	2,088
Armoring scenario 1[b]	1,625	211	1,507	52,737	3,940	1,551	196	95	57,788	954
Armoring scenario 2[c]	1,951	339	1,507	52,746	4,947	1,990	401	95	59,175	1,729
Armoring scenario 3[d]	2,081	395	1,507	52,742	5,461	2,143	456	95	59,905	2,231
Armoring scenario 4[e]	3,000	894	1,507	52,724	6,761	2,741	678	95	62,178	4,114

[a] 3 mm and 9 mm represent annual accelerated rates of sea level rise above the historical rate.

[b] Armoring scenario 1 = areas where there is a legal right to hold back the sea;

[c] armoring scenario 2 = areas that will probably be armored based on the best judgment of local planners;

[d] armoring scenario 3 = the same as scenario 2 except that no armoring is assumed in areas identified by planners where wetland migration might occur due to increased environmental concerns, or doubts about the cost-effectiveness of shore protection);

[e] armoring scenario 4 = areas that should not be armored based on environmental considerations.

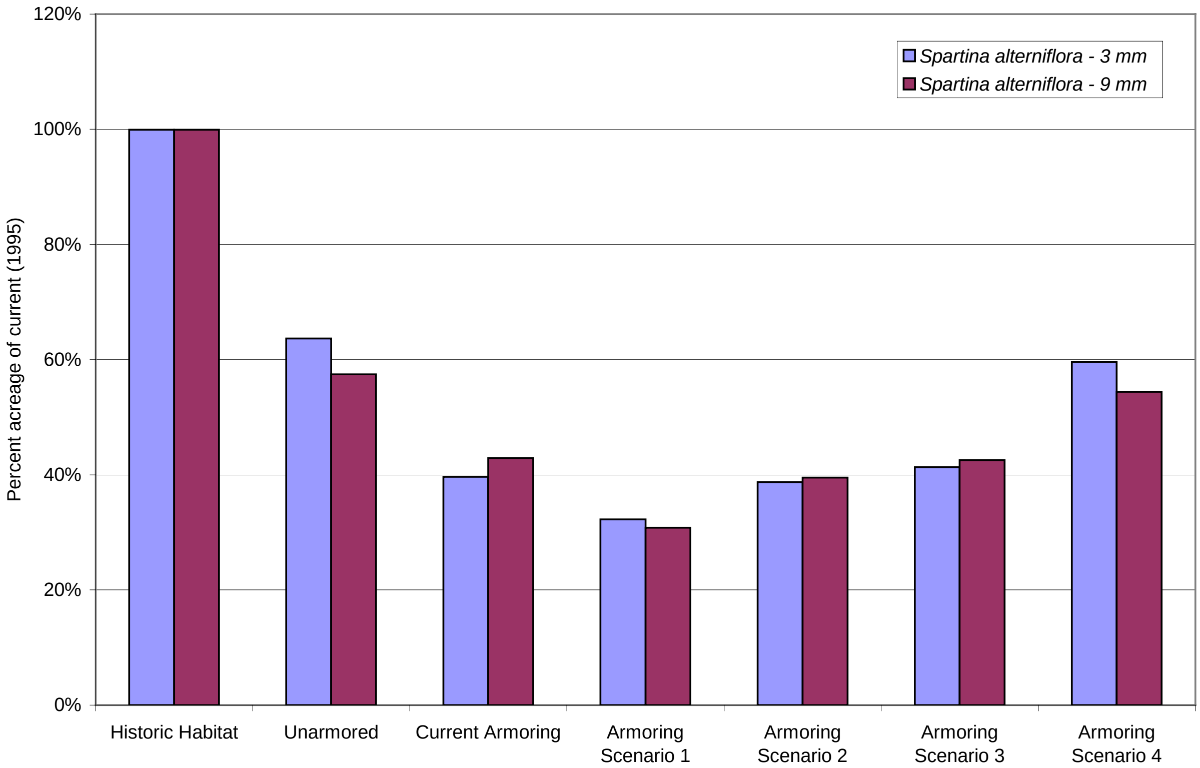

Figure 3.4. Under 3 and 9 mm accelerated sea level rise above historical levels by 2195 (200 years from 1995) and unarmored, current armoring, and four policy-derived armoring scenarios involving different degrees of armoring. (See notes in Table 3.5 for explanation of scenarios.)

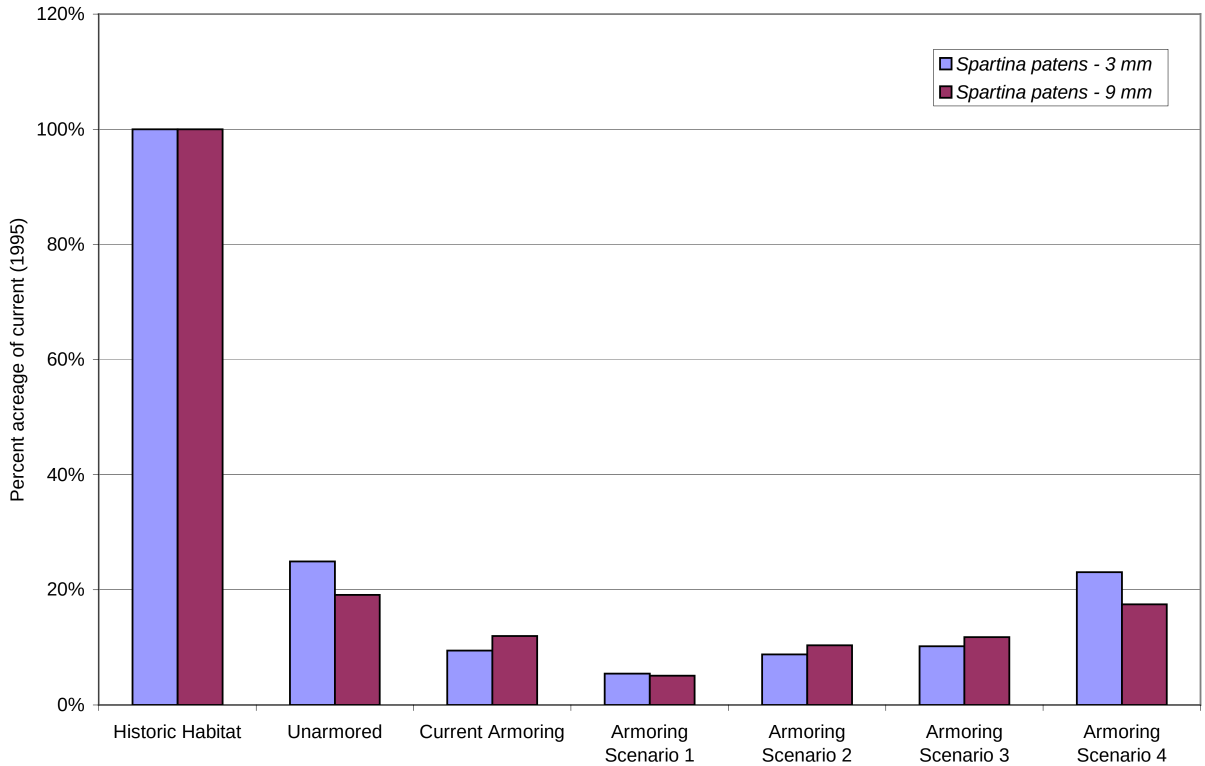

Figure 3.5. Comparison of current and historical acreages of *S. patens* high saltmarsh habitat to inundation-modeled acreages under 3 and 9 mm accelerated sea level rise above historical levels by 2195 (200 years from 1995) and unarmored, current armoring, and four policy-derived armoring scenarios involving different degrees of armoring. (See notes in Table 3.5 for explanation of scenarios.)

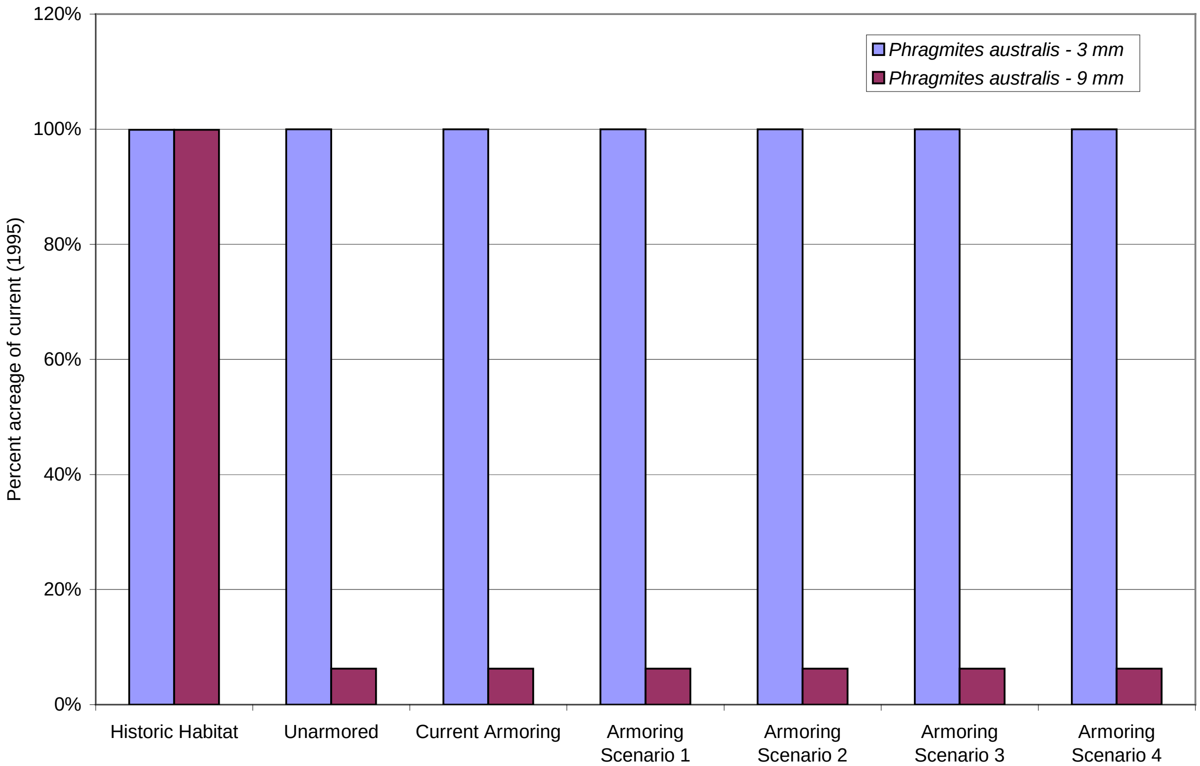

Figure 3.6. Comparison of current and historical acreages of *Phragmites australis* (high saltmarsh and upland) habitat to inundation-modeled acreages under 3 and 9 mm accelerated sea level rise above historical levels by 2195 (200 years from 1995) and unarmored, current armoring, and four policy-derived armoring scenarios involving different degrees of armoring. (See notes in Table 3.5 for explanation of scenarios.)

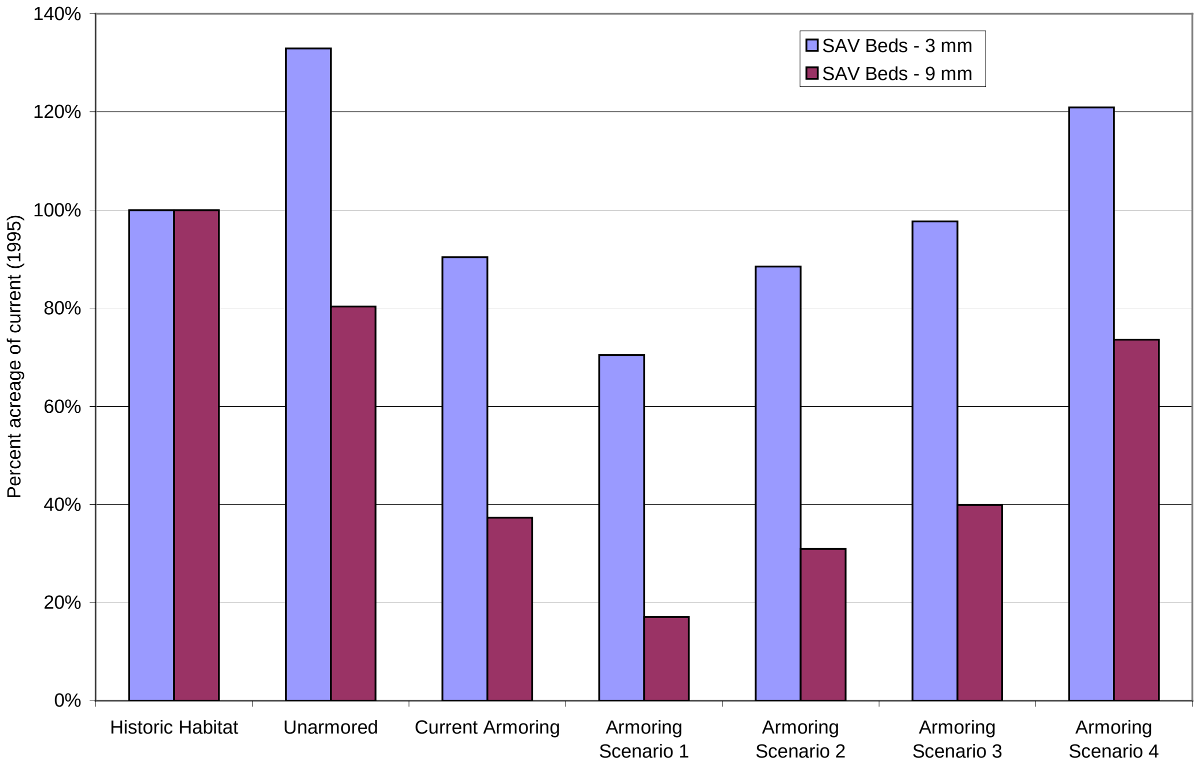

Figure 3.7. Comparison of current and historical acreages of SAV to inundation-modeled acreages under 3 and 9 mm accelerated sea level rise above historical levels by 2195 (200 years from 1995) and unarmored, current armoring, and four policy-derived armoring scenarios involving different degrees of armoring. (See notes in Table 3.5 for explanation of scenarios.)

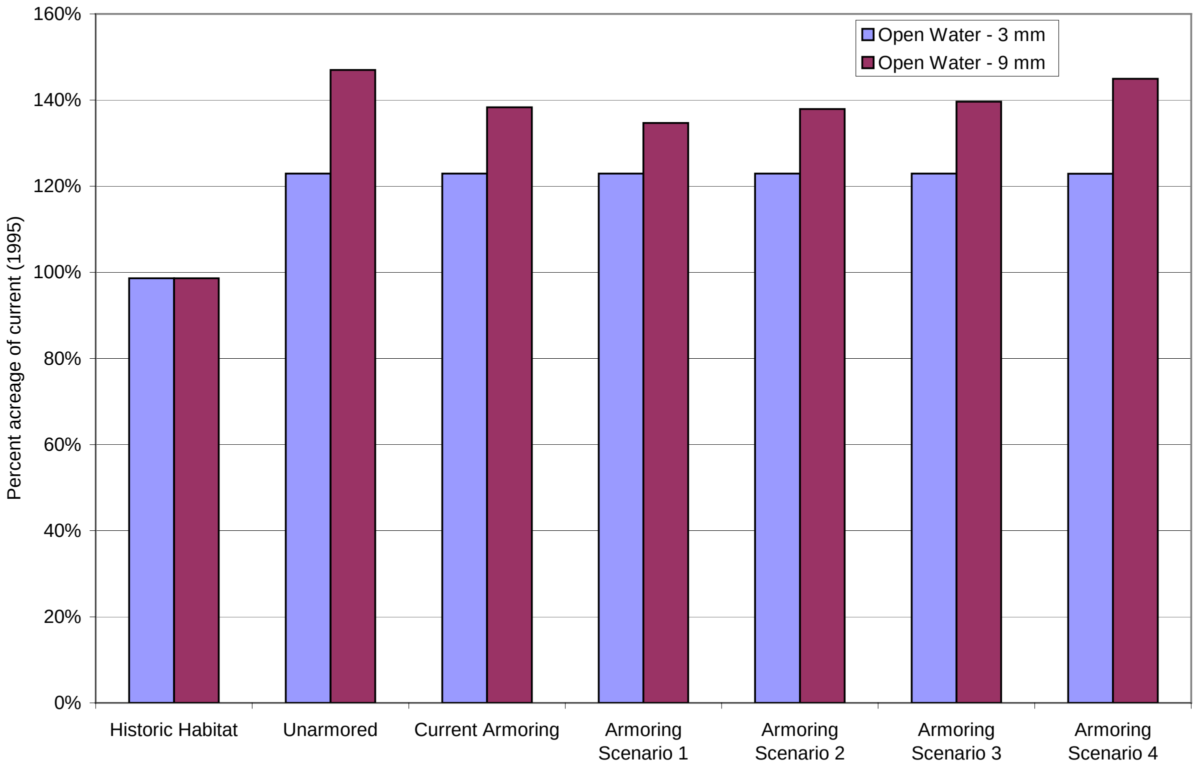

Figure 3.8. Comparison of current and historical acreages of open water to inundation-modeled acreages under 3 and 9 mm accelerated sea level rise above historical levels by 2195 (200 years from 1995) and unarmored, current armoring, and four policy-derived armoring scenarios involving different degrees of armoring. (See notes in Table 3.5 for explanation of scenarios.)

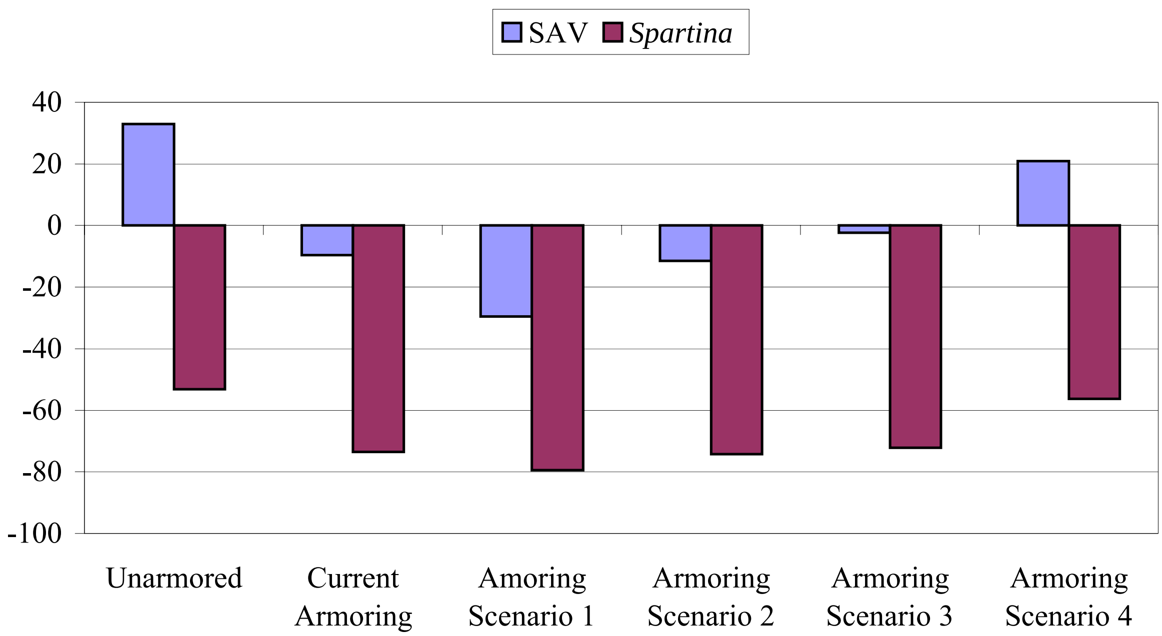

Figure 3.9. Percent change in relative abundances of fish species in *Spartina* and SAV by 2195 under 3 mm accelerated sea level rise. (See notes in Table 3.5 for explanation of scenarios.)

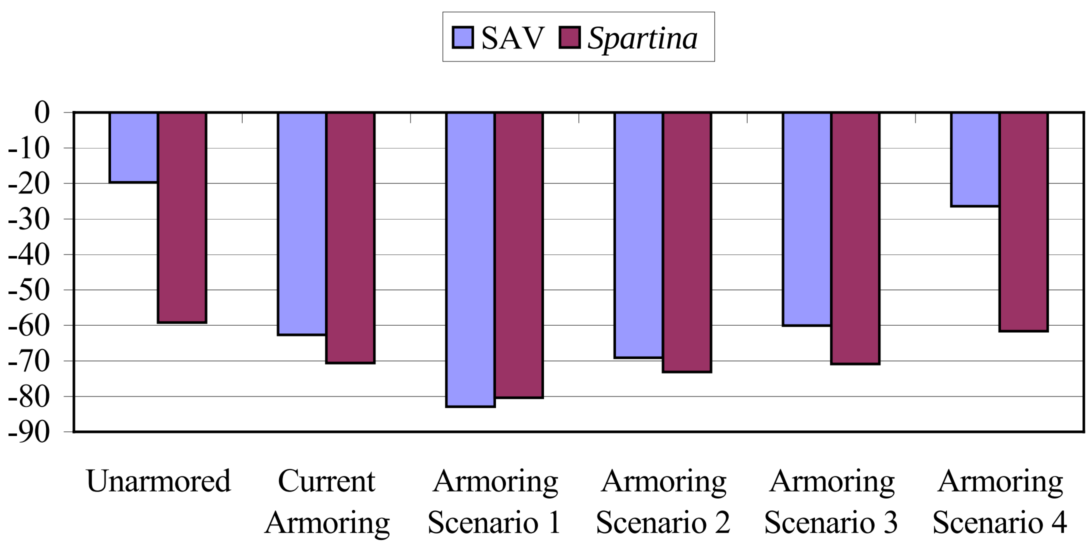

Figure 3.10. Percent changes in relative abundances of fish species in *Spartina* and SAV by 2195 under 9 mm accelerated sea level rise. (See notes in Table 3.5 for explanation of scenarios.)

Table 3.6. Current (1995) estimated annual production of nekton (in kg/ha/yr) in *Spartina* marsh in the study area

	Production under 3 mm accelerated sea level rise		Production under 9 mm accelerated sea level rise	
Scenario	Low estimate	High estimate	Low estimate	High estimate
Current (1995)	133,666	374,265	133,666	374,265

Table 3.7. Estimated annual production in 200 years of nekton (in kg/ha/yr) in *Spartina* marsh in the study area under different rates of accelerated sea level rise and alternative armoring scenarios[a]

	Production under 3 mm accelerated sea level rise		Production under 9 mm accelerated sea level rise	
Scenario	Low estimate	High estimate	Low estimate	High estimate
No armoring	62,575	175,211	54,491	152,576
Current level of armoring	35,432	99,210	39,353	110,187
Armoring scenario 1	27,533	77,093	26,206	73,377
Armoring scenario 2	34,348	96,175	35,876	100,454
Armoring scenario 3	37,134	103,976	38,983	109,151
Armoring scenario 4	58,413	163,557	51,280	143,583

[a] See notes in Table 3.5 for explanation of scenarios.

Changes in Relative Abundances of Finfish in Spartina *Marsh and SAV*

Figure 3.9 shows predicted percent changes in the relative abundances of resident finfish in SAV and *Spartina* marsh under 3 mm accelerated sea level rise and different degrees of armoring based on data in Sogard and Able.[748] Figure 3.10 provides results under 9 mm accelerated sea level rise. SAV-dependent fish species increase under the unarmored scenario and armoring scenario 4 assuming a 3 mm accelerated rate of sea level rise, but decline substantially under all scenarios with a 9 mm rise. By contrast, declines of *Spartina*-dependent fish species are substantial under all sea level rise and armoring scenarios.

Annual Production of Resident and Transient Marsh Nekton

As indicated in the previous section, results of Kneib indicate that production of nekton in *Spartina* marshes ranges from 15 kg/ha/yr (1.5 g m^{-2}) based on P:B ratios to 42 kg/ha/yr (4.2 g m^{-2}) based on trophic transfer of marsh primary production to nekton.[749] To account for uncertainty, these estimates were used as lower and upper bound estimates of production. On this basis, Table 3.6 presents estimated annual production in the study area under current (1995) conditions, and Table 3.7 presents predicted changes by 2195 under the different sea level rise and armoring scenarios.

Annual production of nekton declines substantially as *Spartina* marsh is lost, ranging from a decline of about 50–75 percent under a 3 mm accelerated sea level rise rate to about 60–80 percent under 9 mm. Such potentially dramatic declines in the annual production of nekton is of particular concern because many of these species, such as spot (*Leiostomus xanthurus*) and white perch (*Morone americana*), are important for commercial and recreational fisheries.

Changes in Relative Abundances of Birds in Spartina *Marshes, SAV, and Open Water*

Figure 3.11 shows predicted changes in the relative abundances of representative bird species in SAV, *S. alterniflora*, and *S. patens* under 3 mm accelerated sea level rise and

[748] Sogart and Able, 1991 (see note 94).

[749] Kneib, 2003 (see note 276).

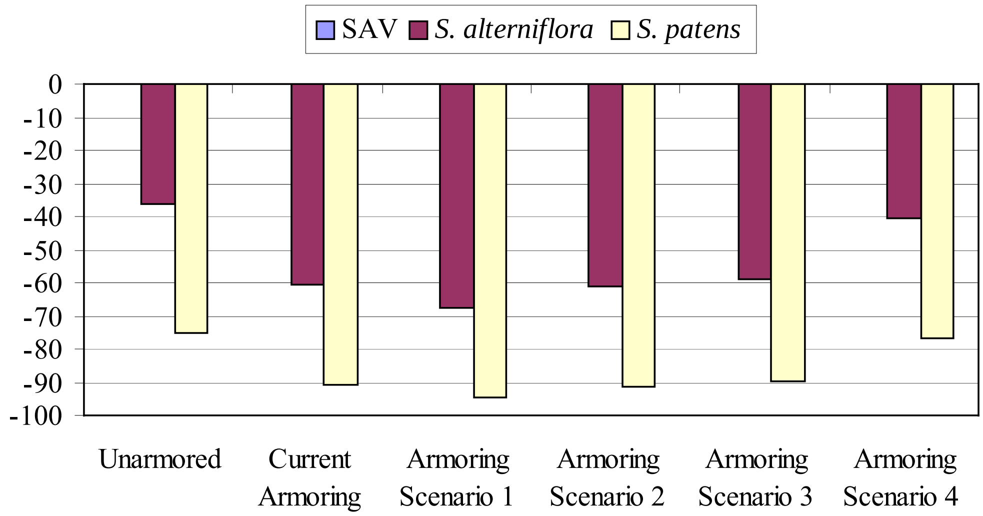

Figure 3.11. Percent changes in relative abundances of bird species by 2195 under 3 mm accelerated sea level rise. (See notes in Table 3.5 for explanation of scenarios.)

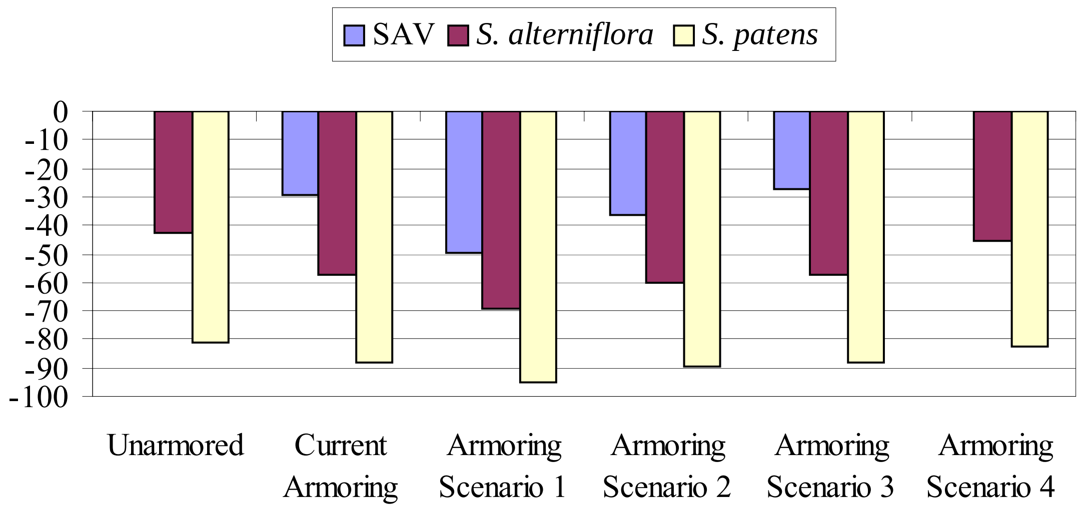

Figure 3.12. Percent changes in relative abundances of bird species by 2195 under 9 mm accelerated sea level rise. (See notes in Table 3.5 for explanation of scenarios.)

different degrees of armoring. Figure 3.12 provides results under 9 mm accelerated sea level rise. The greatest losses occur for songbirds

in *S. patens*, followed by songbirds in *S. alterniflora*. SAV-dependent species such as dabbling ducks show no change under a 3 mm accelerated sea level rise rate, and no change under a 9 mm accelerated sea level rise rate under the unarmored scenario and with minimal armoring (armoring scenario 4). However, under a 9 mm sea level rise, decreases in SAV-dependent bird species are significant with current armoring and armoring scenarios 1, 2, and 3. However, the percent change is still substantially less than for songbirds in *Spartina* marshes.

Conclusions and Directions for Future Research

The inundation and biological production models developed for this study function as intended and can be used to develop an order of magnitude approximation of changes in the production of birds, finfish, and shrimp under a variety of sea level rise and armoring scenarios. Such information can help guide stakeholders and decision-makers as they plan responses to anticipated sea level rise.

One of the unique features of this model is that it evaluates accretion, sea level rise, and habitat in a spatially explicit manner (i.e., on a cell by cell basis). This made it possible to use accretion rates specific to different marsh vegetation types

(1.5 mm/yr for *S. patens*, 2 mm/yr for *S. alterniflora*, and 10 mm/yr for *Phragmites*). Because *Phragmites* is assumed to accrete at such a relatively high rate, this vegetation type is able to keep pace with the 3 mm accelerated sea level rise rate.

In addition, our model is able to capture local variation in mean tide level and therefore sea level rise, rather than treating the entire area as a homogenous unit. This means the model was able to consider local tide levels related to subsidence, etc. The model can also be used to conduct a sensitivity analysis to examine the effects of different values of input parameters on model predictions. Model output can be generated for any time interval of interest.

The inundation model is flexible, and assumptions and mapping rules can be revised as needed for different study sites or to accommodate improved or additional physical and biological data. It is important to gather additional data to test the assumptions of this version of the model and to improve the accuracy and reliability of model predictions. This is particularly important because different scenarios of sea level rise rates and armoring may have different impacts on future coastal habitats than those predicted by our model based on current data and assumptions. This version of the inundation model examines potential changes in tidal marshes, SAV, sandy beaches, and open water habitats only, and makes a number of simplifying assumptions about how these habitats will change in response to sea level rise and shoreline armoring. Further analysis should examine other potentially important physical variables such as slope, overwash, fetch, and sediment inputs from the surrounding watershed to determine their relative influence on habitat predictions.

Future research should also address other habitats in addition to the four major habitat types considered here. For example, there are likely to be changes in the extent and distribution of intertidal mudflats. Loss of intertidal flats is expected to lead to declines in shorebirds such as semipalmated plover (*Charadrius semipalmatus*), red knot (*Calidris canutus*), and dunlin (*Calidris alpina*) that rely on these habitats for feeding during their migrations and over winter.[750]

Colonial nesting birds such as gulls and terns nest on salt marsh islands in the bay,[751] and loss of this habitat could also have important consequences. In 1989, more than 11,000 gulls, primarily laughing gulls (*Larus atricilla*), were observed in Barnegat Bay, and in 1995, 5,000 gulls, mostly herring gulls (*Larus argentatus*) and great black-backed gulls (*Larus marinus*), were observed. There were 5,000 terns observed in 1989 and 2,600 in 1995, mostly common tern (*Sterna hirundo*). In 1989 there was one colony of least tern (*Sterna antillarum*), a state-listed endangered species, and in 1989 there was one colony of Forster's tern (*Sterna forsteri*). Additional loss of the habitats that these species rely on from sea level rise may add significant stress to these populations that are already at risk.

For this analysis, we make the simplifying assumption that in most cases species losses will be proportional to habitat losses. Future versions of the model should examine other possible relationships between habitat loss and production of coastal biota. It will also be important to validate the assumptions of the trophic transfer model and the P:B ratio approach to estimating annual production of nekton. Other changes might include evaluation of the importance of the spatial configuration of habitat patches or patch size. It would also be useful to predict how sandy beach habitat and biota would change if no beach nourishment occurs. Beaches are essential for horseshoe crab spawning, and horseshoe crab eggs are a critical component of the diets of migratory birds. Therefore, losses of beaches could have important consequences for these species.

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[750]Galbraith et al., 2002 (see note 50); Galbraith, H., R. Jones, R. Park, J. Clough, S. Herrod-Julius, B. Harrington, and G. Page, 2003, "Global climate change and sea level rise: potential losses of intertidal habitat for shorebirds," in *Ecological Forecasting: New Tools for Coastal and Marine Ecosystem Management*, N. Valette-Silver and D. Scavia (eds.), NOAA technical memorandum NOS NCCOS 1, NOAA, Silver Spring, MD, pp. 19–22.

[751]USFWS, 1997 (see note 172).

Despite the limitations of the current version of the inundation and biological production models, results of this study make clear that there may be substantial changes in coastal habitats and biota in response to sea level rise and shoreline armoring, and that the model can be used to evaluate the potential effects of shoreline armoring on these resources. For this reason, it is imperative that tools such as these be refined to the extent possible to provide resource managers and stakeholders with the information necessary for planning responses consistent with resource goals.

The technical work that forms the basis for this report (this Section 3.20)was funded by the Global Programs Division of the U.S. Environmental Protection Agency's (EPA's) Office of Atmospheric Programs under Contract No. 68-W02-027. The report itself was prepared by Stratus Consulting with corporate development funds. James G. Titus, the EPA work assignment manager, developed the sea level rise and armoring scenarios that were evaluated as well as the habitat-elevation relationships used in the inundation model. Dr. Michael P. Weinstein of the New Jersey Marine Sciences Consortium, Sandy Hook Field Station provided valuable assistance with the analysis of effects on fish production of changes in marsh habitat. Dr. Michael Kearney of the University of Maryland developed accretion rates. ICF Consulting Inc. provided elevation data, and Industrial Economics developed the armoring scenarios in consultation with local planners. The conclusions presented in this report are those of the authors and do not represent the opinions of subcontractors or the official position of the EPA.

Appendix: GIS Maps of Modeled Habitat Changes

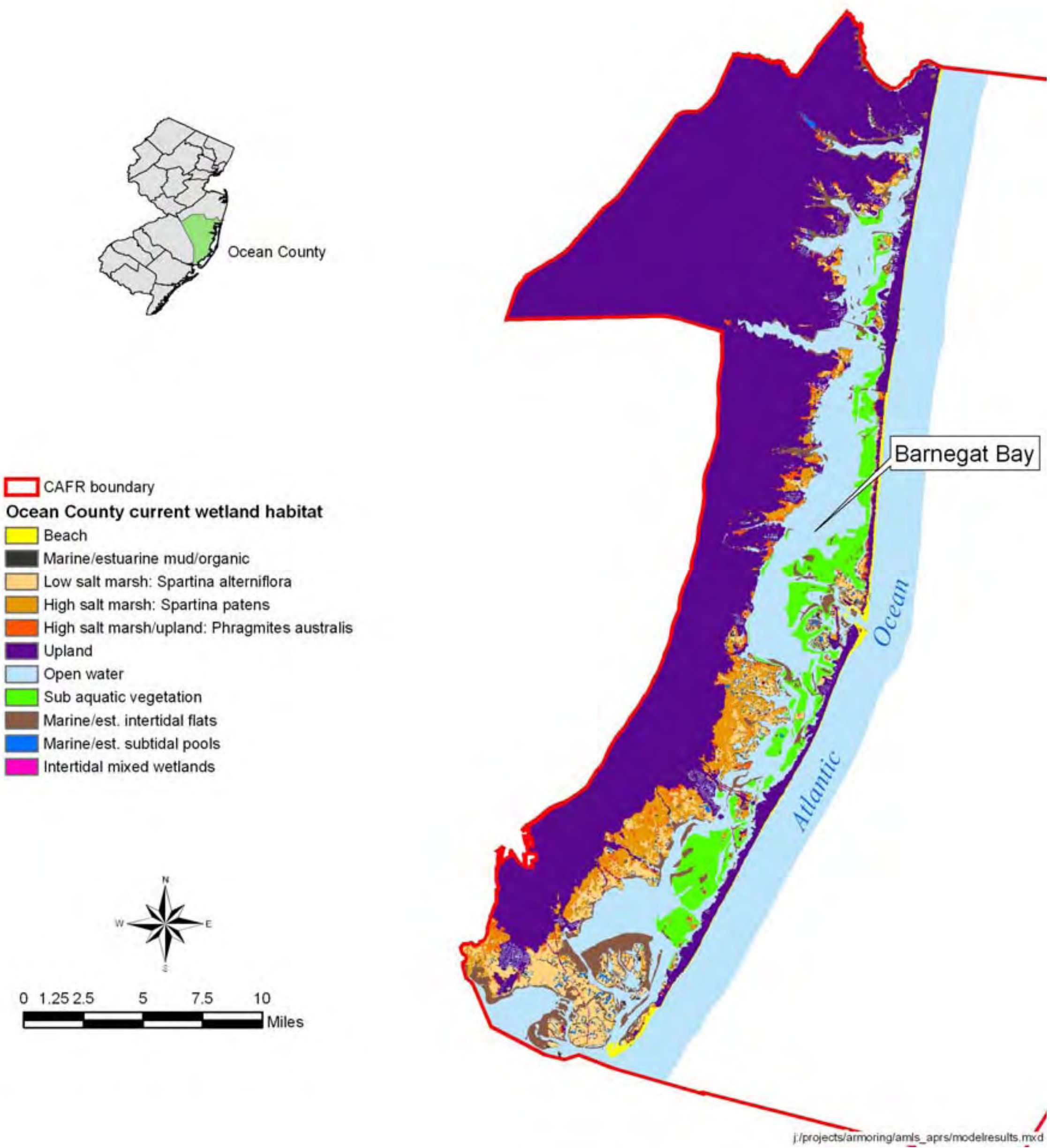

Plate 1. The study area along coastal Ocean County, New Jersey, including Barnegat Bay, inland to the boundary of the zone defined by New Jersey's Coastal Areas Facilities Review Act (CAFRA).

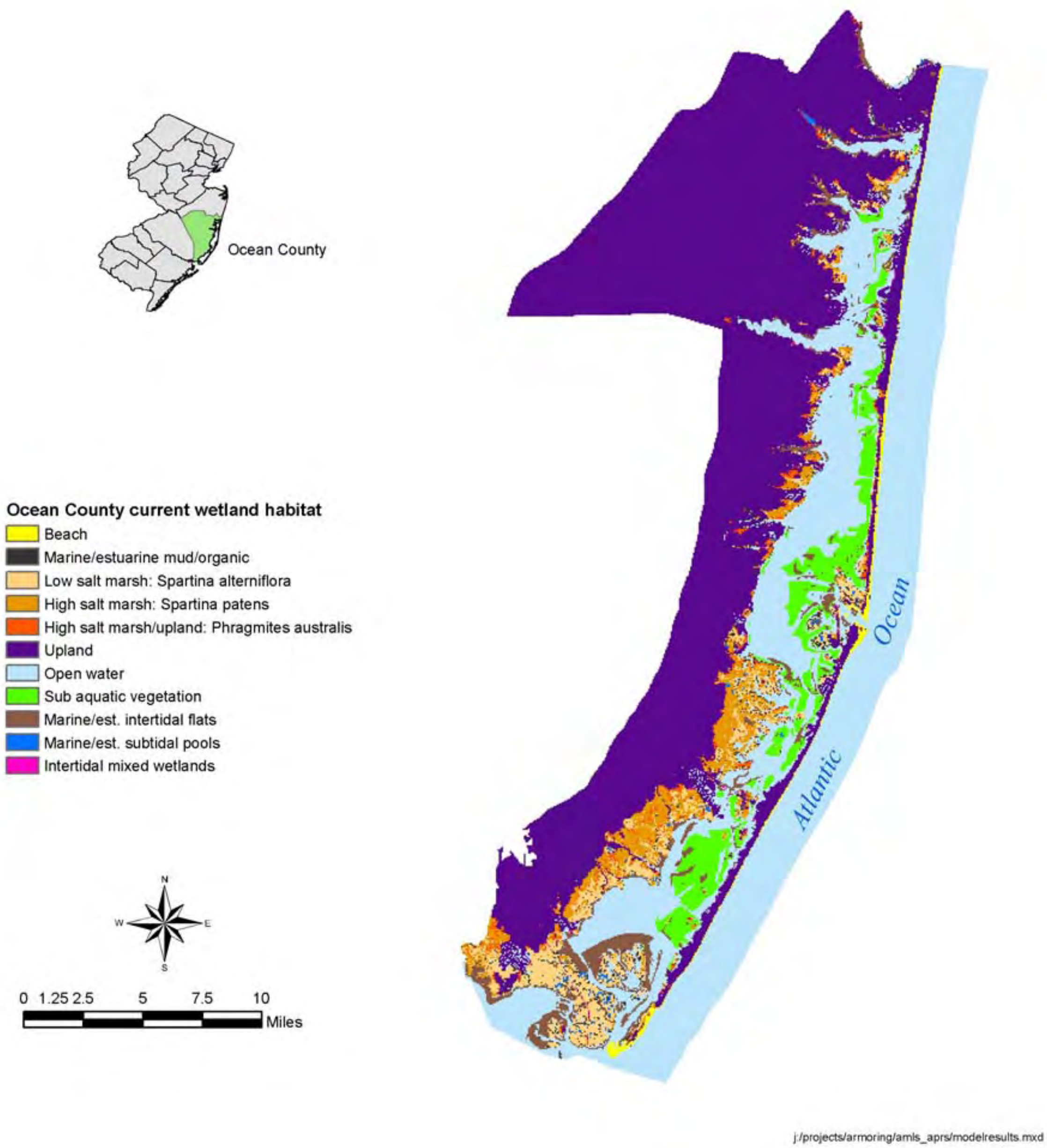

Plate 2. Distribution of wetland habitats as of 1995.

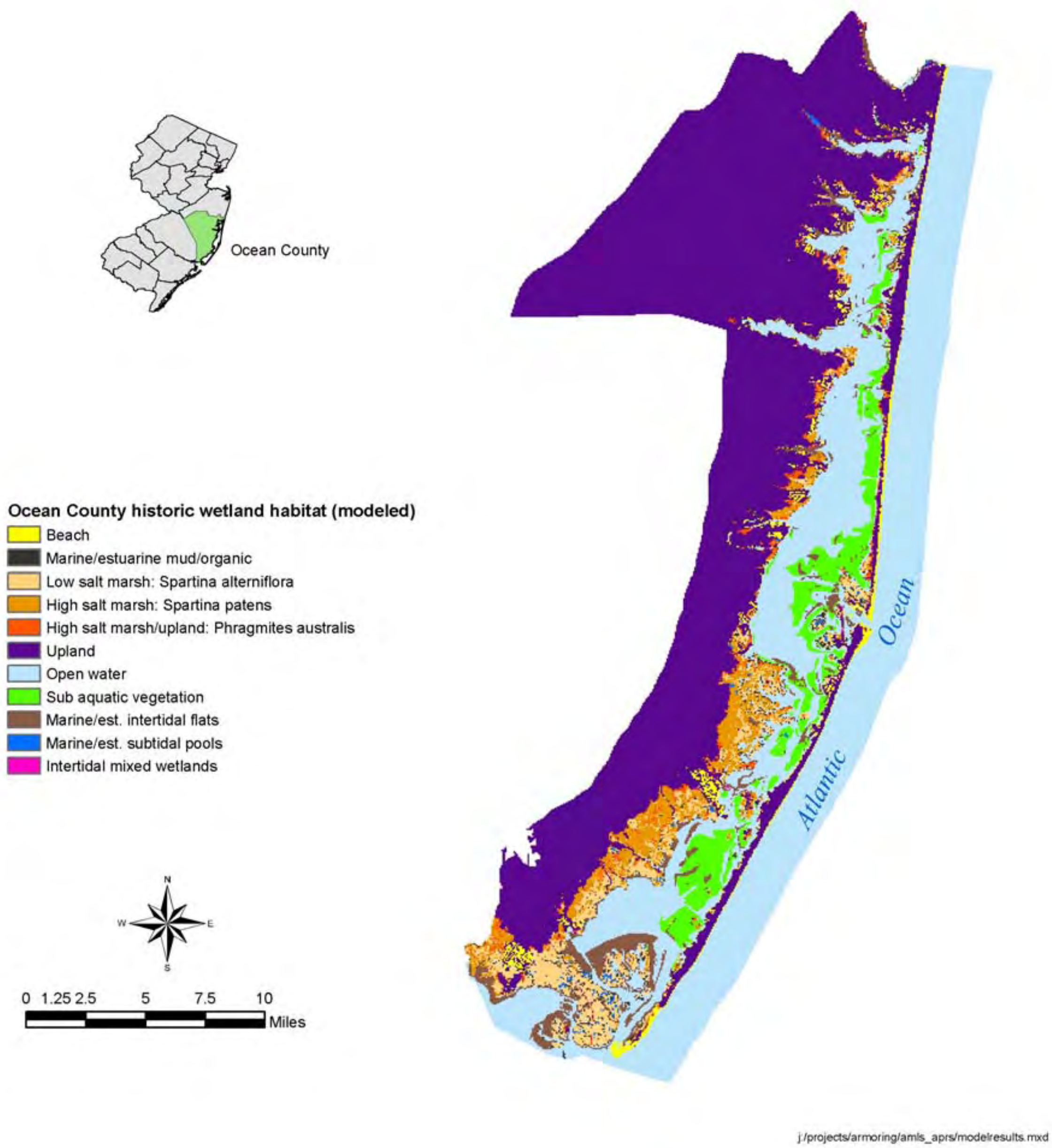

Plate 3. Distribution of wetland habitats estimated by conversion of developed lands into elevation-dependent wetland types.

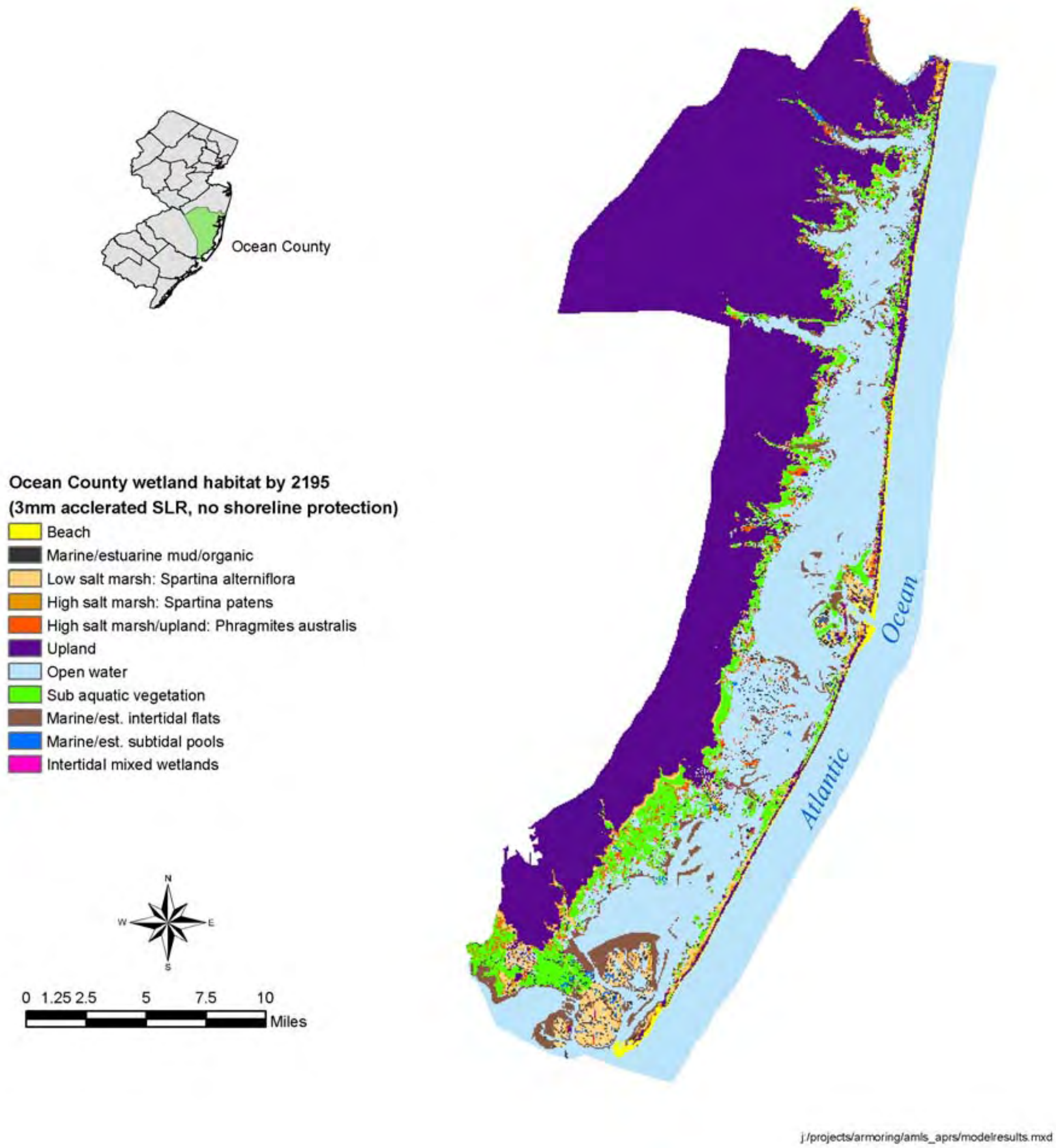

Plate 4. Distribution of wetland habitat types by 2195 modeled with no shoreline protection and 3 mm accelerated rate of SLR above the historic.

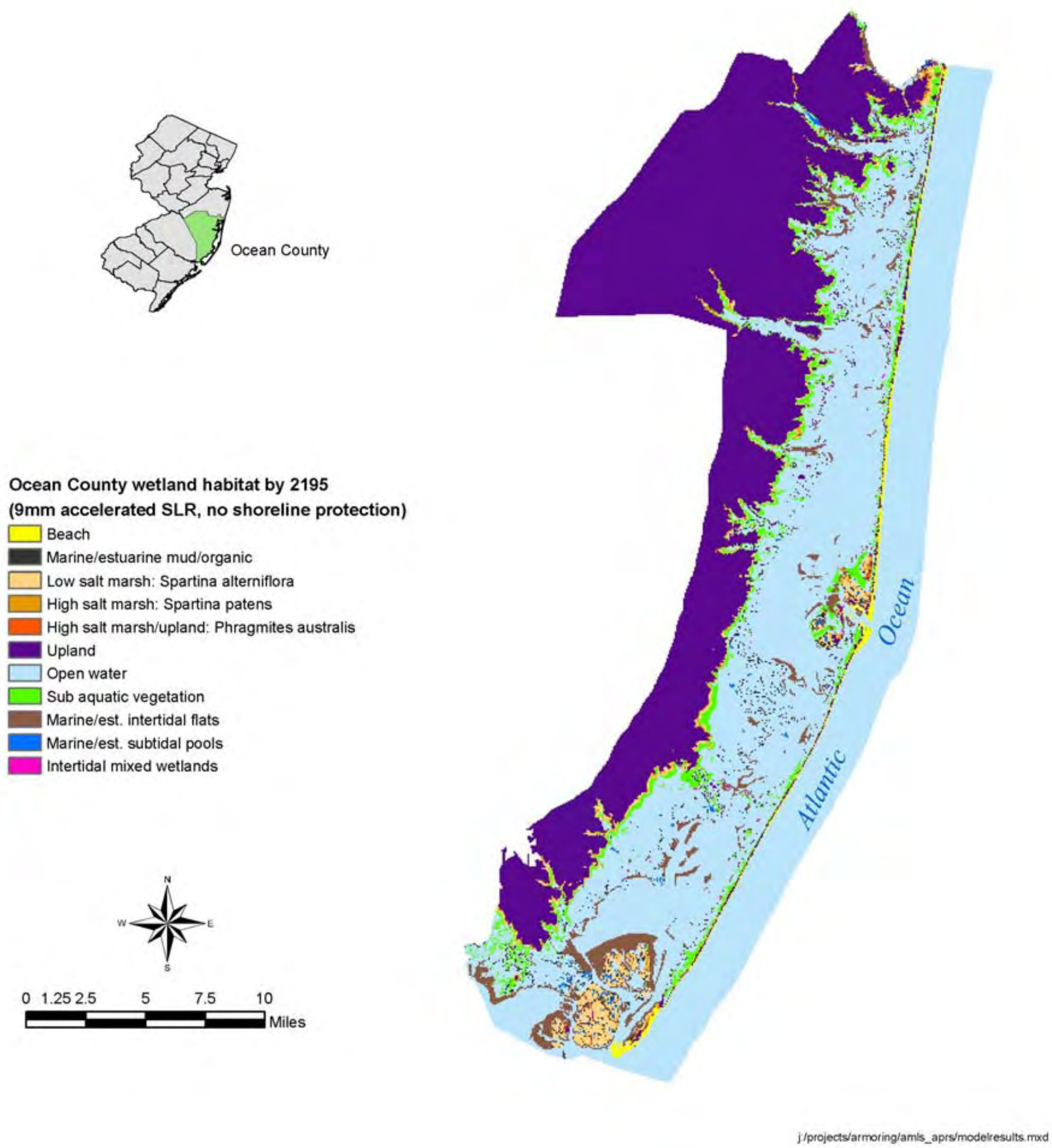

Plate 5. Distribution of wetland habitat types by 2195 modeled with no shoreline protection and 9 mm accelerated rate of SLR above the historic.

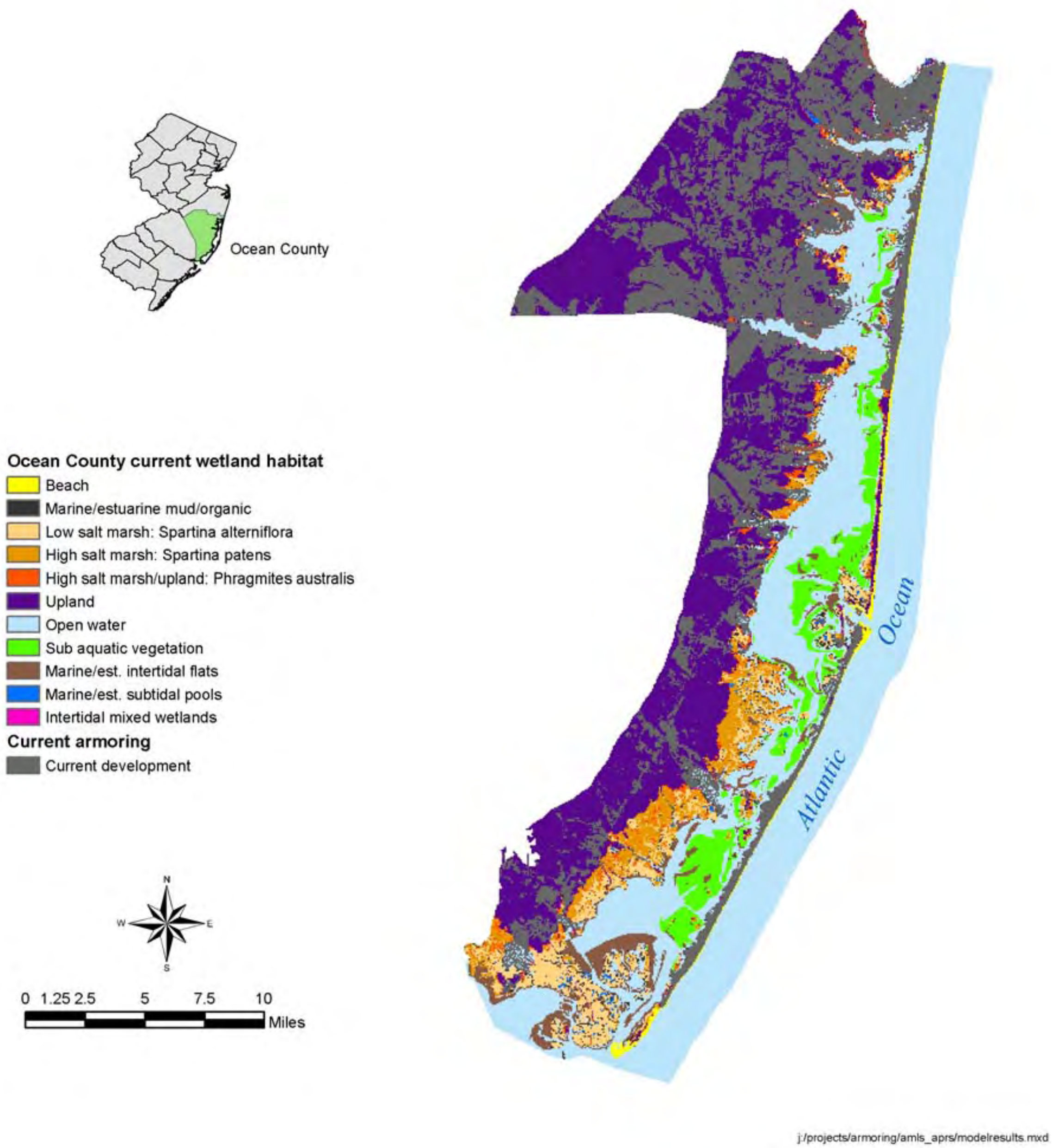

Plate 6. Current armoring scenario — currently developed lands shown on top of wetlands as of 1995.

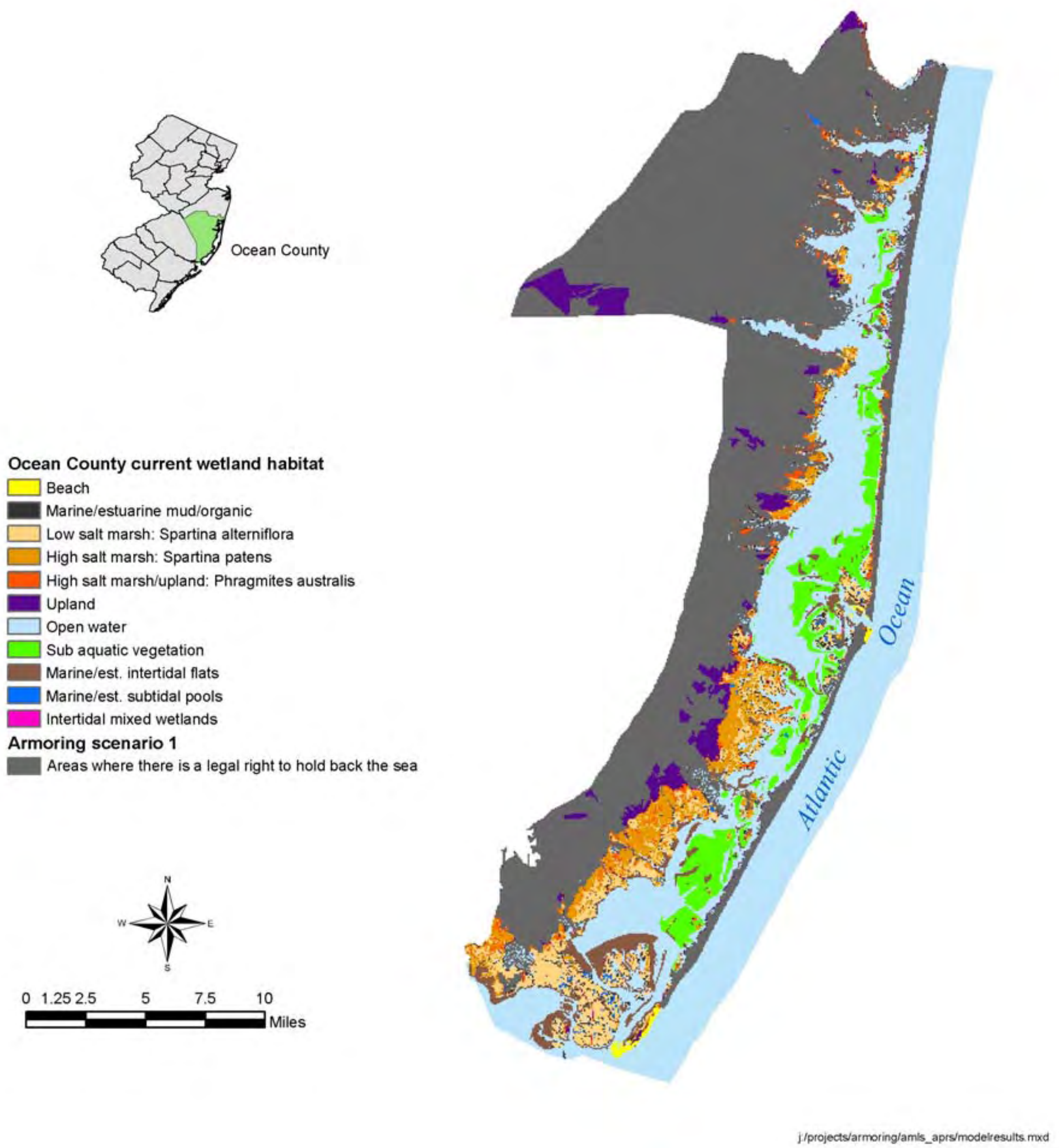

Plate 7. Armoring scenario 1 (areas where there is a legal right to hold back the sea) shown on top of wetlands as of 1995.

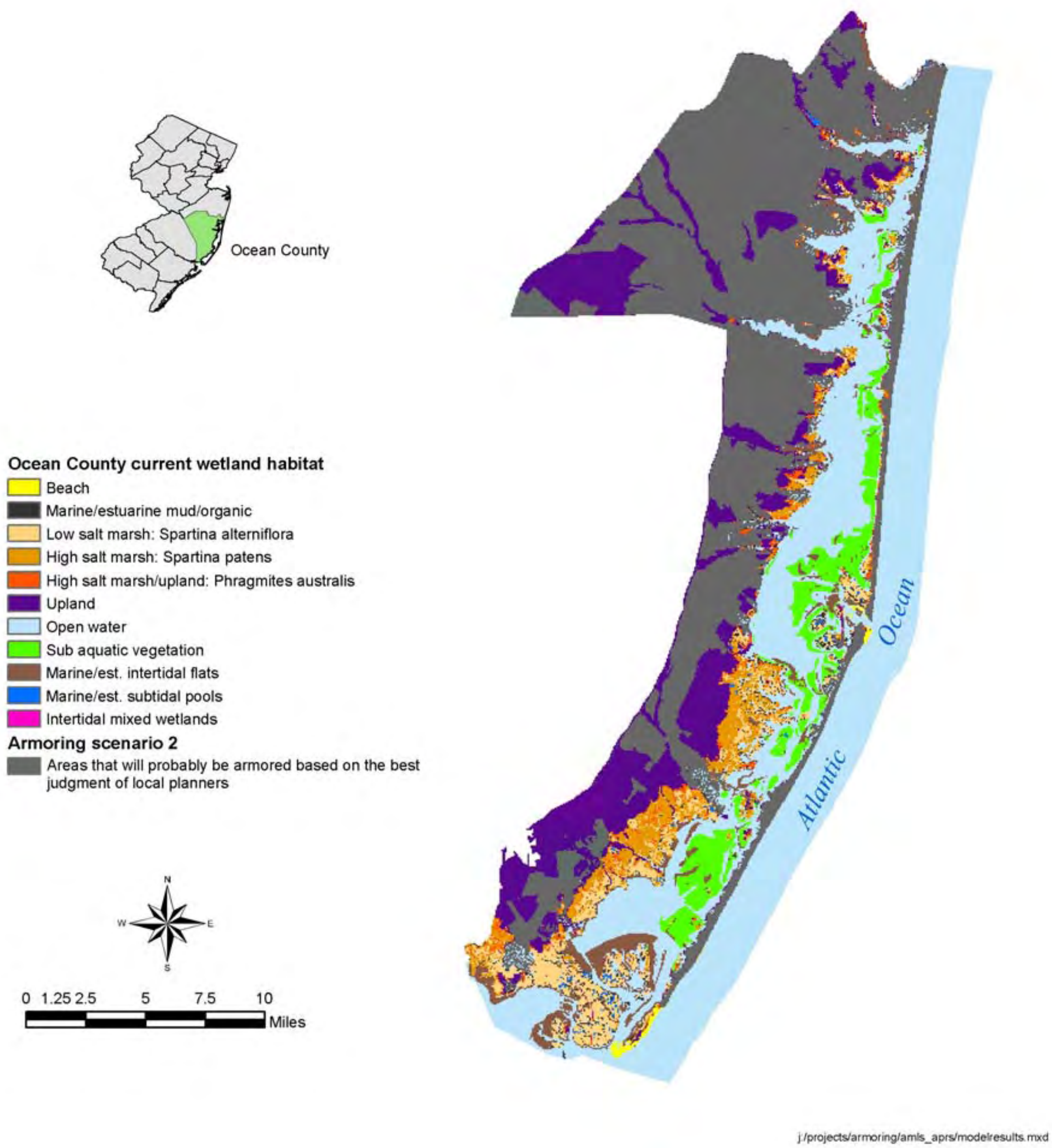

Plate 8. Armoring scenario 2 (areas that will probably be armored based on the best judgment of local planners) shown on top of wetlands as of 1995.

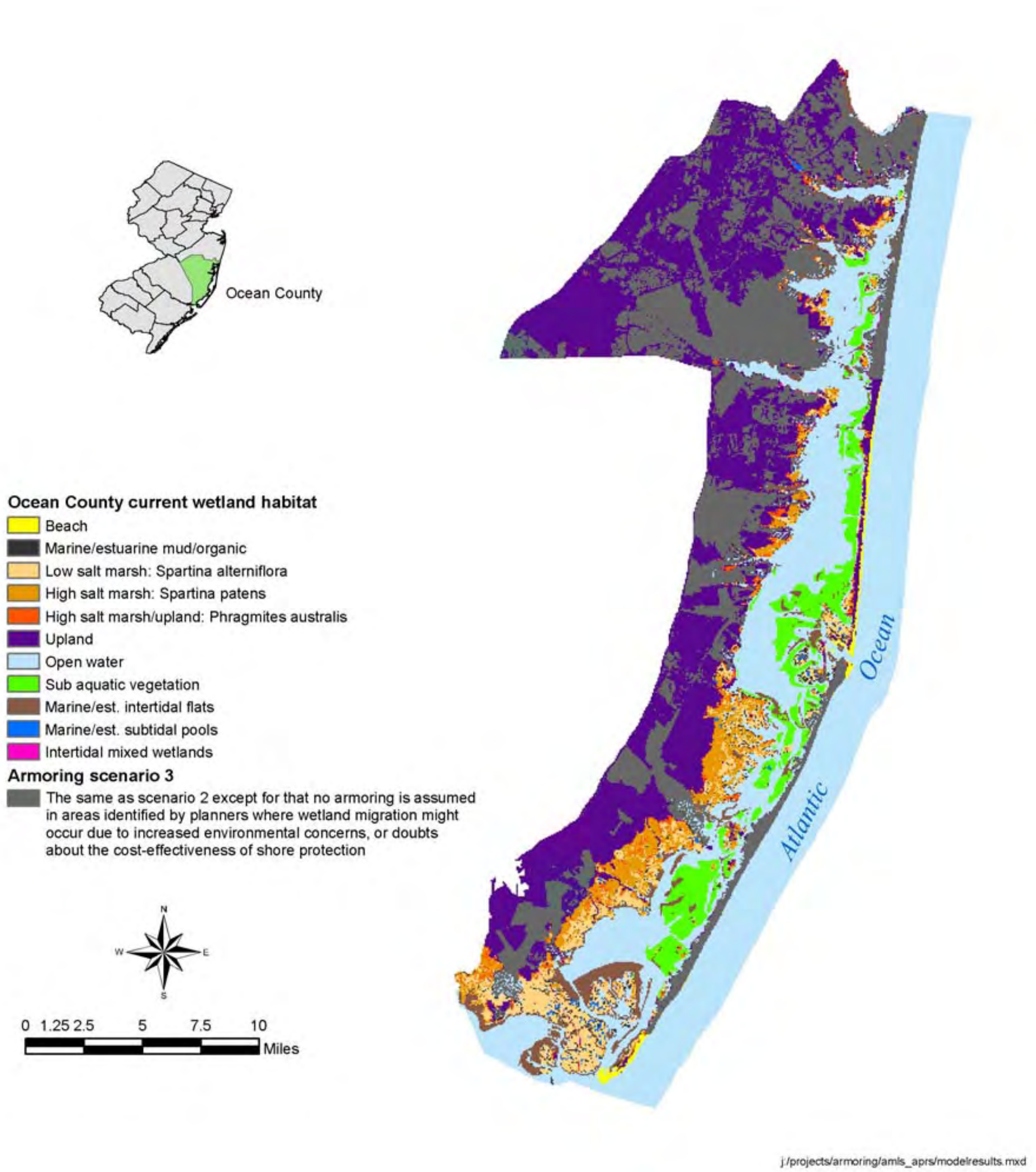

Plate 9. Armoring scenario 3 (the same as scenario 2 except that no armoring is assumed in areas identified by planners where wetland migration might occur due to increased environmental concerns, or doubts about the cost-effectiveness of shore protection) shown on top of wetlands as of 1995.

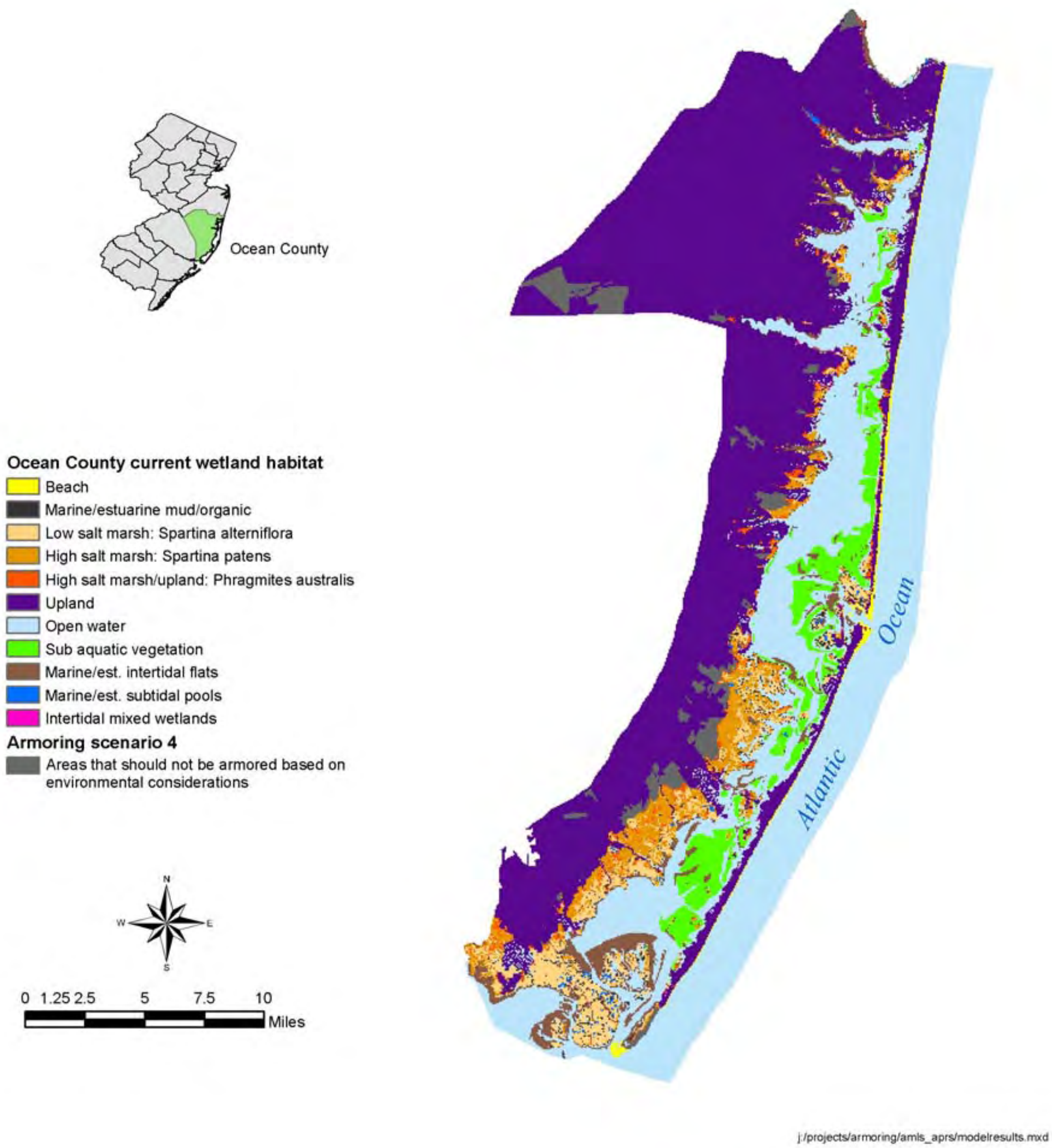

Plate 10. Armoring scenario 4 (areas that should not be armored based on environmental considerations) shown on top of wetlands as of 1995.

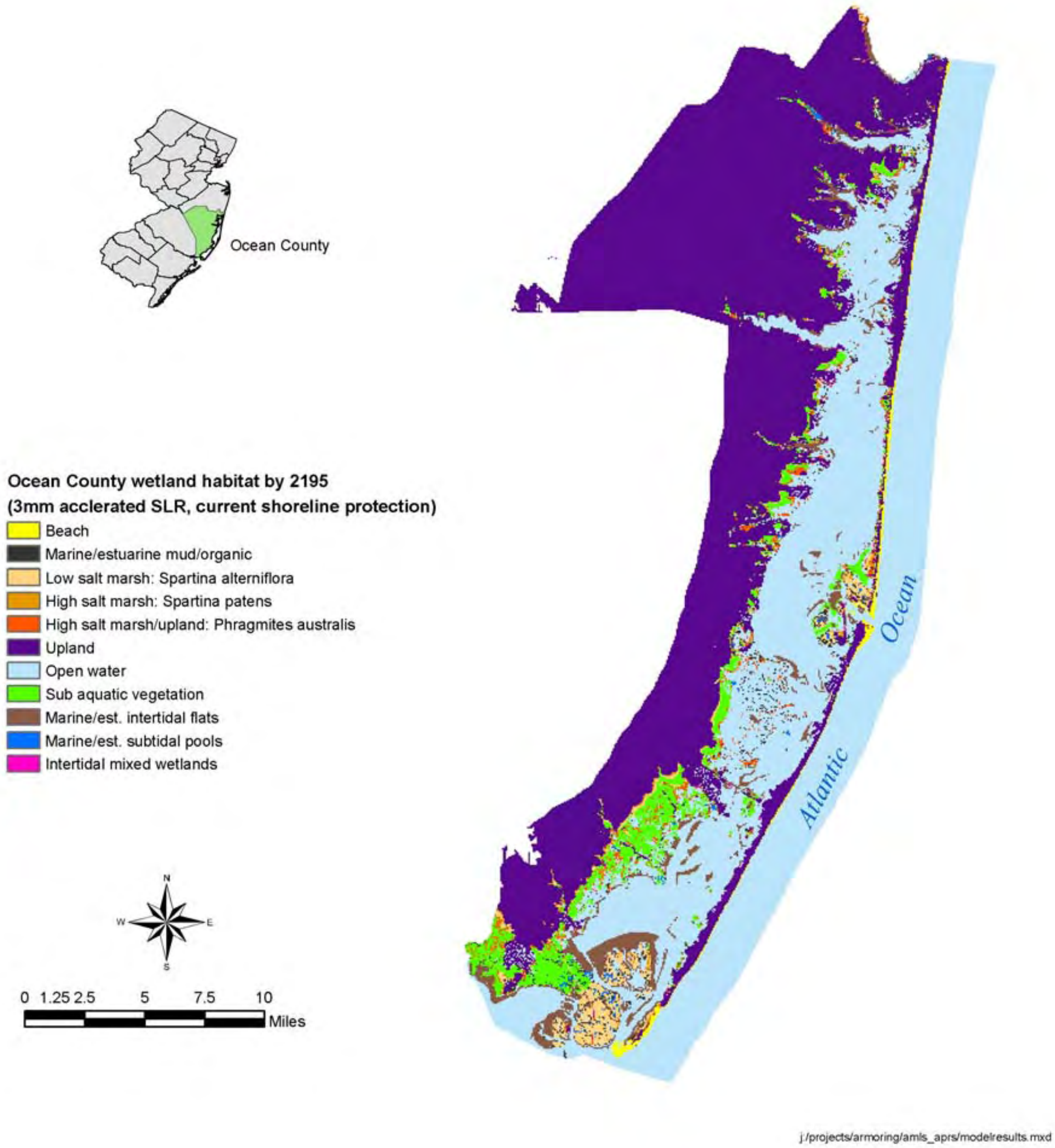

Plate 11. Distribution of wetland habitat types by 2195 modeled with current shoreline protection and 3 mm accelerated rate of SLR above the historic.

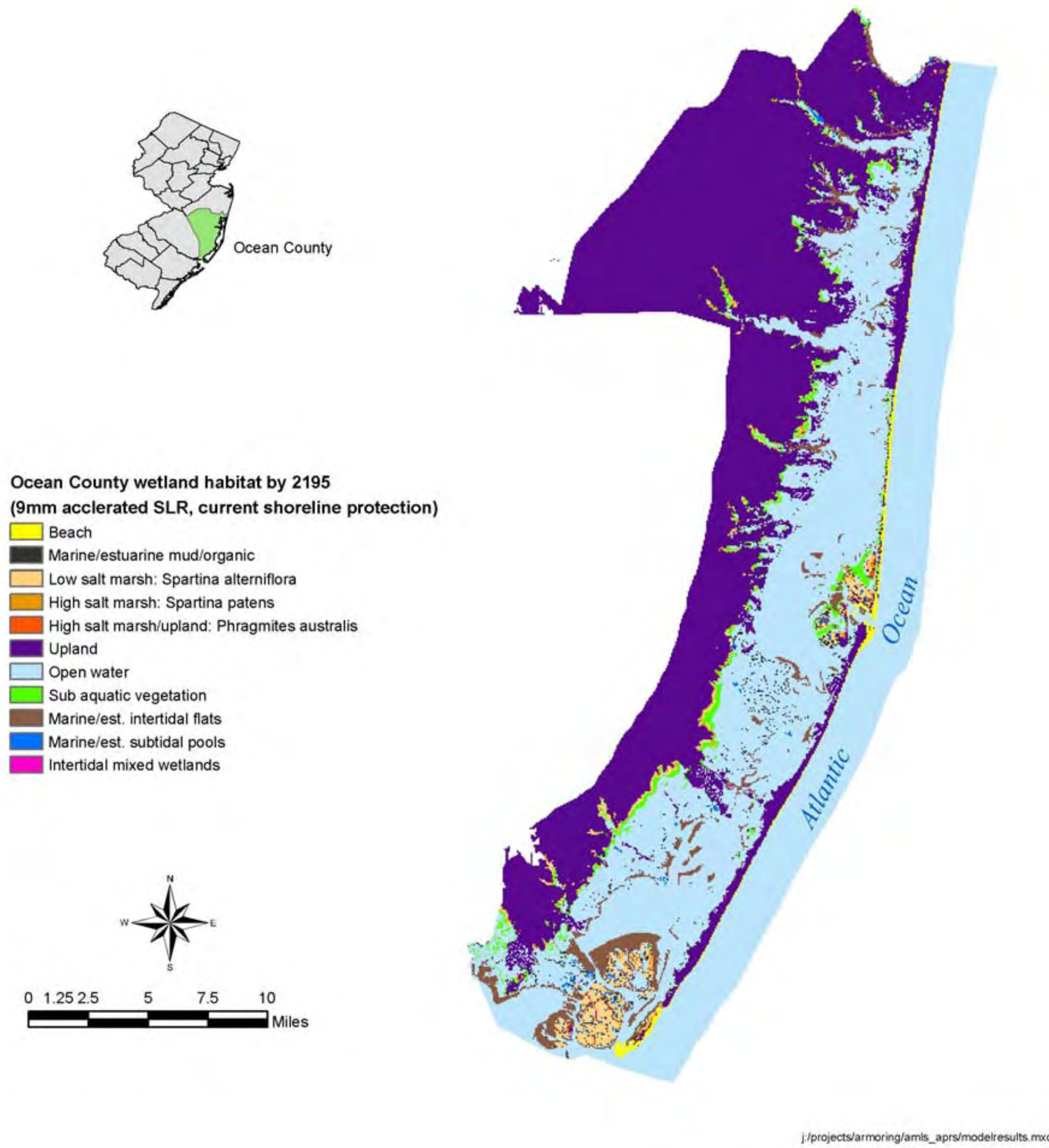

Plate 12. Distribution of wetland habitat types by 2195 modeled with current shoreline protection and 9 mm accelerated rate of SLR above the historic.

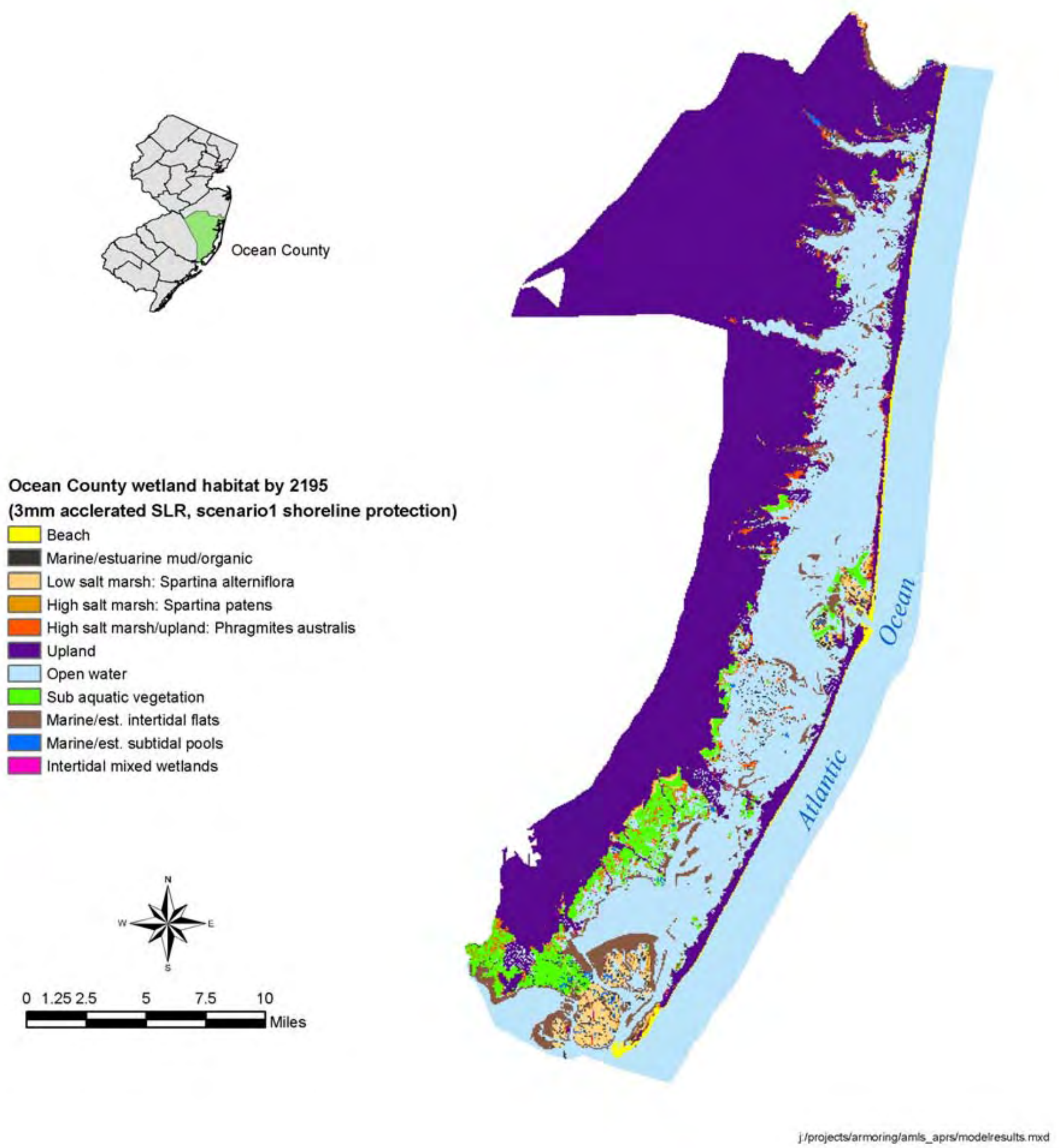

Plate 13. Distribution of wetland habitat types by 2195 modeled with shoreline protection scenario 1 (areas where there is a legal right to hold back the sea) and 3 mm accelerated rate of SLR above the historic.

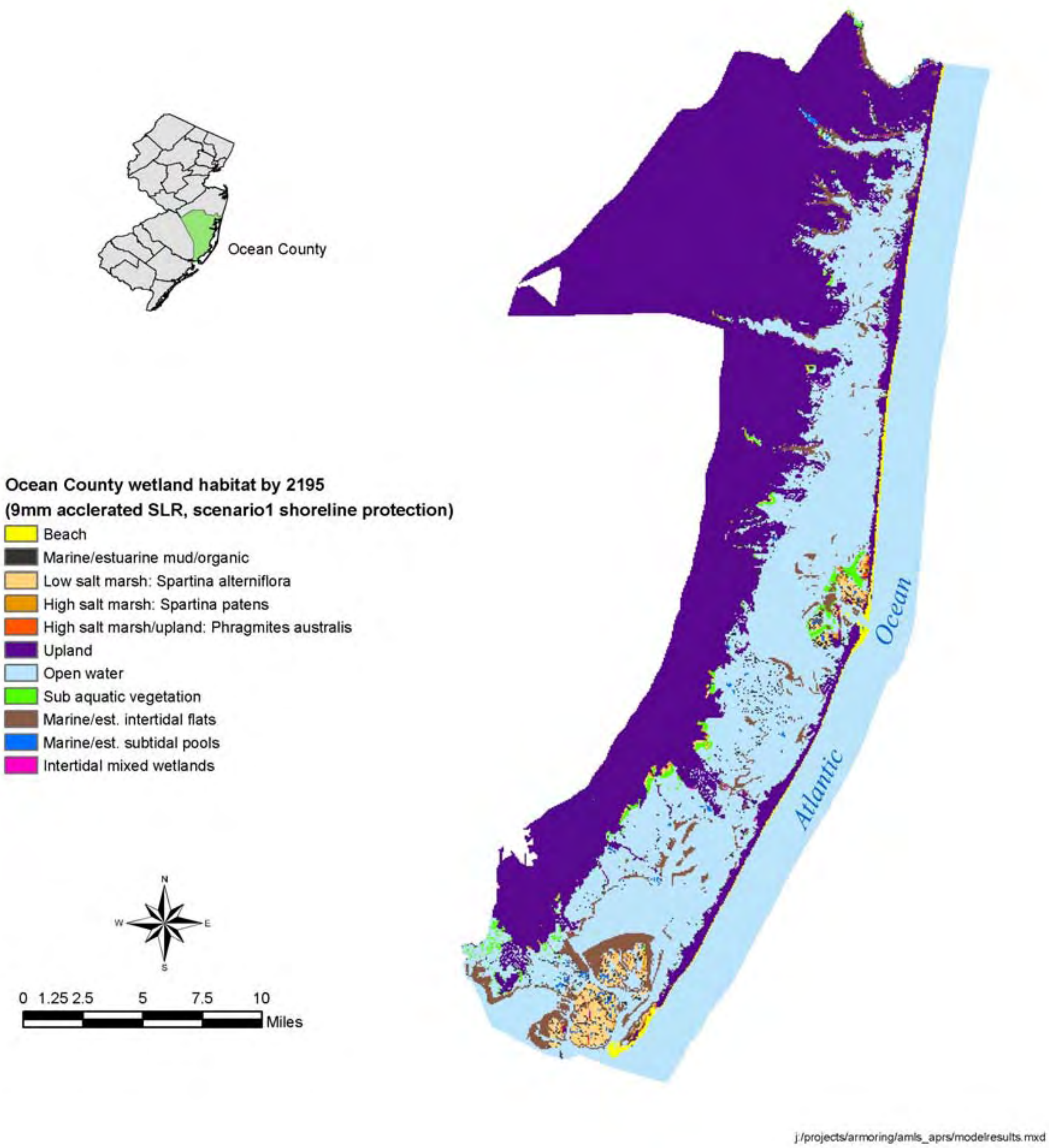

Plate 14. Distribution of wetland habitat types by 2195 modeled with shoreline protection scenario 1 (areas where there is a legal right to hold back the sea) and 9 mm accelerated rate of SLR above the historic.

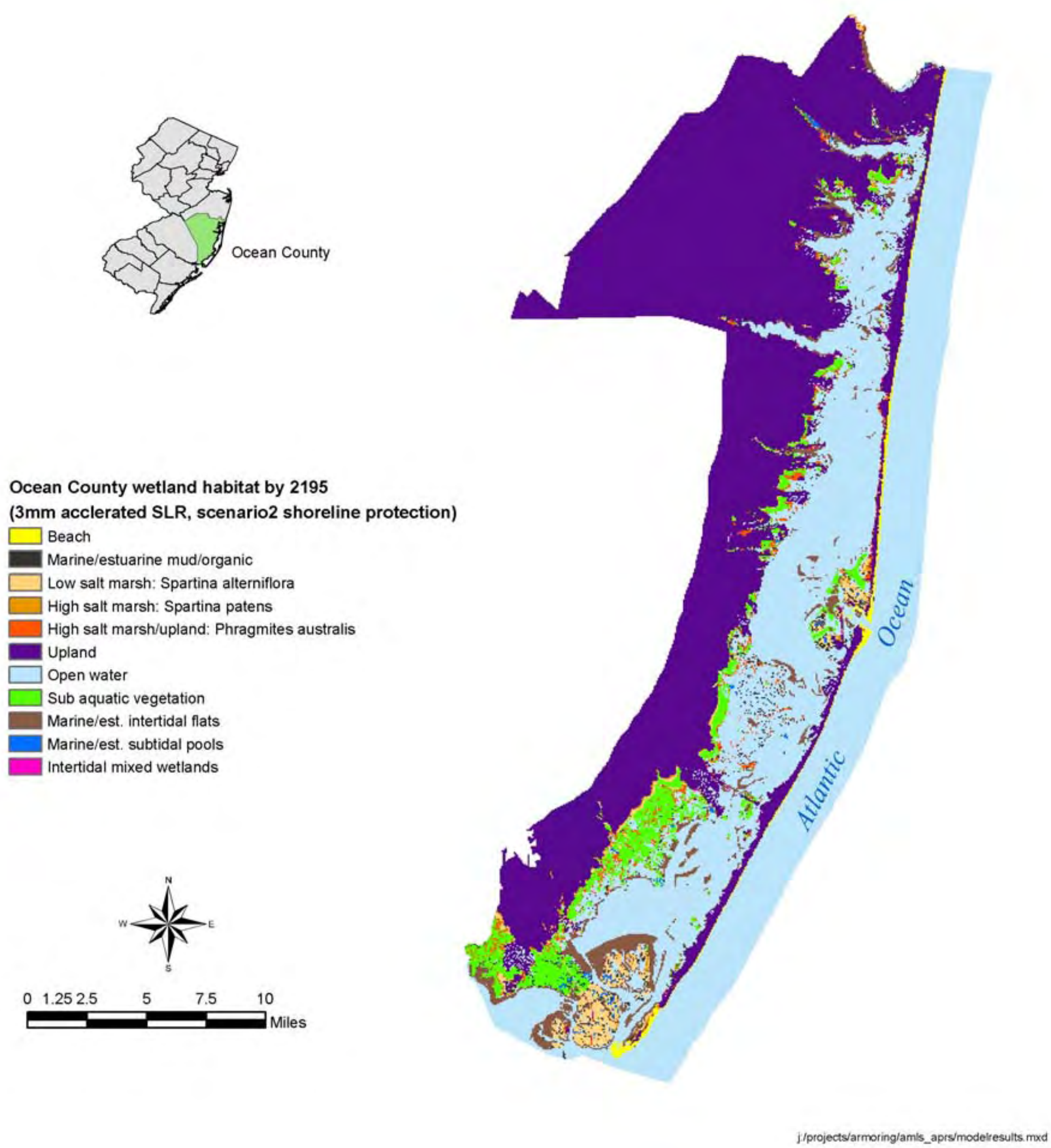

Plate 15. Distribution of wetland habitat types by 2195 modeled with shoreline protection scenario 2 (areas that will probably be armored based on the best judgment of local planners) and 3 mm accelerated rate of SLR above the historic.

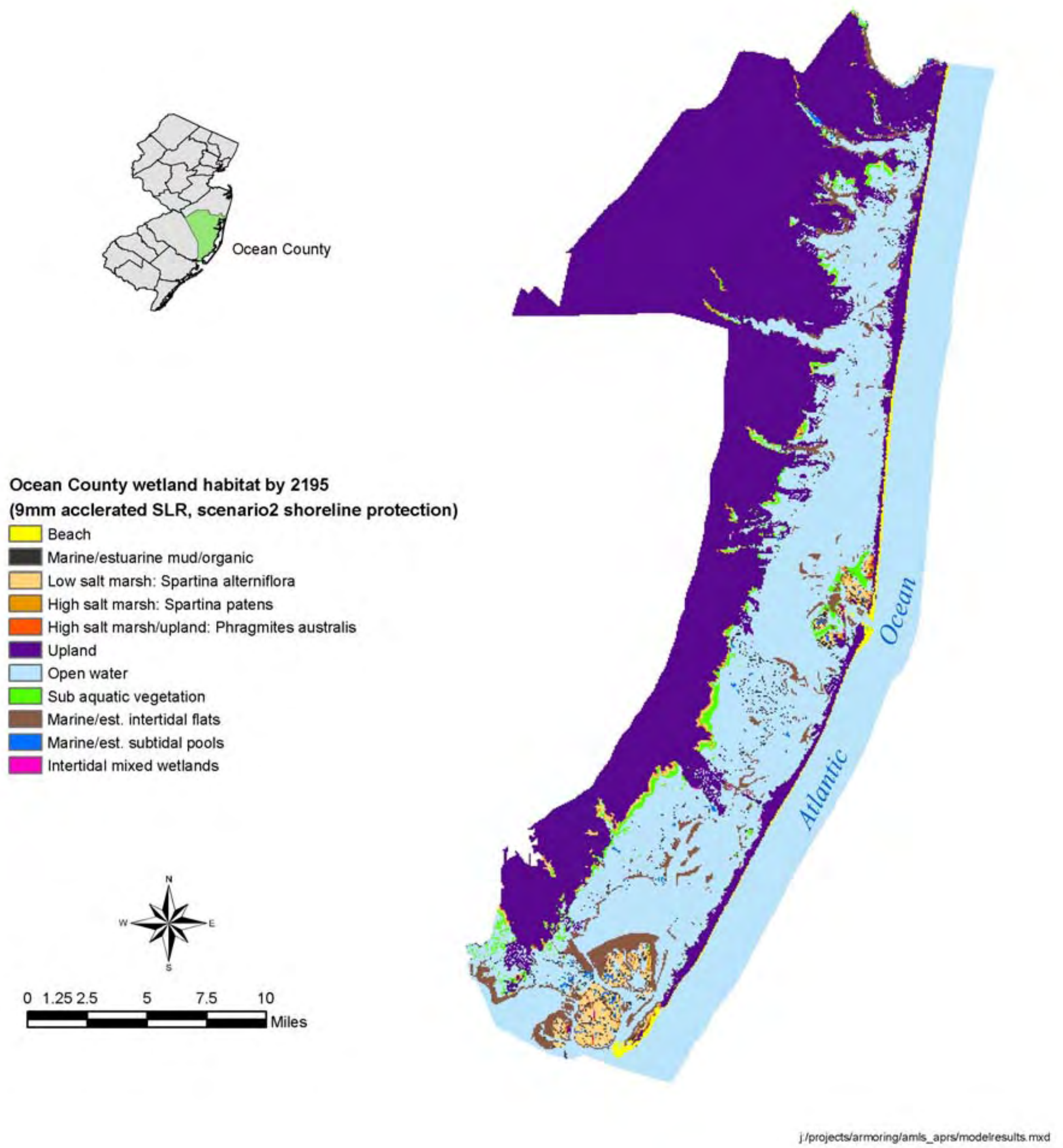

Plate 16. Distribution of wetland habitat types by 2195 modeled with shoreline protection scenario 2 (areas that will probably be armored based on the best judgment of local planners) and 9 mm accelerated rate of SLR above the historic.

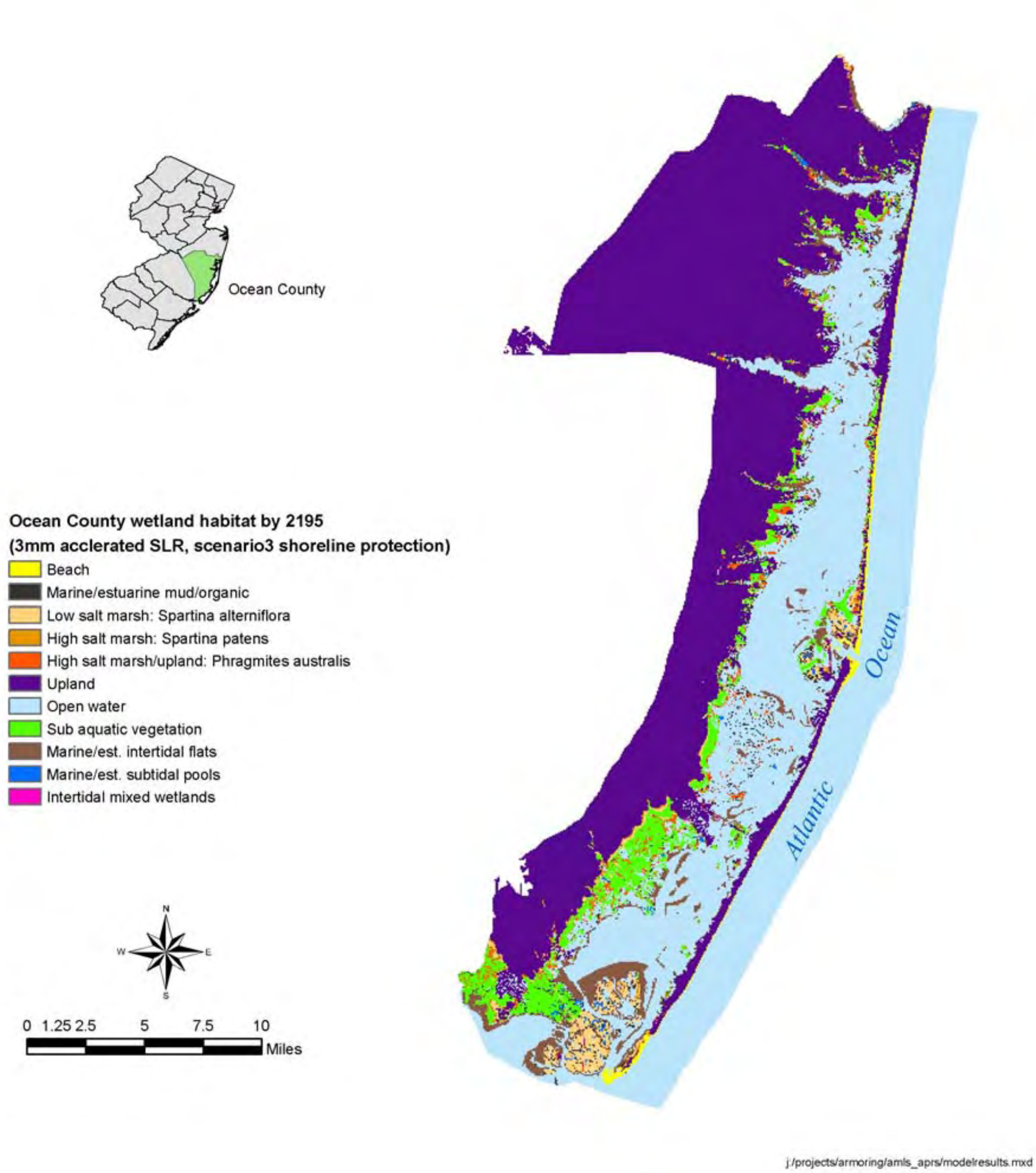

Plate 17. Distribution of wetland habitat types by 2195 modeled with shoreline protection scenario 3 (the same as scenario 2 except that no armoring is assumed in areas identified by planners where wetland migration might occur due to increased environmental concerns, or doubts about the cost-effectiveness of shore protection) and 3 mm accelerated rate of SLR above the historic.

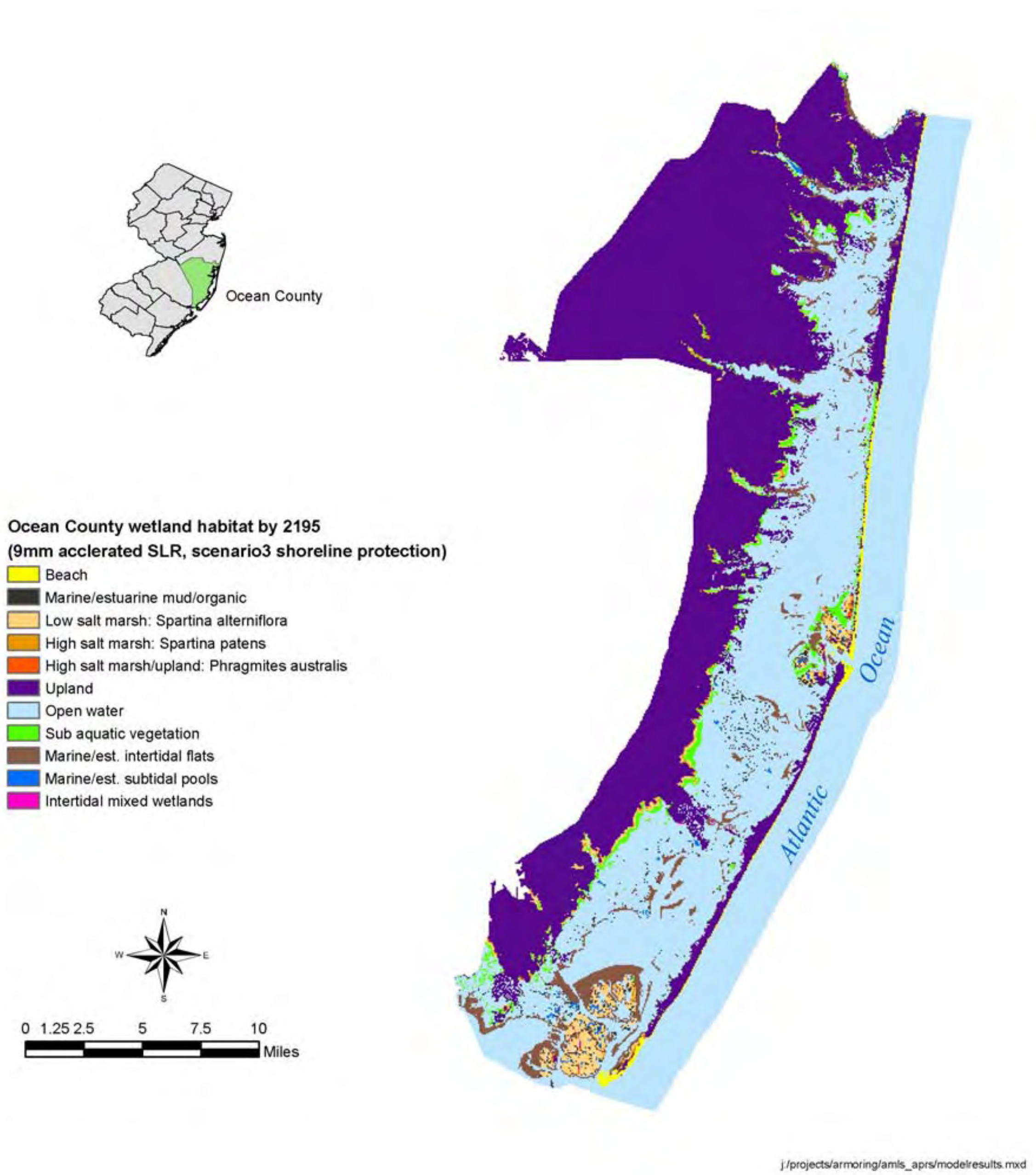

Plate 18. Distribution of wetland habitat types by 2195 modeled with shoreline protection scenario 3 (the same as scenario 2 except that no armoring is assumed in areas identified by planners where wetland migration might occur due to increased environmental concerns, or doubts about the cost-effectiveness of shore protection) and 9 mm accelerated rate of SLR above the historic.

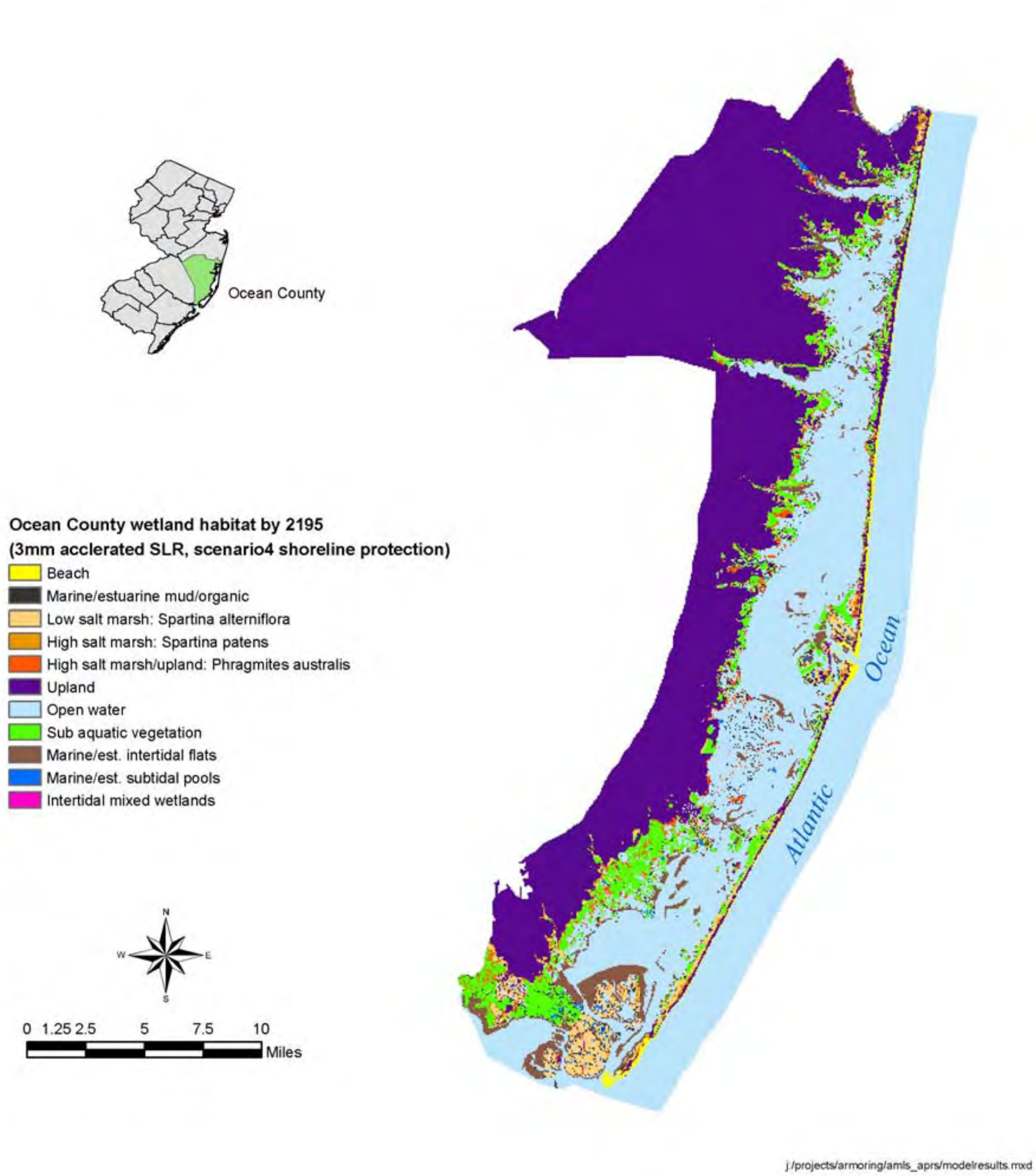

Plate 19. Distribution of wetland habitat types by 2195 modeled with shoreline protection scenario 4 (areas that should not be armored based on environmental considerations) and 3 mm accelerated rate of SLR above the historic.

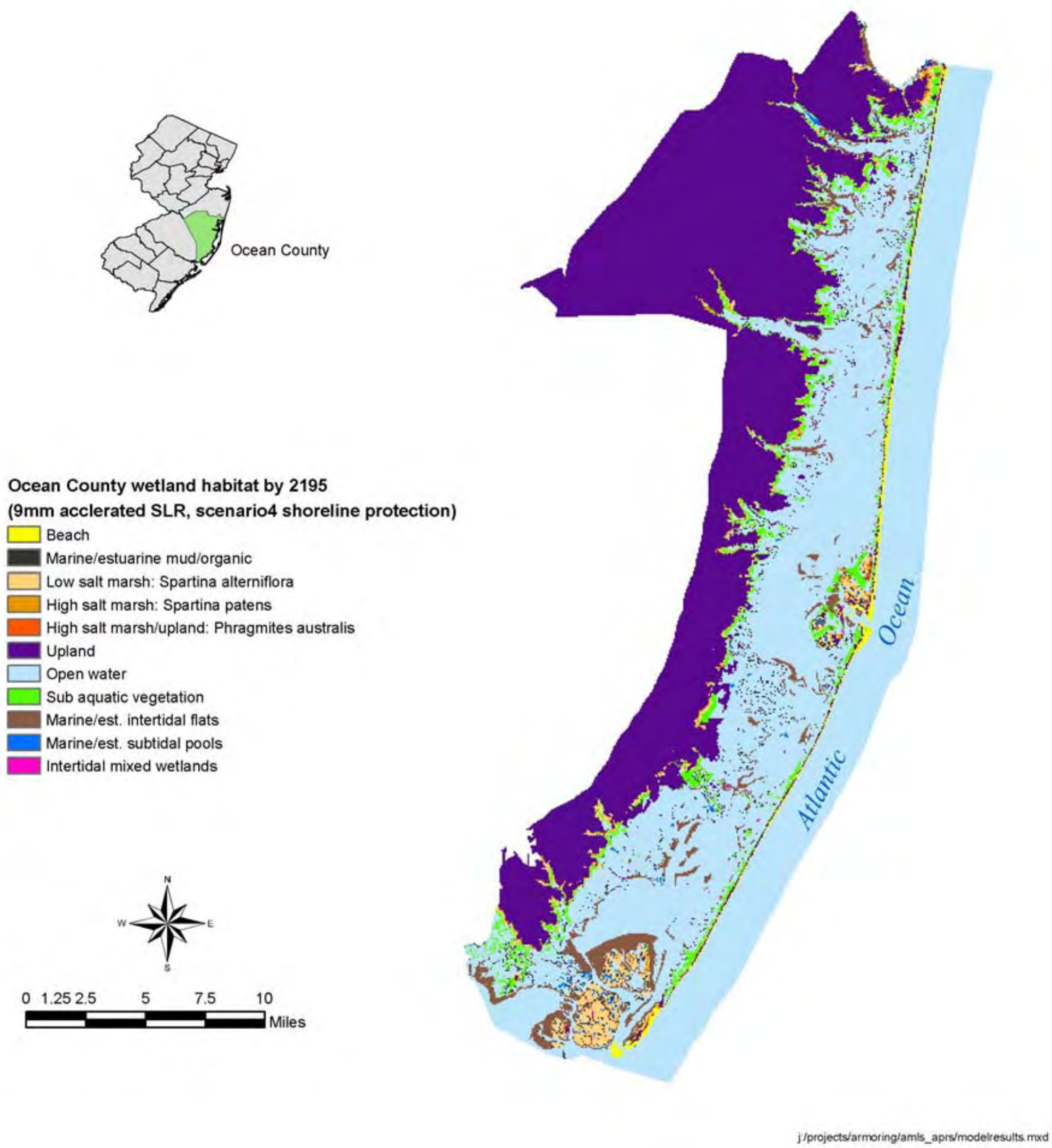

Plate 20. Distribution of wetland habitat types by 2195 modeled with shoreline protection scenario 4 (areas that should not be armored based on environmental considerations) and 9 mm accelerated rate of SLR above the historic.

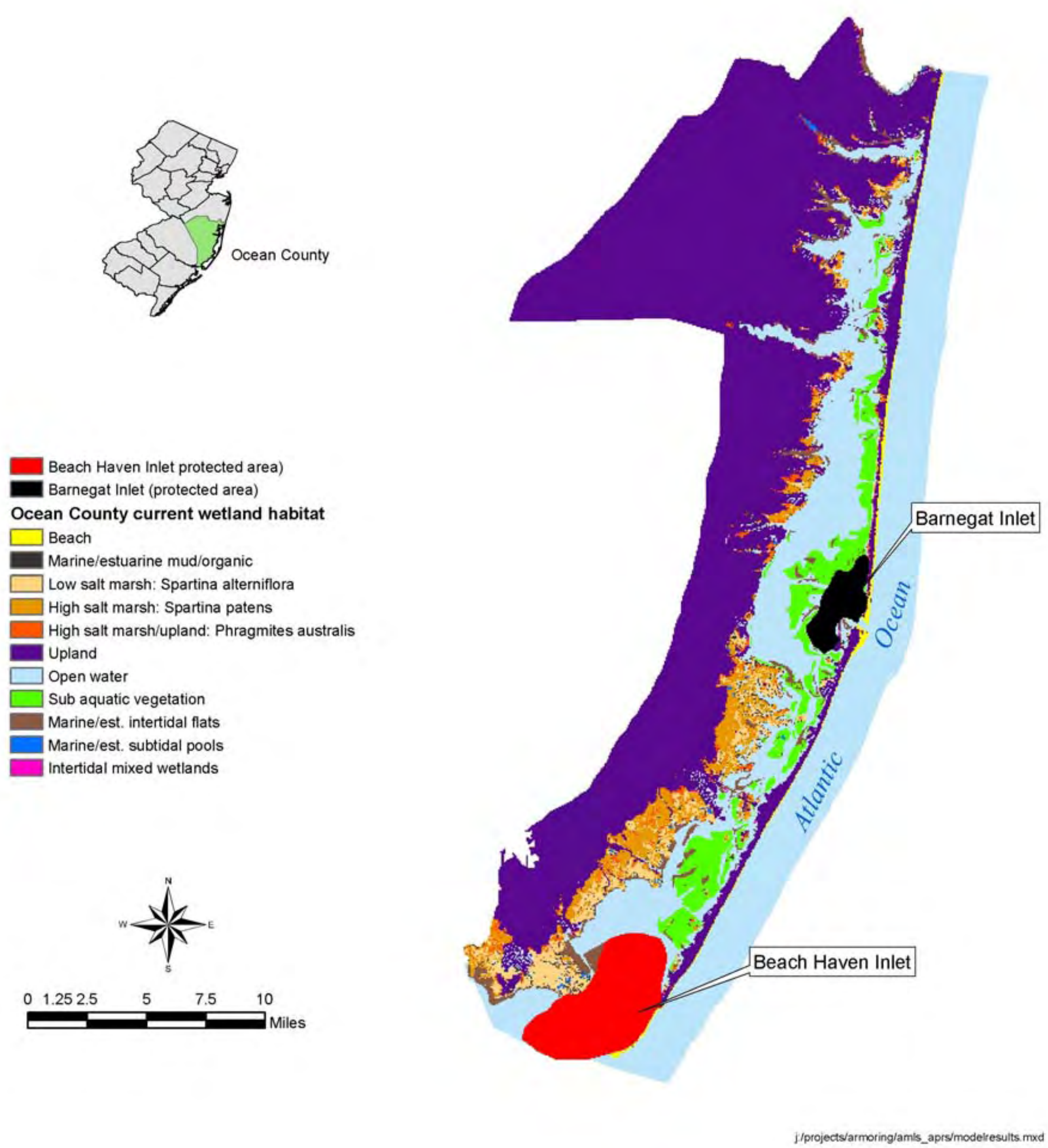

Plate 21. Distribution of wetland habitats as of 1995 with delta areas that were masked from model analysis shown in red and black.