Part II Overview. Societal Impacts and Implications

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The previous chapters in Part I examined some of the impacts of sea-level rise on the Mid-Atlantic, with a focus on the natural environment. Part II examines the implications of sea-level rise for developed lands. Although the direct effects of sea-level rise would be similar to those on the natural environment, people are part of this "built environment"; and people will generally respond to changes as they emerge, especially if important assets are threatened. The choices that people make could be influenced by the physical setting, the properties of the built environment, human aspirations, and the constraints of laws and economics.

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

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

Chapter 6 outlines some of the key factors likely to be a part of any dialogue on whether to protect or retreat in a given area:

- What are the technologies available for shore protection and the institutional measures that might help foster a retreat?
- What is the relationship between land use and shore protection?
- What are the environmental and social consequences of shore protection and retreat?
- Is shore protection sustainable?

Most areas lack a plan that specifically addresses whether the shore will retreat or be protected. Even in those areas where a state plans to hold the line or a park plans to allow the shore to retreat, the plan is based on existing conditions. Current plans do not consider the costs or environmental consequences of sustaining shore protection for the next century and beyond.

One of the most important decisions that people make related to sea-level rise is the decision to live or build in a low-lying area. Chapter 7 provides an uncertainty range of the population and number of households with a direct stake in possible inundation as sea level rises. The results are based on census data for the year 2000, and thus are not estimates the number of people or value of structures that *will* be affected, but rather estimate the number of people who have a stake *today* in the possible future consequences of rising sea level. Because census data estimates the total population of a given census block, but does not indicate where in that block the people live or the elevation of their homes, the estimates in Chapter 7 should not be viewed as the number of people whose homes would be lost. Rather, it estimates the number of people who inhabit a parcel of land with at least some land within a given elevation above the sea. The calculations in this Chapter build quantitatively on some of the elevation studies discussed in Chapter 2, and consider uncertainties in both the elevation data and the location of homes within a given census block. Chapter 7 also summarizes a study sponsored by the U.S Department of Transportation on the potential impacts of global sea-level rise on the transportation infrastructure.

Chapter 8 looks at the implications of sea-level rise for public access to the shore. The published literature suggests that the direct impact of sea level rise on public access would be minor because the boundary between public and private lands moves inland as the shore retreats. But responses to sea-level rise could have a substantial impact. One common response (publicly funded beach nourishment) sometimes increases public access *to* the shore; but another class of responses (privately funded shoreline armoring) can eliminate public access *along* the shore if the land seaward of the shore protection structure erodes. In parts of New Jersey, regulations governing permits for shoreline armoring avoid this impact by requiring property owners to provide access along the shore *inland* of the new shore protection structures.

Finally, Chapter 9 examines the implications of rising sea level for flood hazard mitigation, with a particular focus on the implications for the Federal Emergency Management Agency (FEMA) and other coastal floodplain managers. Rising sea level increases the vulnerability of coastal areas to flooding because higher sea level increases the frequency of floods by providing a higher base for flooding to build upon. Erosion of the shoreline could also make flooding more likely because erosion removes dunes and other natural protections against storm waves. Higher sea level also raises groundwater levels, which can increase basement flooding and increase standing water. Both the higher groundwater tables and higher surface water levels can slow the rate at which areas drain, and thereby increase the flooding from rainstorms.

Chapter 9 opens with results of studies on the relationship of coastal storm tide elevations and sea-level rise in the Mid-Atlantic. It then provides background on government agency floodplain management and on state activities related to flooding and sea-level rise under the Coastal Zone Management Act. Federal agencies, such as FEMA, are beginning to specifically plan for future climate change in their strategic planning. Some coastal states, such as Maryland, have conducted state-wide assessments and studies of the impacts of sea-level rise and have taken steps to integrate this knowledge with local policy decisions.

The chapters in Part II incorporate the underlying sea-level rise scenarios of this Product differently, because of the differences in the underlying analytical approaches. Chapter 6 evaluates the population and property vulnerable to a 100-centimeter rise in sea level, and summarizes a study by the U.S. Department of Transportation concerning the impact of a 59-centimeter rise. Chapters 6, 8 and 9 provide qualitative analyses that are generally valid for the entire uncertainty range of future sea level rise.

Chapter 6. Shore Protection and Retreat

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KEY FINDINGS

- Many options are available for protecting land from inundation, erosion, and flooding ("shore protection"), or for minimizing hazards and environmental impacts by removing development from the most vulnerable areas ("retreat").
- Coastal development and shore protection can be mutually reinforcing. Coastal development often encourages shore protection because shore protection costs more than the market value of undeveloped land, but less than the value of land and structures. Shore protection sometimes encourages coastal development by making a previously unsafe area safe for development. Under current policies, shore protection is common along developed shores and rare along shores managed for conservation, agriculture, and forestry. Policymakers have not decided whether the practice of protecting development should continue as sea level rises, or be modified to avoid adverse environmental consequences and increased costs of shore protection.
- Most shore protection structures are designed for the current sea level, and retreat policies that rely on setting development back from the coast are designed for the current rate of sea-level rise. Those structures and policies would not necessarily accommodate a significant acceleration in the rate of sea-level rise.

- Although shore protection and retreat both have environmental impacts, the long-term impacts of shore protection are likely to be greater.
- In the short-term, retreat is more socially disruptive than shore protection. In the long-term, however, shore protection may be more disruptive—especially if it fails or proves to be unsustainable.
- We do not know whether "business as usual" shore protection is sustainable.
- A failure to plan now could limit the flexibility of future generations to implement preferred adaptation strategies. Short-term shore protection projects can impair the flexibility to later adopt a retreat strategy. By contrast, short-term retreat does not significantly impair the ability to later erect shore protection structures inland from the present shore.

6.1 TECHNIQUES FOR SHORE PROTECTION AND RETREAT

Most of the chapters in this Product discuss some aspect of shore protection and retreat. This Section provides an overview of the key concepts and common measures for holding back the sea or facilitating a landward migration of people, property, wetlands, and beaches. Chapter 9 discusses floodproofing and other measures that accommodate rising sea level without necessarily involving choosing between shore protection and retreat.

6.1.1 Shore Protection

The term "shore protection" generally refers to a class of coastal engineering activities that reduce the risk of flooding, erosion, or inundation of land and structures (USACE, 2002). The term is somewhat of a misnomer because shore-protection measures protect land and structures immediately inland of the shore rather than the shore itself[9]. Shore-protection structures sometimes eliminate the existing shore, and shore protection does not necessarily mean environmental preservation. This Product focuses on shore-protection measures that prevent dry land from being flooded, or converted to wetlands or open water.

Shore-protection measures can be divided into two categories: shoreline armoring and elevating land surfaces. Shoreline armoring replaces the natural shoreline with an artificial surface, but areas inland of the shore are generally untouched. Elevating land surfaces, by contrast, can maintain the natural character of the shore, but requires rebuilding all vulnerable land. Some methods are hybrids of both approaches. For centuries, people have used both shoreline armoring (Box 6.1) and elevating land surfaces (Box 6.2) to reclaim dry land from the sea. This Section discusses how those approaches might be used to prevent a rising sea level from converting dry land to open water. For a comprehensive discussion, see the *Coastal Engineering Manual* (USACE, 2002).

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[9] The shore is the land immediately in contact with the water.

BOX 6.1 Historic use of Dikes to Reclaim Land in the Delaware Estuary

Until the twentieth century, tidal wetlands were often converted to dry land through the use of dikes and drainage systems very similar to the systems that might be used to prevent land from being inundated as sea level rises. Nowhere in the United States was more marsh converted to dry land than along the Delaware River and Delaware Bay. A Dutch governor of New Jersey diked the marsh on Burlington Island, New Jersey. In 1680, after the English governor took possession of the island, observers commented that the marsh farm had achieved greater yields of grain than nearby farms created by clearing woodland (Danckaerts, 1913). In 1675, an English governor ordered the construction of dikes to facilitate construction of a highway through the marsh in New Castle County, Delaware (Sebold, 1992).

Colonial (and later state) governments in New Jersey chartered and authorized “meadow companies” to build dikes and take ownership of the reclaimed lands. During the middle of the nineteenth century, the state agriculture department extolled the virtues of reclaimed land for growing salt hay. By 1866, 20,000 acres of New Jersey’s marshes had been reclaimed from Delaware Bay, mostly in Salem and Cumberland counties (Sebold, 1992). In 1885, the U.S. Department of Agriculture cited land reclamation in Cumberland County, New Jersey, as among the most impressive in the nation (Nesbit, 1885, as quoted in Sebold, 1992). By 1885, land reclamation had converted 10,000 out of 15,000 acres of the marsh in New Castle County to agricultural lands, as well as 8,000 acres in Delaware’s other two counties (Nesbit, 1885). In Pennsylvania, most of the reclaimed land was just south of the mouth of the Schuylkill along the Delaware River, near the present location of Philadelphia International Airport.

During the twentieth century, these land reclamation efforts were reversed. In many cases, lower prices for salt hay led farmers to abandon the dikes (DDFW, 2007). In some cases, where dikes remain, rising sea level has limited the ability of dikes to drain the land, and the land behind the dike has converted to marsh, such as the land along the Gibbstown Levee (See Box A1.4 in Appendix 1and Figure 11.4 c and d). Efforts are under way to restore the hydrology of many lands that were formerly diked (DDFW, 2007). In areas where dikes protect communities from flooding, however, public officials area also considering the possibility of upgrading the dikes and drainage systems.

Box 6.2 Creation of the National Monument Area in Washington D.C. through Nineteenth Century Dredge and Fill

Like many coastal cities, important parts of Washington, D.C. are on land that was previously created by filling wetlands and navigable waterways. When the city of Washington was originally planned, the Potomac River was several times as wide immediately south of Georgetown as above Georgetown (see Box Figure 6.2). L’Enfant’s plan put the President’s residence just northeast of the mouth of Tiber Creek. Thus, the White House grounds originally had a tidal shoreline. To improve navigation, canals connected Tiber Creek to the Anacostia River (Bryan, 1914). The White House and especially the Capitol were built on high ground immune from flooding, but much of the land between the two was quite low.

During the nineteenth century, soil eroded from upstream farming was deposited in the wide part of the river where the current slowed, which created wide mudflats below Georgetown. The success of railroads made canals less important, while the increasing population converted the canals into open sewers. During the early 1870s, Governor Boss Shephard had the canals filled and replaced with drain pipes. A large dredge-and-fill operation excavated Washington Channel from the mudflats, and used the material to create the shores of the Tidal Basin and the dry land on which the Lincoln Memorial, Jefferson Memorial, Reflecting Pool, East Potomac Park, and Hains Point sit today (Bryan, 1914). Similarly, about half of the width of the Anacostia River was filled downstream from Poplar Point, creating what later became the U.S. Naval Air Station (now part of Bolling Air Force Base).

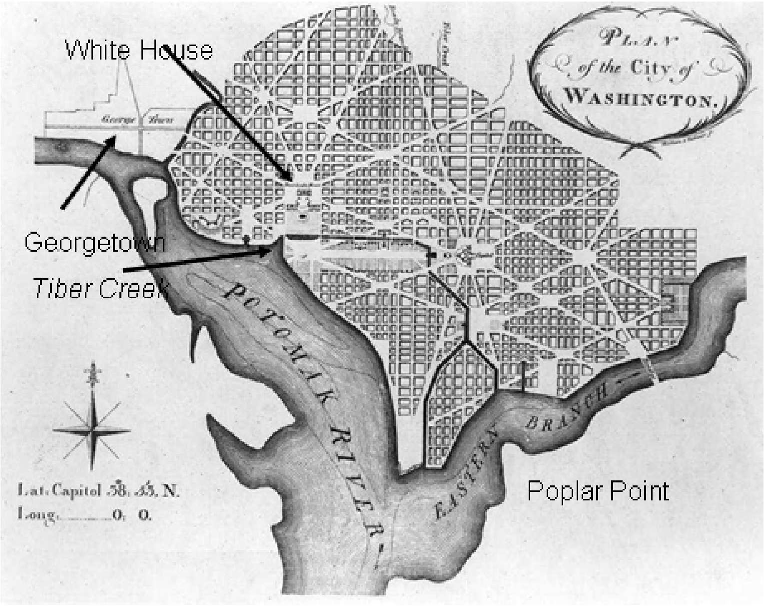


Figure Box 6.2 L'Enfant's Plan for the City of Washington
Source: Library of Congress (Labels for White House, Georgetown, and Tiber Creek added).

6.1.1.1 Shoreline Armoring

Shoreline armoring involves the use of structures to keep the shoreline in a fixed position or to prevent flooding when water levels are higher than the land. Although the term is often synonymous with "shoreline hardening", some structures are comprised of relatively soft material, such as earth and sand.

Keeping the shoreline in a fixed position

Seawalls are impermeable barriers designed to withstand the strongest storm waves and to prevent overtopping during a storm. During calm periods, their seaward side may either be landward of a beach or in the water. Seawalls are often used along important transportation routes such as highways or railroads (Figure 6.1a).

Figure 6.1 Seawalls and Bulkheads (a) Galveston Seawall in Texas (May 2003) and (b) Bulkheads with intervening beach along Magothy River in Anne Arundel County, Maryland (August 2005).

Bulkheads are vertical walls designed to prevent the land from slumping toward the water (Figure 6.1b). They must resist waves and currents to accomplish their design intent, but unlike seawalls, they are not designed to withstand severe storms. They are usually found along estuarine shores where waves have less energy, particularly in marinas and other places where boats are docked, and residential areas where homeowners prefer a tidy shoreline. Bulkheads hold soils in place, but they do not normally extend high enough to keep out foreseeable floods. Like seawalls, their seaward sides may be inland of a beach (or marsh) or in the water.

Retaining structures include several types of structures that serve as a compromise between a seawall and a bulkhead. They are often placed at the rear of beaches and are unseen. Sometimes they are sheet piles driven downward into the sand; sometimes they are long, cylindrical, sand-filled “geo-tubes” (Figure 6.2). Retaining structures are often concealed as the buried core of an artificial sand dune. Like seawalls, they are intended to be a final line of defense against waves after a beach erodes during a storm; but they can not survive wave attack for long.

Figure 6.2 Geotube (a) before and (b) after being buried by beach sand at Bolivar Peninsula, Texas (May 2003).

Revetments are walls whose sea side follows a slope. Like the beach they replace, their slope makes them more effective at dissipating the energy of storm waves than bulkheads and seawalls. As a result, revetments are less likely than bulkheads and seawalls to cause the beach immediately seaward to erode (USACE, 1995), which makes them less likely to fail during a storm (Basco, 2003; USACE, 1995). Some revetments are smooth walls, while others have a very rough appearance (Figure 6.3).

Figure 6.3 Two types of stone revetments (a) near Surfside, Texas and (b) at Jamestown, Virginia.

Protecting Against Flooding or Permanent Inundation

Dikes are high, impermeable earthen walls designed to keep the area behind them dry. They can be set back from the shoreline if the area to be protected is a distance inland and usually require an interior drainage system. Land below mean low water requires a pumping system to remove rainwater and any water that seeps through the ground below the dike. Land whose elevation is between low and high tide can be drained at low tide, except during storms (Figure 6.4a).

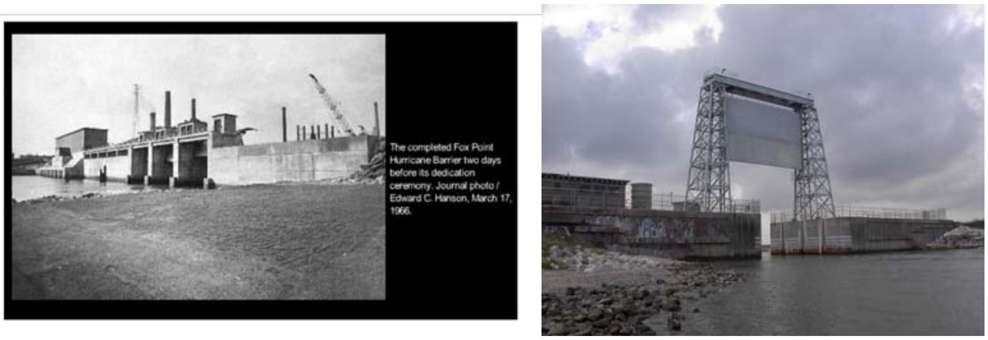
Dunes are accumulations of windblown sand and other materials which function as a temporary barrier against wave runup and overwash (Figure 6.4b, see also Section 6.1.1.2).

Figure 6.4 (a) A dike in Miami-Dade County, Florida, and (b) a newly-created dune in Surf City, New Jersey.

Tide gates are barriers across small creeks or drainage ditches. By opening during low tides and closing during high tides, they enable a low-lying area above mean low water to drain without the use of pumps (Figure 6.5).

Figure 6.5: The tide gate at the mouth of Army Creek on the Delaware side of the Delaware River. The tide gate drains flood and rain water out of the creek to prevent flooding. The five circular mechanisms on the gate open and close to control water flow (courtesy NOAA Photo Library).

Storm surge barriers are similar to tide gates, except that they close only during storms rather than during high tides, and they are usually much larger, closing off an entire river or inlet. The barrier in Providence, Rhode Island (Figure 6.6) has gates that are lowered during a storm; the Thames River Barrier in London, by contrast, has a submerged barrier, which allows tall ships to pass. As sea level rises and storm surges become higher (see Chapter 9), these barriers must be closed more frequently. The gates in Providence, Rhode Island (Figure 6.6), for example, are currently closed an average of 19 days per year (NOAA Coastal Services Center, 2008).



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

Figure 6.6 Storm surge barriers. (a) Fox Point Hurricane Barrier, Providence, Rhode Island (March 1966) and (b) Moses Lake Floodgate, Texas City, Texas (March 2006).

6.1.1.2 Elevating Land Surfaces

A second general approach to shore protection is to elevate land and structures. Tidal marshes have long adapted to sea-level rise by elevating their land surfaces to keep pace with the rising sea (Chapter 4). Elevating land and structures by the amount of sea-level rise can keep a community's assets at the same elevation relative to the sea and thereby prevent them from becoming more vulnerable as sea level rises. These measures are sometimes collectively known as "soft" shore protection.

Beachfill, also known as *beach nourishment* or s*and replenishment,* involves the purposeful addition of the native beach material (usually sand but possibly gravel) to a beach to make it higher and wider. Sand from an offshore or inland source is added to a beach to provide a buffer against wave action and flooding (USACE, 2002; Dean and Dalrymple, 2002). Placing sand onto an eroding beach can offset the erosion that would otherwise occur over a limited time; but erosion processes continue, necessitating periodic re-nourishment.

Dunes are often part of a beach nourishment program. Although they also occur naturally, engineered dunes are designed to intercept wind-transported sand and keep it from being blown inland and off the beach. Planting dune grass and installing sand fencing increases the effectiveness and stability of dunes.

Elevating land and structures is the equivalent of a beachfill operation in the area landward of the beach. In most cases, existing structures are temporarily elevated with hydraulic jacks and a new masonry wall is built up to the desired elevation, after which the house is lowered onto the wall (See Figure 12.5). In some cases the house is moved to the side, pilings are drilled, and the house is moved onto the pilings. Finally, sand, soil, or gravel are brought to the property to elevate the land surface. After a severe hurricane in 1900, most of Galveston, Texas was elevated by more than one meter (NRC, 1987). This form of shore protection can be implemented by individual property owners as needed, or as part of a comprehensive program. Several federal and state programs exist for elevating homes, which has become commonplace in some coastal areas, especially after a major flood (see also Chapters 9 and 10).

Dredge and fill was a very common approach until the 1970s, but it is rarely used today because of the resulting loss of tidal wetlands. Channels were dredged through the marsh, and the dredge material was used to elevate the remaining marsh to create dry land (*e.g.*, Nordstrom, 1994). The overall effect was that tidal wetlands were converted to a combination of dry land suitable for home construction and navigable waterways to provide boat access to the new homes. The legacy of previous dredge-and-fill projects includes a large number of very low-lying communities along estuaries, including the bay sides of many developed barrier islands. Recently, some wetland restoration projects have used a similar approach to create wetlands, by using material from dredged navigation channels to elevate shallow water up to an elevation that sustains wetlands. (USFWS, 2008; see Section 11.2.2 in Chapter 11).

6.1.1.3 Hybrid Approaches to Shore Protection

Several techniques are hybrids of shoreline armoring and the softer approaches to shore protection. Often, the goal of these approaches is to retain some of the storm-resistance of a hard structure, while also maintaining some of the features of natural shorelines. *Groins* are hard structures perpendicular to the shore extending from the beach into the water, usually made of large rocks, wood, or concrete (see Figure 6.7b.). Their primary effect is to diminish forces that transport sand along the shore. Their protective effect is often at the expense of increased erosion farther down along the shore; so they are most useful where an area requiring protection is updrift from an area where shore erosion is more acceptable. *Jetties* are similar structures intended to guard a harbor entrance, but they often act as a groin, causing large erosion on one side of the inlet and accretion on the other side.

Breakwaters are hard structures placed offshore, generally parallel to the shore (see Figure 6.7a). They can mitigate shore erosion by preventing large waves from striking the shore. Like groins, breakwaters often slow the transport of sand along the shore, and thereby increase erosion of shores adjacent to the area protected by the breakwaters.

Dynamic revetments (also known as *cobble beaches*) are a hybrid of beach nourishment and hard structures, in which an eroding mud or sand beach in an area with a light wave climate is converted to a cobble or pebble beach (see Figure 6.7d). The cobbles are heavy enough to resist erosion, yet small enough to create a type of beach environment (USACE, 1998; Komar, 2007; Allan *et al.*, 2005).

Recently, several state agencies, scientists, environmental organizations, and property owners have become interested in measures designed to reduce erosion along estuarine shores, while preserving more habitat than bulkheads and revetments (see Box 6.3). "*Living Shorelines*" are shoreline management options that allow for natural coastal processes to remain through the strategic placement of plants, stone, sand fill, and other structural and organic materials. They often rely on native plants, sometimes supplemented with groins, breakwaters, stone sills, or biologs[10] to reduce wave energy, trap sediment, and filter runoff, while maintaining (or increasing) beach or wetland habitat (NRC, 2007).

Box 6.3 Shore Protection Alternatives in Maryland: Living Shorelines

Shore erosion and methods for its control are a major concern in estuarine and marine ecosystems. However, awareness of the negative impacts that many traditional shoreline protection methods have, including loss of wetlands and their buffering capacities, impacts on nearshore biota, and ability to withstand storm events, has grown in recent years. Non-structural approaches, or hybrid-type projects that combine a marsh fringe with groins or breakwaters, are being considered along all shorelines except for those with large waves (from either boat traffic or a long fetch). The initial cost for these projects is often significantly less than for bulkheads or revetments; the long-run cost can be greater or less depending on how frequently the living shoreline must be rebuilt.

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

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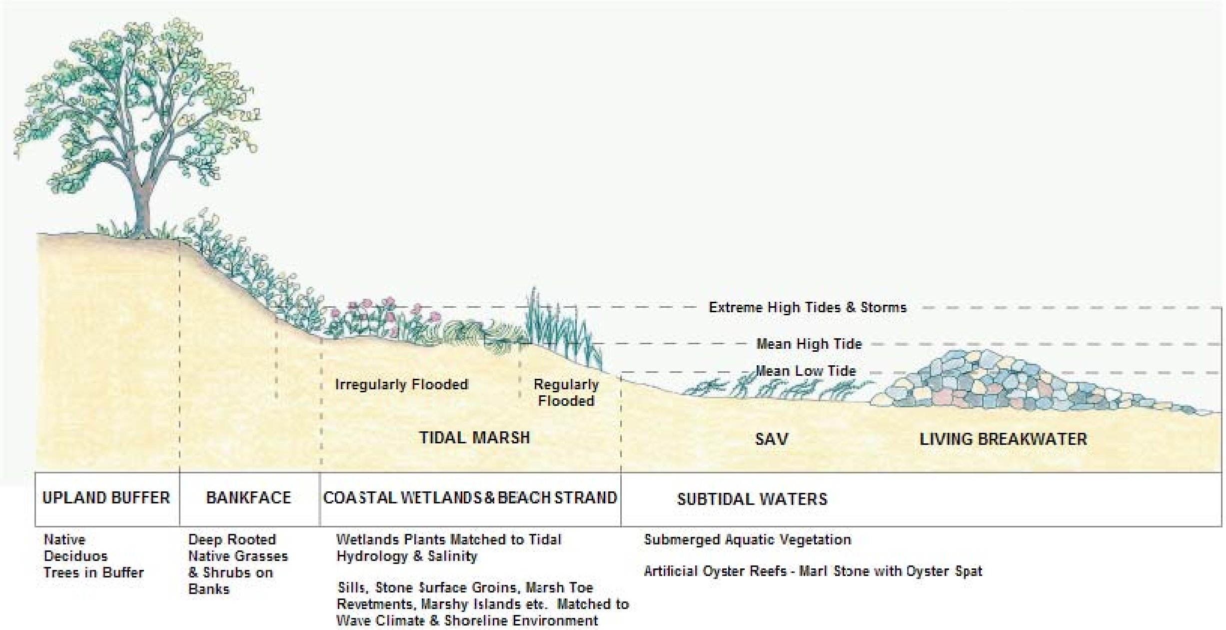
[10] Biologs are assemblages of woody, organic, and biodegradable material in a log-shaped form.



Box Figure 6.3 Depiction of Living Shoreline Treatments from the Jefferson Patterson Park and Museum, Patuxent River.

Sources: Content developed by David G. Burke for Jefferson Patterson Park and Museum, <www.jefpat.org>.

In addition to the hybrid techniques, communities often use a combination of shoreline armoring and elevation. Many barrier island communities apply beach nourishment on the ocean side, while armoring the bay side. Ocean shore protection projects in urban areas sometimes include both beach nourishment and a seawall to provide a final line of defense if the beach erodes during a storm. Beach nourishment projects along estuaries often include breakwaters to reduce wave erosion (Figure 6.7a), or a terminal groin to keep the sand within the area meant to be nourished (see Figure 6.7 c).

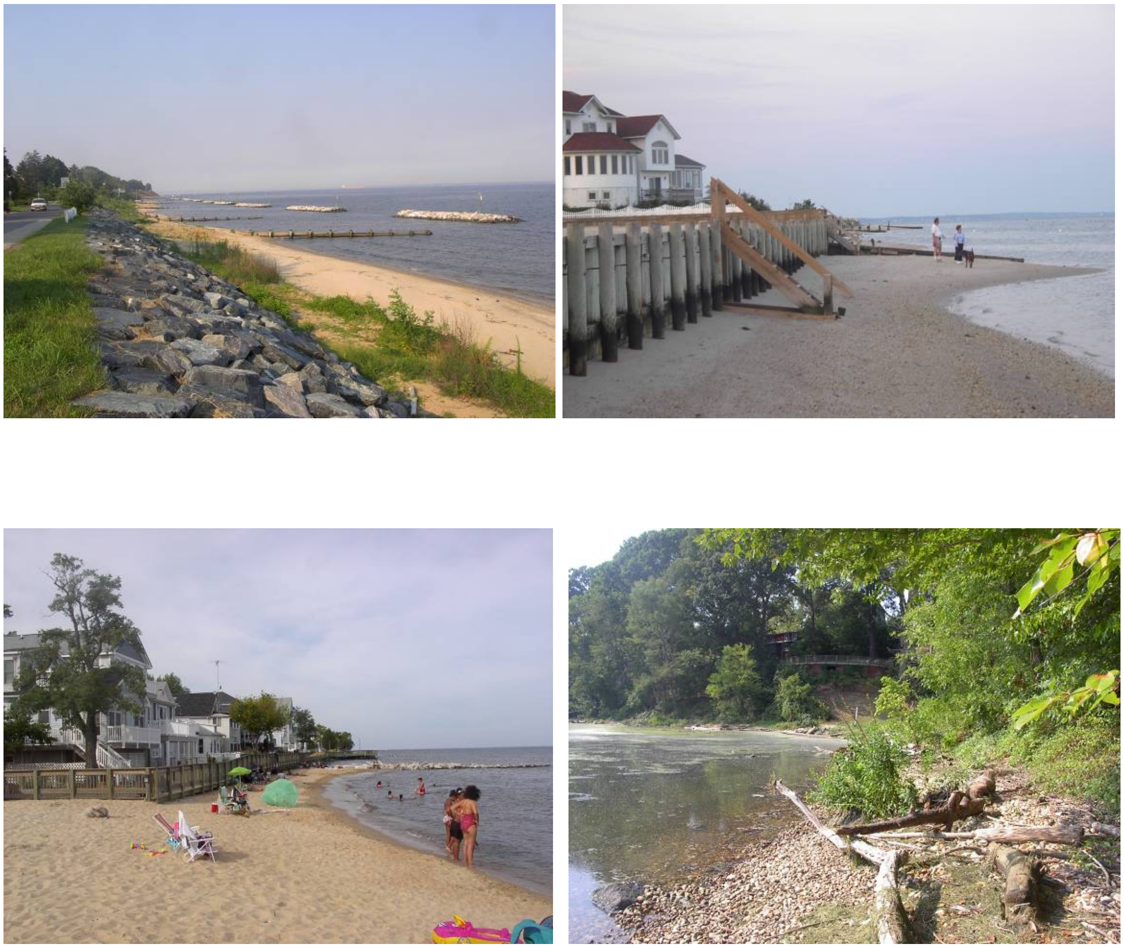


Figure 6.7 Hybrid approaches to shore protection. (a) Breakwaters and groins along Chesapeake Bay in Bay Ridge (near Annapolis) Maryland (July 2008). The rock structures parallel to the shore in the bay are breakwaters; the structures perpendicular to the shore are groins; (b) wooden groins and bulkhead along the Peconic Estuary on Long Island, New York (September 2006). The beach is wider near the groin and narrower between groins; (c) a nourished beach with a terminal groin at North Beach (Maryland) (September 2008); (d) a dynamic revetment placed over the mud shore across Swan Creek from the Fort Washington (Maryland) unit of National Capital Parks East. Logs have washed onto the shore since the project was completed (July 2008).

6.1.2 Retreat

The primary alternative to "shore protection" is commonly known as *retreat* (or *relocation*). Shore protection generally involves coastal engineering to manage the forces of nature and environmental engineering to manage environmental consequences. By contrast, retreat often emphasizes the management of human expectations, so that people do not make investments inconsistent with the eventual retreat.

A retreat can either occur as an unplanned response in the aftermath of a severe storm or as a planned response to avoid the costs or other adverse effects of shore protection. In Great Britain, an ongoing planned retreat is known as "managed realignment" (Rupp-Armstrong and Nicholls, 2007; Shih and Nicholls, 2007; UK Environment Agency, 2007; Midgley and McGlashan, 2004). An optimal retreat generally requires a longer lead time than shore protection (*e.g.*, Yohe and Neumann, 1997; Titus, 1998; IPCC CZMS, 1992) because the economic investments in buildings and infrastructure, and human investment in businesses and communities, can have useful lifetimes of many decades or longer. Therefore, planning, regulatory, and legal mechanisms usually play a more important role in facilitating a planned retreat than for shore protection, which for most projects can be undertaken in a matter of months or years. Some retreat measures are designed to ensure that a retreat occurs in areas where shores would otherwise be protected; other measures are designed to decrease the costs of a retreat but not necessarily change the likelihood of a retreat occurring. For a comprehensive review, see *Shoreline Management Technical Assistance Toolbox* (NOAA, 2006). The most widely assessed and implemented measures are discussed below.

Relocating structures is possibly the most engineering-related activity involved in a retreat. The most ambitious relocation in the Mid-Atlantic during the last decade has been the landward relocation of the Cape Hatteras Lighthouse (Figure 6.8a; see also Section A1.G.4.2 in Appendix 1). More commonplace are the routine "structural moving" activities involved in relocating a house back several tens of meters within a given shorefront lot, and the removal of structures threatened by shore erosion (Figure 6.8b).

Figure 6.8 Relocating structures along the Outer Banks (a) Cape Hatteras Lighthouse after relocation at the Cape Hatteras National Seashore, Buxton, North Carolina (June 2002); the original location is outlined in the foreground, and.(b) a home threatened by shore erosion in Kitty Hawk, North Carolina (June 2002). The geotextile sand bags are used to protect the septic system.

Buyout programs provide funding to compensate landowners for losses from coastal hazards by purchasing vulnerable property. In effect, these programs transfer some of the risk of sea-level rise from the property owner to the public, which pays the cost (see Chapter 12).

Conservation easements are an interest in land that allows the owner of the easement to prevent the owner of the land from developing it. Land conservation organizations have purchased non-development easements along coastal bays and Chesapeake Bay in Maryland (MALPF, 2003). In most cases, the original motivation for these purchases has been the creation of a buffer zone to protect the intertidal ecology (MDCPB, 1999; MALPF, 2003). These vacant lands also leave room for landward migration of wetlands and beaches (a concept also recognized in New Jersey Coastal Management Program

2006). Organizations can also create buffers specifically for the purpose of accommodating rising sea level. Blackwater Wildlife Refuge in Maryland and Gateway National Recreation Area in New York both own considerable amounts of land along the water onto which wetlands and beaches, respectively, could migrate inland.

Acquisition programs involve efforts by government or a conservation entity to obtain title to the land closest to the sea. Titles may be obtained by voluntary transactions, eminent domain, or dedication of flood-prone lands as part of a permitting process. In Barnegat Light, New Jersey and Virginia Beach, Virginia, for example, governments own substantial land along the shore between the Atlantic Ocean and the oceanside development.

Setbacks are the regulatory equivalent to conservation easements and purchase programs. The most common type of setback used to prepare for sea-level rise is the *erosion-based setback*, which prohibits development on land that is expected to erode within a given period of time. North Carolina requires new structures to be set back from the primary dune based on the current erosion rate times 30 years for easily moveable homes, or 60 years for large immoveable structures (see Section A1.G.4.1 in Appendix 1). Maine's setback rule assumes a 60 centimeter (cm) rise in sea level during the next 100 years[11,12].

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[11] 06-096 Code of Maine Rules §355.5(C), (2007).
[12] 06-096 Code of Maine Rules §355.5(C), (2007).

Flood hazard regulations sometimes prohibit development based on elevation, rather than proximity to the shore. Aside from preventing flood damages, these *elevation-based setbacks* can ensure that there is room for wetlands or other intertidal habitat to migrate inland as sea level rises in areas that are vulnerable to inundation rather than wave-generated erosion. Two counties in Delaware prohibit development in the 100-year floodplain along the Delaware River and Delaware Bay (Section A1.D.2.2 in Appendix 1).

Rolling easements are regulatory mechanisms (Burka, 1974) or interests in land (Titus, 1998) that prohibit shore protection and instead allow wetlands or beaches to migrate inland as sea level rises. Rolling easements transfer some of the risk of sea-level rise from the environment or the public to the property owner (Titus, 1998). When implemented as a regulation, they are an alternative to prohibiting all development in the area at risk, which may be politically infeasible, inequitable, or a violation of the "takings clause" of the U.S. Constitution (Titus, 1998; Caldwell and Segall, 2007). When implemented as an interest in land, they are an alternative to outright purchases or conservation easements (Titus, 1998).

The purpose of a rolling easement is to align the property owner's expectations with the dynamic nature of the shore (Titus, 1998). If retreat is the eventual objective, property owners can more efficiently prepare for that eventuality if they expect it than if it takes them by surprise (Yohe *et al*., 1996; Yohe and Neumann, 1997). Preventing development in the area at risk through setbacks, conservations easements, and land purchases can also be effective—but such restrictions could be costly if applied to thousands of square kilometers of valuable coastal lands (Titus, 1991). Because rolling easements allow development but preclude shore protection, they are most appropriate for areas where preventing development is not feasible and shore protection is unsustainable. Conversely, rolling easements are not useful in areas where shore protection or preventing development are preferred outcomes.

Rolling easements were recognized by the common law along portions of the Texas Gulf Coast (*Feinman v. State; Matcha v. Mattox*) and reaffirmed by the Texas Open Beaches Act[13], with the key purpose being to preserve the public right to traverse the shore. Massachusetts and Rhode Island prohibit shoreline armoring along some estuarine shores so that ecosystems can migrate inland, and several states limit armoring along ocean shores (see Chapter 11). Rolling easements can also be implemented as a type of conservation easement, purchased by government agencies or conservancies from willing sellers, or dedicated as part of a planning review process (Titus, 1998); but to date, rolling easements have only been implemented by regulation.

Density restrictions allow some development but limit densities near the shore. In most cases, the primary motivation has been to reduce pollution runoff into estuaries; but they also can facilitate a retreat by decreasing the number of structures potentially lost if shores retreat. Maryland limits development to one home per 8.1 hectares (20 acres)

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[13] TEX. NAT. RES. CODE ANN. §§ 61.001-.178 (West 1978 & Supp. 1998).

within 305 meters (m) (1000 feet [ft]) of the shore in most coastal areas (see Section A1.F.2.1 in Appendix 1). In areas without public sewer systems, zoning regulations often restrict densities (*e.g.*, Accomack County, 2008; U.S. EPA, 1989).

Size limitations also allow development but limit the intensity of the development placed at risk. Moreover, small structures are relocated more easily than a large structure. North Carolina limits the size of new commercial or multi-family residential buildings to 464 square meters (sq m) (5000 square feet [sq ft]) in the area that would be subject to shore erosion during the next 60 years given the current rate of shore erosion, or within 36 m (120 ft) of the shore, whichever is farther inland[14]. Maine's Sand Dune Rules prohibit structures taller than 10.7 m (35 ft) or with a "footprint" greater than 232 sq m (2500 sq ft) in all areas that are potentially vulnerable to a 60 cm rise in sea level[15].

6.1.3 Combinations of Shore Protection and Retreat

Although shore protection and retreat are fundamentally different responses to sea-level rise, strategies with elements of both approaches are possible. In most cases, a given parcel of land at a particular time is either being protected or not—but a strategy can vary with both time and place, or hedge against uncertainty about the eventual course of action.

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[14] 15A NCAC 07H. 0305-0306. The required setback for single-family homes and smaller commercial structures is half as great (see Section A1.G.4 in Appendix 1 for details).

[15] 06-096 Code of Maine Rules §355 (5) (D). (2007).

Time. Sometimes a community switches from retreat to protection. It is common to allow shores to retreat as long as only vacant land is lost, but to erect shore protection structures once homes or other buildings are threatened. Setbacks make it more likely that an eroding shore will be allowed to retreat (Beatley *et al*., 2002; NRC, 1987; NOAA, 2007); once the erosion reaches the setback line, the economics of shore protection are similar to what they would have been without the setback. Conversely, protection can switch to retreat. Property owners sometimes erect low-cost shore protection (*e.g.*, geotextile sandbags, shown in Figure 6.7b) that extends the lifetimes of their property, but ultimately fails in a storm. Increasing environmental implications or costs of shore protection may also motivate a switch from protection to retreat (see Section 6.5). To minimize economic and human impacts, retreat policies based on rolling easements can be designed to take effect 50 to 100 years hence, until which time protection might be allowed (Titus, 1998).

Place. Different responses operate on different scales. In general, a project to retreat or protect a given parcel will usually have effects on other parcels. For example, sand provided to an open stretch of ocean beach will be transported along the shore a significant distance by waves and currents; hence, beach nourishment along the ocean coast generally involves at least a few kilometers of shoreline or an entire island. Along estuaries, however, sands are not transported as far—especially when the shoreline has an indentation—so estuarine shore protection can operate on a smaller scale. Shoreline armoring that protects one parcel may cause adjacent shores to erode or accrete. Nevertheless, along tidal creeks and other areas with small waves, it is often feasible to protect one home with a hard structure, while allowing an adjacent vacant lot to erode. In areas with low density zoning, it may be possible to protect the land immediately surrounding a home while the rest of the lot converts to marsh, mudflat, or shallow water habitat.

Uncertainty. Some responses to sea-level rise may be appropriate in communities whose eventual status is unknown. Floodproofing homes (see Chapter 9), elevating evacuation routes, and improving drainage systems can provide cost-effective protection from flooding in the short term, whether or not a given neighborhood will eventually be protected or become subjected to tidal inundation. A setback can reduce hazards whether or not a shore protection project will eventually be implemented.

6.2 WHAT FACTORS INFLUENCE THE DECISION WHETHER TO PROTECT OR RETEAT?

6.2.1 Site-Specific Factors

Private landowners and government agencies who contemplate possible shore protection are usually motivated by either storm damages or the loss of land (NRC, 2007). They inquire about possible shore protection measures, investigate the costs and consequences of one or more measures, and consider whether undertaking the costs of shore protection is preferable to the consequences of not doing so. For most homeowners, the costs of shore protection include the costs of both construction and necessary government permits; the benefits include the avoided damages or loss of land and structures. Businesses might also consider avoided disruptions in business operations. Regulatory authorities that issue or deny permits for private shore protection consider possible impacts of shore protection on the environment, public access along ocean shores, and whether the design minimizes those impacts (NRC, 2007). Government agencies consider the same factors as private owners as well as public benefits of shore protection, such as greater recreational opportunities from wider beaches, increased development made possible by the shore protection (where applicable), and public safety.

Accelerated sea-level rise does not change the character of those considerations, but it would increase the magnitude of both the benefits and the consequences (monetary and otherwise) of shore protection. In some areas, accelerated sea-level rise would lead communities that are unprotected today to adopt shore protection; in other areas, the increased costs of shore protection may begin to outweigh the benefits. No published study provides a comprehensive assessment of how sea-level rise changes the costs and benefits of shore protection. However, the available evidence suggests that the environmental and social impacts could increase more than proportionately with the rate of sea-level rise (see Section 6.3 and 6.4). A case study of Long Beach Island, New Jersey (a densely developed barrier island with no high-rise buildings) concluded that shore protection is more cost-effective than retreat for the first 50 to 100 cm of sea-level rise (Titus, 1990). If the rise continues to accelerate, however, then eventually the costs of protection would rise more rapidly than the benefits, and a strategic retreat would then become the more cost-effective response, assuming that the island could be sustained by a landward migration. An economic analysis by Yohe *et al.* (1996) found that higher rates of sea-level rise make shore protection less cost-effective in marginal cases.

6.2.2 Regional Scale Factors

Potential benefits and consequences are usually the key to understanding whether a particular project will be adopted. At a broader scale, however, land use and shoreline environment are often indicators of the likelihood of shore protection. Land use provides an indicator of the resources being protected, and the shoreline environment provides an indicator of the type of shore protection that would be needed.

Most land along the mid-Atlantic ocean coast is either developed or part of a park or conservation area. This region has approximately 1,100 kilometers (almost 700 miles) of shoreline along the Atlantic Ocean. Almost half of this coastline consists of ocean beach resorts with dense development and high property values. Federal shore protection has been authorized along most of these developed shores. These lands are fairly evenly spread throughout the mid-Atlantic states, except Virginia (see Section A1.E.2.1 in Appendix 1). However, a large part of the coast is owned by landowners who are committed to allowing natural shoreline processes to operate, such as The Nature Conservancy, National Park Service (see Section 11.2.1), and U.S. Fish and Wildlife Service. These shores include most of North Carolina’s Outer Banks, all of Virginia’s Atlantic coast except for part of Virginia Beach and a NASA installation, more than two-thirds of the Maryland coast and New York’s Fire Island. The rest of the ocean coast in this region is lightly developed, yet shore protection is possible for these coasts as well due to the presence of important coastal highways.

Development is less extensive along many estuaries than along the ocean coast. The greatest concentrations of low-lying undeveloped lands along estuaries are in North Carolina, the Eastern Shore of Chesapeake Bay, and portions of Delaware Bay. Development has come more slowly to the lands along the Albemarle and Pamlico Sounds in North Carolina than to other parts of the mid-Atlantic coast (Hartgen, 2003.) Maryland law prevents development along much of the Chesapeake Bay shore (Section A1.F.2.1 in Appendix 1), and a combination of floodplain regulations and aggressive agricultural preservation programs limit development along the Delaware Bay shore in Delaware (Section A1.D.2.2 in Appendix 1). Yet there is increasing pressure to develop land along tidal creeks, rivers, and bays (USCOP, 2004; DNREC, 2000; Titus, 1998), and barrier islands are in a continual state of redevelopment in which seasonal cottages are replaced with larger homes and high-rises (*e.g.*, Randall, 2003).

If threatened by rising sea level, these developed lands (*e.g.*, urban, residential, commercial, industrial, transportation) would require shore protection for current land uses to continue. Along estuaries, the costs of armoring, elevating, or nourishing shorelines are generally less than the value of the land to the landowner, suggesting that under existing trends shore protection would continue in most of these areas. But there are also some land uses for which the cost and effort of shore protection may be less attractive than allowing the land to convert to wetland, beach, or shallow water. Those land uses might include marginal farmland, conservations lands, portions of some recreational parks, and even portions of back yards where lot sizes are large. Along the ocean, shore protection costs are greater—but so are land values.

Shore protection is likely along much of the coastal zone, but substantial areas of undeveloped (but developable) lands remain along the mid-Atlantic estuaries, where either shore protection or wetland migration could reasonably be expected to occur (NRC, 2007; Yohe *et al*., 1996; Titus *et al*., 1991). Plans and designs for the development of those lands generally do not consider implications of future sea-level rise (see Chapter 11). A series of studies have been undertaken that map the likelihood of shore protection along the entirety of the U.S. Atlantic Coast as a function of land use (Nicholls *et al.*, 2007; Titus, 2004, 2005; Clark, 2001; Nuckols, 2001).

6.2.3 Mutual Reinforcement Between Coastal Development and Shore Protection

Lands with substantial shore protection are more extensively developed than similar lands without shore protection, both because shore protection encourages development and development encourages shore protection. People develop floodplains, which leads to public funding for flood control structures, which in turn leads to additional development in the area protected (*e.g.*, Burby, 2006). Few studies have measured this effect, but possible mechanisms include:

- Flood insurance rates that are lower in protected areas (see Chapter 10);
- Development that may be allowed in locations that might otherwise be off limits;
- Erosion-based setbacks that require less of a setback if shore protection slows or halts erosion (see Section 6.1); and
- Fewer buildings that are destroyed by storms, so fewer post-disaster decisions to abandon previously developed land (*e.g.*, Weiss, 2006) would be expected.

The impact of coastal development on shore protection is more firmly established. Governments and private landowners generally implement a shore protection project only when the value of land and structures protected is greater than the cost of the project (see Sections 6.1 and 12.2.3).

6.3 WHAT ARE THE ENVIRONMENTAL CONSEQUENCES OF RETREAT AND SHORE PROTECTION?

In the natural setting, sea-level rise can significantly alter barrier islands and estuarine environments (Chapters 3, 4, and 5). Because a policy of retreat allows natural processes to work, the environmental impacts of retreat in a developed area can be similar to the impacts of sea-level rise in the natural setting, provided that management practices are adopted to restore lands to approximately their natural condition before they are inundated, eroded, or flooded. In the absence of management practices, possible environmental implications of retreat include:

- Contamination of estuarine waters from flooding of hazardous waste sites (Flynn *et al.*, 1984) or areas where homes and businesses store toxic chemicals;
- Increased flooding (Wilcoxen, 1986; Titus *et al.,* 1987) or infiltration into public sewer systems (Zimmerman and Cusker, 2001);
- Groundwater contamination as septic tanks and their drain fields become submerged;
- Debris from abandoned structures; and

- Interference with the ability of wetlands to keep pace or migrate inland due to features of the built landscape (*e.g.*, elevated roadbeds, drainage ditches, and impermeable surfaces).

Shore protection generally has a greater environmental impact than retreat (see Table 6.1). The impacts of beach nourishment and other soft approaches are different than the impacts of shoreline armoring.

Beach nourishment affects the environment of both the beach being filled and the nearby seafloor "borrow areas" that are dredged to provide the sand. Adding large quantities of sand to a beach is potentially disruptive to turtles and birds that nest on dunes and to the burrowing species that inhabit the beach (NRC, 1995), though less disruptive in the long term than replacing the beach and dunes with a hard structure. The impact on the borrow areas is a greater concern: The highest quality sand for nourishment is often contained in a variety of shoals which are essential habitat for shellfish and related organisms (USACE, 2002). For this reason, the U.S. Army Corps of Engineers has denied permits to dredge sand for beach nourishment in New England (*e.g.*, NOAA Fisheries Service, 2008; USACE, 2008a). As technology improves to recover smaller, thinner deposits of sand offshore, a greater area of ocean floor must be disrupted to provide a given volume of sand. Moreover, as sea level rises, the required volume is likely to increase, further expanding the disruption to the ocean floor.

As sea level rises, shoreline armoring eventually eliminates ocean beaches (IPCC, 1990); estuarine beaches (Titus, 1998), wetlands (IPCC, 1990), mudflats (Galbraith *et al*., 2002), and very shallow open water areas by blocking their landward migration. By redirecting wave energy, these structures can increase estuarine water depths and turbidity nearby, and thereby decrease intertidal habitat and submerged aquatic vegetation. The more environmentally sensitive "living shoreline" approaches to shore protection preserve a narrow strip of habitat along the shore (NRC, 2007); however, they do not allow large-scale wetland migration. To the extent that these approaches create or preserve beach and marsh habitat, it is at the expense of the shallow water habitat that would otherwise develop at the same location.

The issue of wetland and beach migration has received considerable attention in the scientific, planning, and legal literature for the last few decades (NRC, 1987; Barth and Titus, 1984; IPCC, 1990). Wetlands and beaches provide important natural resources, wildlife habitat, and storm protection (see Chapter 5). As sea level rises, wetlands and beaches can potentially migrate inland as new areas become subjected to waves and tidal inundation—but not if human activities prevent such a migration. For example, early estimates (*e.g.*, U.S. EPA, 1989) suggested that a 70 cm rise in sea level over the course of a century would convert 65 percent of the existing mid-Atlantic wetlands to open water, and that this region would experience a 65 percent overall loss if all shores were protected so that no new wetlands could form inland. The results in Chapter 4 are broadly consistent with the 1989 study. That loss would only be 27 percent, however, if new wetlands were able to form on undeveloped lands, and 16 percent if existing developed areas converted to marsh as well.

Very little land has been set aside for the express purpose of ensuring that wetlands and other tidal habitat can migrate inland as sea level rises (see Chapter 11 of this Product; Titus, 2000), but those who own and manage estuarine conservation lands do allow wetlands to migrate onto adjacent dry land. With a few notable exceptions[16], the managers of most conservation lands along the ocean and large bays allow beaches to erode as well (see Chapter 11) The potential for landward migration of coastal wetlands is limited by the likelihood that many shorelines will be preserved for existing land uses (*e.g.*, U.S. EPA, 1989; IPCC, 1990; Nicholls *et al*., 1999). Some preliminary studies (*e.g.*, Titus, 2004) indicate that in the mid-Atlantic region, the land potentially available for new wetland formation would be almost twice as great if future shore protection is limited to lands that are already developed, than if both developed and legally developable lands are protected.

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[16] Exceptions include Cape May Meadows in New Jersey (protecting freshwater wetlands near the ocean), beaches along both sides of Delaware Bay (horseshoe crab habitat) and Assateague Island, Maryland (to prevent the northern part of the island from disintegrating).

Table 6.1 Selected Measures for Responding to Sea-Level Rise: Objective and Environmental Effects

Response Measure	Method for Protection or Retreat	Key Environmental effects
Shoreline armoring that interferes with waves and currents		
Breakwater	Reduce erosion	May attract marine life; downdrift erosion
Groin	Reduce erosion	May attract marine life; downdrift erosion
Shoreline armoring used s to define a shoreline		
Seawall	Reduce erosion, protect against flood and wave overtopping	Elimination of beach; scour and deepening in front of wall; erosion exacerbated at terminus
Bulkhead	Reduce erosion, protect new land fill	Prevents inland migration of wetlands and beaches. Wave reflection erodes bay bottom, preventing SAV. Prevents amphibious movement from water to land.
Revetment	Reduce erosion, protect land from storm waves, protect new land fill	Prevents inland migration of wetlands and beaches. Traps horseshoe crabs and prevents amphibious movement. May create habitat for oysters and refuge for some species.
Shoreline armoring used protect against floods and/ or permanent inundation		
Dike	Prevents flooding and permanent inundation (when combined with a drainage system).	Prevents wetlands from migrating inland. Thwarts ecological benefits of floods (*e.g*., annual sedimentation, higher water tables, habitat during migrations, productivity transfers)
Tide gate	Reduces tidal range by draining water at low tide and closing at high tide.	Restricts fish movement. Reduced tidal range reduces intertidal habitat. May convert saline habitat to freshwater habitat.
Storm surge barrier	Eliminates storm surge flooding; could protect against all floods if operated on a tidal schedule	Necessary storm surge flooding in salt marshes is eliminated.
Elevating land		
Dune	Protect inland areas from storm waves, provide a source of sand during storms to offset erosion.	Can provide habitat; can set up habitat for secondary dune colonization behind it
Beachfill	Reverses shore erosion, and provide some protection from storm waves.	Short-term loss of shallow marine habitat; could provide beach and dune habitat
Elevate land and structures	Avoid flooding and inundation from sea-level rise by elevating everything as much as sea rises.	Deepening of estuary unless bay bottoms are elevated as well.
Retreat		
Setback	Delay the need for shore protection by keeping development out of the most vulnerable lands.	Impacts of shore protection delayed until shore erodes up to the setback line. Impacts of development also reduced.
Rolling easement	Prohibit shore protection structures.	Impacts of shore protection structures avoided.
Density or size restriction	Reduce the benefits of shore protection and thereby make it less likely.	Depends on whether owners of large lots decide to protect shore. Impacts of intense development reduced.

6.4 WHAT ARE THE SOCIETAL CONSEQUENCES OF SHORE PROTECTION AND RETREAT AS SEA LEVEL RISES?

6.4.1 Short-Term Consequences

Shore protection generally is designed to enable existing land uses to continue. By insulating a community from erosion, storms, and other hazards, the social consequences of sea-level rise can be minimal, at least for the short term. In the Netherlands, shore protection helped to foster a sense of community as residents battled a common enemy (Disco, 2006). In other cases, the interests of some shorefront property owners may diverge from the interests of other residents (NRC, 2007). For example, many property owners in parts of Long Beach Island, New Jersey strongly supported beach nourishment—but some shorefront owners in areas with wide beaches and dunes have been reluctant to provide the state with the necessary easements (NJDEP, 2006; see Section A1.C.2 in Appendix 1).

Allowing shores to retreat can be disruptive. If coastal erosion is gradual, one often sees a type of coastal blight in what would otherwise be a desirable community, with exposed septic tanks and abandoned homes standing on the beach, and piles of rocks or geotextile sand bags in front of homes that remain occupied (Figures 6.8b and 6.9). If the loss of homes is episodic, communities can be severely disrupted by the sudden absence of neighbors who previously contributed to the local economy and sense of community (IPCC, 1990; Perrin *et al.*, 2008; Birsch and Wachter, 2006). People forced to relocate after disasters are often at increased risk to both health problems (Yzermans *et al.*, 2005) and depression (Najarian *et al.*, 2001).

Figure 6.9 The adverse impacts of retreat on safety and aesthetic appeal of recreational beaches (a) Exposed septic tank and condemned houses at Kitty Hawk, North Carolina (June 2002); (b) Beach unavailable for recreation where homes were built to withstand shore erosion and storms, at Nags Head, North Carolina (June 2007).

6.4.2 Long-Term Consequences

The long-term consequences of a retreat can be similar to the short-term consequences. In some areas, however, the consequences may become more severe over time. For example, a key roadway originally set far back from the shore may become threatened and have to be relocated. In the case of barrier islands, the long-term implications of retreat depend greatly on whether new land is created on the bay side to offset oceanfront erosion. If so, communities can be sustained as lost oceanfront homes are rebuilt on the bay side; if not, the entire community could be eventually lost.

The long-term consequences of shore protection could be very different from the short-term consequences. As discussed below, shore protection costs could escalate. The history of shore protection in the United States suggests that some communities would respond to the increased costs by tolerating a lower level of shore protection, which could lead eventually to dike failures (Seed *et al.*, 2005; Collins, 2006) and resulting unplanned retreat. In other cases, communities would not voluntarily accept a lower level of protection, but the reliance on state or federal funding can lead to a lower level while awaiting funds (a common situation for communities awaiting beach nourishment). For communities that are able to keep up with the escalated costs, tax burdens would increase, possibly leading to divisive debates over a reconsideration of the shore protection strategy.

6.5 HOW SUSTAINABLE ARE SHORE PROTECTION AND RETREAT?

Coastal communities were designed and built without recognition of rising sea level. Thus, people in areas without shore protection will have to flood-proof structures (see Chapter 9), implement shore protection, (Section 6.1.1) or plan a retreat (Section 6.1.2). Those who inhabit areas with shore protection are potentially vulnerable as well. Are the known approaches to shore protection and retreat sustainable, that is, can they be maintained for the foreseeable future?

Most shore protection structures are designed for current sea level and may not accommodate a significant rise. Seawalls (Kyper and Sorenson, 1985; NRC, 1987), bulkheads (Sorenson *et al.*, 1984.), dikes, (NRC, 1987), sewers (Wilcoxen, 1986) and drainage systems (Titus *et al.*, 1987) are designed based on the waves, water levels, and rainfall experienced in the past. If conditions exceed what the designers expect, disaster can result—especially when sea level rises above the level of the land surface. The failure of dikes protecting land below sea level resulted in the deaths of approximately 1800 people in the Netherlands in a 1953 storm (Roos and Jonkman, 2006), and more than 1000 people in the New Orleans area from Hurricane Katrina in 2005 (Knabb *et al.*, 2005). A dike along the Industrial Canal in New Orleans which failed during Katrina had been designed for sea level approximately 60 cm lower than today, because designers did not account for the land subsidence during the previous 50 years (Interagency Performance Evaluation Taskforce, 2006).

One option is to design structures for future conditions. Depending on the incremental cost of designing for higher sea level compared with the cost of rebuilding later, it may be economically rational to build in a safety factor today to account for future conditions, such as higher and wider shore protection structures (see Chapter 10). But doing so is not always practical. Costs generally rise more than proportionately with higher water levels[17]. Project managers would generally be reluctant to overdesign a structure for today's conditions (Schmeltz, 1984). Moreover, aesthetic factors such as loss of waterfront views or preservation of historic structures (*e.g.*, Charleston Battery in South Carolina; see Figure 6.10) can also make people reluctant to build a dike or seawall higher than what is needed today.

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[17] Weggel *et al*., (1989) estimate that costs are proportional to the height of the design water level raised to the 1.5 power.

Figure 6.10. Historic homes along the Charleston Battery. Charleston, South Carolina. (April 2004).

6.5.1 Is "Business as Usual" Shore Protection Sustainable?

Public officials and property owners in densely developed recreational communities along the mid-Atlantic coast generally expect governmental actions to stabilize shores. But no one has assessed the cost and availability of sand required to keep the shorelines in their current locations through beach nourishment even if required sand is proportional to sea-level rise, which previous assessments of the cost of sea level rise have assumed (*e.g.*, U.S. EPA, 1989; Leatherman, 1989; Titus *et al.*, 1991). The prospects of barrier island disintegration and segmentation examined in Chapter 3 would require much more sand to stabilize the shore. Maintaining the shore may at first seem to require only the simple augmentation of sand along a visible beach, but over a century or so other parts of the coastal environment would capture increasing amounts of sand to maintain elevation relative to the sea. In effect, beach nourishment would indirectly elevate those areas as well (by replacing sand from the beach that is transported to raise those areas), including the ocean floor immediately offshore, tidal deltas, and eventually back-barrier bay bottoms and the bay sides of barrier islands. Similarly, along armored shores in urban areas, land that is above sea level today would become farther and farther below sea level, increasing the costs of shore protection and setting up greater potential disasters in the event of a dike failure. It is not possible to forecast whether these costs will be greater than what future generations will choose to bear. But in those few cases where previous generations have bequeathed this generation with substantial communities below sea level, a painful involuntary relocation sometimes occurs after severe storms (*e.g.*, New Orleans after Katrina).

Most retreat policies are designed for current rates of sea-level rise and would not necessarily accommodate a significant acceleration in the rate of sea-level rise. Erosion-based setbacks along ocean shores generally require homes to be set back from the primary dune by a distance equal to the annual erosion rate times a number years intended to represent the economic lifetime of the structure (*e.g.*, in North Carolina, 60 years times the erosion rate for large buildings [see Section A1.G.1 in Appendix 1). If sea-level rise accelerates and increases the erosion rate, then the buildings will not have been protected for the presumed economic lifetimes. Yet larger setback distances may not be practicable if they exceed the depth of buildable lots. Moreover, erosion-based setback policies generally do not articulate what will happen once shore erosion consumes the setback. The retreat policies followed by organizations that manage undeveloped land for conservation purposes may account for foreseeable erosion, but not for the consequences of an accelerated erosion that consumes the entire coastal unit.

6.5.2 Sustainable Shore Protection May Require Regional Coordination

Regional Sediment Management is a relatively new strategy or planning tool for managing sand as a resource (NRC, 2007). The strategy recognizes that coastal engineering projects have regional impacts on sediment transport processes and availability. This approach includes:

- Conservation and management of sediments in along the shore and immediate offshore areas, viewing sand as a resource;

- Attempt to design with nature, understanding sediment movement in a region and the interrelationships of projects and management actions;
- Conceptual and programmatic connections among all activities that involve sediment in a region (*e.g.*, navigation channel maintenance, flood and storm damage reduction, ecosystem restoration and protection, beneficial uses of dredged material);
- Connections between existing and new projects to use sediment more efficiently;
- Improved program effectiveness through collaborative partnerships between agencies; and
- Overcoming institutional barriers to efficient management (Martin, 2002).

The Philadelphia and New York Districts of the U.S. Army Corps of Engineers have a joint effort at regional sediment management for the Atlantic coast of New Jersey (USACE, 2008b). By understanding sediment sources, losses, and transport; how people have altered the natural flow; and ways to work with natural dynamics, more effective responses to rising sea level are possible.

One possible way to promote better regional sediment management would be the development of a set of "best sediment management practices". Previously, standard practices have been identified to minimize the runoff of harmful sediment into estuaries (NJDEP, 2004; City of Santa Cruz, 2007). A similar set of practices for managing sediments along shores could help reduce the environmental and economic costs of shore protection, without requiring each project to conduct a regional sediment management study.

6.5.3 Either Shore Protection or a Failure to Plan can Limit the Flexibility of Future Generations

The economic feasibility of sustained shore protection as sea level rises is unknown, as is the political and social feasibility of a planned retreat away from the shore. The absence of a comprehensive long-term shoreline plan often leaves property owners with the assumption that the existing development can and should be maintained. Property-specific shoreline armoring and small beach nourishment projects further reinforce the expectation that the existing shoreline will be maintained indefinitely, often seeming to justify additional investments by property owners in more expensive dwellings (especially if there is a through-road parallel to the shore).

Shore protection generally limits flexibility more than retreat. Once shore protection starts, retreat can be very difficult to enact because investments and expectations are based on the protection, which in turn increases the economic justification for continued shore protection. A policy of retreat can be more easily replaced with a policy of shore protection, because people do not make substantial investments on the assumption that the shore will retreat. This is not to say that all dikes and seawalls would be maintained and enlarged indefinitely if sea level continues to rise. Nevertheless, the abandonment of floodprone communities rarely (if ever) occurs because of the potential vulnerability or cost of flood protection, but rather in the aftermath of a flood disaster (*e.g.*, Missouri State Emergency Management Agency, 1995).

CHAPTER 6 REFERENCES

* Indicates non-peer reviewed literature; available upon request

Accomack County, 2008: *Respecting the Past, Creating the Future: The Accomack County Comprehensive Plan:* Revised Draft. Accomac, Virginia: Planning Department, Accomack County. [Note: The town and county are spelled differently.]

Allan, J.C., R. Geitgey, and R. Hart, 2005: *Dynamic Revetments for Coastal Erosion in Oregon: Final Report*. Oregon Department of Transportation, Salem. <http://www.oregon.gov/ODOT/TD/TP_RES/docs/Reports/DynamicRevetments.pdf>

Basco, D.R., 2003: Shore protection projects. In: *Coastal Engineering Manual*. Engineer manual 1110-2-1100. U.S. Army Corps of Engineers, Washington, DC, Part V, chapter 3.

Barth, M.C. and J.G. Titus (eds.), 1984: *Greenhouse Effect and Sea Level Rise: A Challenge for this Generation*. Van Nostrand Reinhold, New York, 325 pp.

Beatley, T., D.J Brower, and A.K. Schwab, 2002: *An Introduction to Coastal Zone Management*. Island Press, Washington DC, 285 pp.

Birch, E.L. and S.M. Wachter (eds.), 2006: *Rebuilding Urban Places after Disaster: Lessons from Katrina*. University of Pennsylvania Press, Philadephia, 375 pp.

Bryan, W.B, 1914: *A Hisory of the National Capital from its Foundation Through the Period of Adoption of the Organic Act.* The Macmillan Company, New York, 2 volumes.

Burka, P., 1974: Shoreline erosion: implications for public rights and private ownership. *Coastal Zone Management Journal,* **1(2)**, 175-195.

Burby, R.J., 2006: Hurricane Katrina and the paradoxes of government disaster policy: bringing about wise governmental decisions for hazardous areas. *The Annals of the American Academy of Political and Social Science*, **604(1)**, 171-191.

Caldwell, M. and C. Segall, 2007: No day at the beach: sea level rise, ecosystem loss, and public access along the California coast. *Ecology Law Quarterly*, **34(2)**, 533-578.

City of Santa Cruz, 2007: Construction work: best management practices. In: *Best Management Practices Manual for the City's Storm Water Management Program*. City of Santa Cruz Public Works Department, Planning Department, Santa Cruz, CA, chapter 4. <http://www.ci.santa-cruz.ca.us/pw/Stormwater2004/Att9Update.pdf>

Clark, W., 2001: Planning for sea level rise in North Carolina. In: *Coastal Zone '01*. Proceedings of the 12th Biennial Coastal Zone Conference, Cleveland, OH, July 15-19, 2001. NOAA Coastal Services Center, Charleston, SC.

Collins, D., 2006: Challenges to reducing flood risk. In: *Participatory Planning and Working with Natural Processes On The Coast*. Dutch National Institute for Coastal and Marine Management, The Hague, the Netherlands.

Danckaerts, J., 1913: Journal of Jasper Danckaerts, 1679-1680 By Jasper Danckaerts, Peter Sluyter. "Published 1913. C. Scribner's Sons. <http://books.google.com/books?id=khcOAAAAIAAJ&dq=jasper+danckaerts> Accessed on 1/14/08. The present translation is substantially that of Mr. Henry C. Murphy, as presented in his edition of 1867, under title: "Journal of a voyage to New York and a tour in several of the American colonies in 1679-80, by Jaspar Dankers and Peter Sluyter.".

* **DDFW** (Delaware Division of Fish and Wildlife), 2007: *Northern Delaware Wetlands Rehabilitation Program*. [website] <http://www.dnrec.state.de.us/fw/intmrmt.htm>

Dean, R.G. and R.A. Dalrymple, 2002: *Coastal Processes with Engineering Applications*. Cambridge University Press, New York, 475 pp.

Disco, C., 2006: Delta blues. *Technology and Culture,* **47(2)**, 341-348

* **DNREC** (Department of Natural Resource and Environmental Control), 2000: *Land Use and Population*. [Delaware Department of Natural Resource and Environmental Control, Dover], 1 p. <http://www.dnrec.state.de.us/dnrec2000/Admin/WholeBasin/InlandBays/land.pdf>

Feinman v. State, 717 S.W.2d 106, 111 (Tex. App. 1986).

Flynn, T.J., S.G. Walesh, J.G. Titus, and M.C. Barth, 1984: Implications of sea level rise for hazardous waste sites in coastal floodplains. In: *Greenhouse Effect and Sea Level Rise: A Challenge for this Generation* [Barth, M.C. and J.G. Titus (eds.)].Van Nostrand Reinhold Company, New York, pp. 271-294.

Galbraith, H., R. Jones, R. 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.

* **Hartgen**, D.T., 2003: *Highways and Sprawl in North Carolina*. University of North Carolina, Charlotte, 124 pp. <http://www.johnlocke.org/policy%5Freports/2003092541.html>

Interagency Performance Evaluation Taskforce, 2006: *Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System*. U.S. Army Corps of Engineers, Washington, DC.

IPCC (Intergovernmental Panel on Climate Change), 1990: *Strategies for Adaptation to Sea Level Rise*. Report of the Coastal Zone, Management Subgroup, IPCC Response Strategies Working Group. Ministry of Transport, Public Works and Water Management, The Hague, the Netherlands, 122 pp.

IPCC CZMS (Intergovernmental Panel on Climate Change, Coastal Zone Management Subgroup), 1992: *Global Climate Change and the Rising Challenge of the Sea*. IPCC Response Strategies Working Group. The Hague, the Netherlands.

Knabb, R.D., J.R. Rhome, and D.P. Brown, 2005: *Tropical Cyclone Report: Hurricane Katrina, 23-30 August 2005*. National Hurricane Center, Miami, FL, 43 pp. <http://www.nhc.noaa.gov/pdf/TCR-AL122005_Katrina.pdf>

Komar, P.D., 2007: The design of stable and aesthetic beach fills: learning from nature In: *Coastal Sediments '07*. Proceedings of the Sixth International Symposium on Coastal Engineering and Science of Coastal Sediment Processes, May 13–17, 2007, New Orleans, LA. [Kraus, N.C. and J.D. Rosati (eds.]. American Society of Civil Engineers, Reston, VA, pp. 420-433.

Kyper, T.N. and R.M. Sorensen, 1985: The impact of selected sea level rise scenarios on the beach and coastal structures at Sea Bright, N.J. In: *Coastal Zone '85*. Proceedings of the Fourth Symposium on Coastal and Ocean Management, Omni International Hotel, Baltimore, Maryland, July 30-August 2, 1985. American Society of Civil Engineers, New York, pp. 2645-2661.

Leatherman, S.P., 1989: Nationwide assessment of beach nourishment requirements associated with accelerated sea level rise. In: *The Climate Change on the United States. Appendix: B, Sea Level Rise*. EPA 230-05-89-052. U.S. Environmental Protection Agency, Washington, DC, pp. 2-1 to 2-30. <http://epa.gov/climatechange/effects/coastal/appB.html>

MALPF (Maryland Agricultural Land Preservation Foundation), 2003: *Maryland's Land Conservation Programs: Protecting the Chesapeake Bay Watershed*. Maryland Agricultural Land Preservation Foundation, [Annapolis]. <http://www.malpf.info/reports/GovernorReport121703.pdf>

Martin, L.R., 2002: *Regional Sediment Management: Background and Overview of Initial Implementation*. IWR Report 02-PS-2. U.S. Army Corps of Engineers Institute for Water Resources, Ft. Belvoir, VA, 75 pp.

<http://www.iwr.usace.army.mil/inside/products/pub/iwrreports/02ps2sed_man.pdf>

Matcha v. Mattox, 711 S.W.2d 95, 100 (Tex. App. 1986).

MDCBP (Maryland Coastal Bays Program), 1999: *Today's Treasures for Tomorrow: Towards a Brighter Future.* A Comprehensive Conservation and Management Plan for Maryland's Coastal Bays. Maryland Coastal Bays Program, Berlin, 181 pp. <http://mdcoastalbays.org/archive/2003/ccmp.pdf>

Midgley, S. and D.J. McGlashan, 2004: Planning and management of a proposed managed realignment project: Bothkennar, Forth Estuary, Scotland. *Marine Policy*, **28(5)**, 429-435.

Missouri State Emergency Management Agency, 1995: *Out of Harm's Way: The Missouri Buyout Program*. Missouri State Emergency Management Agency, Jefferson City, 16 pp.

Najarian, L.M., A.K. Goenjian, D. Pelcovitz, F. Mandel, and B. Najarian, 2001: The effect of relocation after a natural disaster. *Journal of Traumatic Stress*, **14(3)**, 511-526.

Nesbit, D.M., 1885: *Tide Marshes of the United States*. USDA special report 7. Government Printing Office, Washington, DC (as cited in Sebold, 1992).

Nicholls, R.J., F.M.J. Hoozemans, and M. Marchand, 1999: Increasing flood risk and wetland losses due to global sea-level rise: regional and global analyses. *Global Environmental Change*, **9(Supplement 1)**, S69-S87.

Nicholls, R.J., P.P. Wong, V.R. Burkett, J.O. Codignotto, J.E. Hay, R.F. McLean, S. Ragoonaden and C.D. Woodroffe, 2007: Coastal systems and low-lying areas. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der

Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK, and New York, pp. 315-356.

NJDEP (New Jersey Department of Environmental Protection), 2004: Impacts on development of runoff. In: *New Jersey Stormwater Best Management Practices Manual*. New Jersey Department of Environmental Protection, Trenton, [8 pp.] <http://www.nj.gov/dep/stormwater/tier_A/pdf/NJ_SWBMP_1%20print.pdf>

NJDEP (New Jersey Department of Environmental Protection), 2006: *Assessment and Enhancement Strategy: FY 2006 - 2010*. Coastal Management Office, New Jersey Department of Environmental Protection, Trenton, 85 pp. <http://www.state.nj.us/dep/cmp/309_combined_strat_7_06.pdf>

NOAA (National Oceanic and Atmospheric Administration), 2006: *The Shoreline Management Technical Assistance Toolbox* [web site] <http://coastalmanagement.noaa.gov/shoreline.html>

NOAA (National Oceanic and Atmospheric Administration), 2007: *Construction Setbacks*. [web site] NOAA Ocean & Coastal Resource Management. <http://coastalmanagement.noaa.gov/initiatives/shoreline_ppr_setbacks.html>

NOAA Coastal Services Center, 2008: The rising tide: how Rhode Island is addressing sea level rise. *Coastal Services,* **11(3)**, 4-6, 9.

NOAA Fisheries Service, 2008: *Northeast Region, Habitat Conservation Division, Monthly Highlights*, **March-April**, 3 pp. <http://www.nero.noaa.gov/hcd/08highlights/March-April08.pdf>

Nordstrom, K.F., 1994: Developed coasts. In: *Coastal Evolution: Late Quaternary Shoreline Morphodynamics* [Carter, R.W.G. and C.D. Woodroffe (eds.)]. Cambridge University Press, Cambridge, UK, pp. 477-509.

NRC (National Research Council), 1987: *Responding to Changes in Sea Level: Engineering Implications*. National Academy Press, Washington, DC, 148 pp.

NRC (National Research Council), 1995: *Beach Nourishment and Protection*. National Academy Press, Washington, DC, 333 pp.

NRC (National Research Council), 2007: *Mitigating Shore Erosion along Sheltered Coasts*. National Academies Press, Washington, DC, p. 51 [174 pp.]

Nuckols, W., 2001: Planning for sea level rise along the Maryland shore. In: *Coastal Zone '01*: Proceedings of the 12th Biennial Coastal Zone Conference. NOAA, Silver Spring, MD.

Perrin, P.B., A. Brozyna, A.B. Berlick, F.F. Desmond, H.J. Ye, and E. Boycheva, 2008: Voices from the post-Katrina Ninth Ward: an examination of social justice, privilege, and personal growth. *Journal for Social Action in Counseling and Psychology*, **1(2)**, 48-61.

Randall, M.M., 2003: Coastal development run amuck: a policy of retreat may be the only hope. *Journal of Environmental Law and Litigation*, **18(1)**, 145-186.

Roos, A. and B. Jonkman, 2006: Flood risk assessment in the Netherlands with focus on the expected damages and loss of life. In *Flood Risk Management: Hazards, Vulnerability and Mitigation Measures*. [Schanze, J., E. Zeman and J. Marsalek (eds.)]. Springer, Berlin, pp. 169-182.

Rupp-Armstrong, S. and R.J. Nicholls, 2007: Coastal and estuarine retreat: a comparison of the application of managed realignment in England and Germany. *Journal of Coastal Research,* **23(6)**, 1418-1430.

Schmeltz, E.J., 1984: Comments. In: *Greenhouse Effect and Sea Level Rise: A Challenge for This Generation*. [Barth, M.C. and J.G. Titus (eds.)]. Van Nostrand Reinhold Company, New York, pp. 300-305.

Sebold, K.R., 1992: *From Marsh to Farm: The Landscape Transformation of Coastal New Jersey*. U.S. Department of Interior, National Park Service, Historic American Buildings Survey/Historic American Engineering Record, Washington, DC. <http://www.nps.gov/history/history/online_books/nj3/index.htm>

Seed, R.B., P.G. Nicholson, R.A. Dalrymple, J. Battjes, R.G. Bea, G. Boutwell, J.D. Bray, B.D. Collins, L.F. Harder, J.R. Headland, M. Inamine, R.E. Kayen, R. Kuhr, J.M. Pestana, R. Sanders, F. Silva-Tulla, R. Storesund, S. Tanaka, J. Wartman, T.F. Wolff, L. Wooten, and T. Zimmie, 2005: *Preliminary Report on the Performance of the New Orleans Levee Systems in Hurricane Katrina on August 29, 2005*. Report no. UCB/CITRIS – 05/01. University of California at Berkeley and American Society of Civil Engineers, Berkeley.

Shih, S.C.W. and R.J. Nicholls, 2007: Urban managed realignment: application to the Thames Estuary, London. *Journal of Coastal Research,* **23(6)**, 1525-1534.

Sorensen, R.M., R.N. Weisman, and G.P. Lennon, 1984: Control of erosion, inundation, and salinity intrusion caused by sea level rise. In: *Greenhouse Effect and Sea Level Rise: A Challenge for This Generation* [Barth, M.C. and J.G. Titus, (eds.)]. Van Nostrand Reinhold Company, New York, pp. 179-214.

Titus, J.G., 1990: Greenhouse effect, sea-level rise, and barrier Islands: case study of Long Beach Island, New Jersey. *Coastal Management*, **18**, 65-90.

Titus, J.G., 1991: Greenhouse effect and coastal wetland policy: how Americans could abandon an area the size of Massachusetts at minimum cost. *Environmental Management*, **15(1)**, 39-58.

Titus, J.G., 1998: Rising seas, coastal erosion and the taking clause: how to save wetlands and beaches without hurting property owners. *Maryland Law Review*, **57(4)**, 1277-1399.

Titus, J.G., 2000: Does the US government realize that the sea is rising? How to restructure federal programs so that wetlands and beaches survive. *Golden Gate University Law Review,* **30(4)**, 717-778.

* **Titus**, J.G., 2004: Maps that depict the business-as-usual response to sea level rise in the decentralized United States of America. Presented at: *Global Forum on*

Sustainable Development, Paris, 11-12 November 2004. Organization of Economic Cooperation and Development, Paris.

Titus, J.G., 2005: Does shoreline armoring violate the Clean Water Act? Rolling easements, shoreline planning, and other responses to sea level rise. In: *America's Changing Coasts: Private Rights and Public Trust*. [Whitelaw D.M. and G.R. Visgilio (eds.)]. Edward Elgar Publishing, Cheltenham, UK, Northampton, MA, 248 pp.

Titus, J.G., C.Y. Kuo, M.J. Gibbs, T.B. LaRoche, M.K. Webb, and J.O. Waddell, 1987: Greenhouse effect, sea level rise, and coastal drainage systems. *Journal of Water Resources Planning and Management*, **113(2)**, 216-227.

Titus, J.G., R.A. Park, S.P. Leatherman, J.R. Weggel, M.S. Greene, P.W. Mansel, S. Brown, G. Gaunt, M. Treehan, and G. Yohe. 1991: Greenhouse effect and sea level rise: the cost of holding back the sea. *Coastal Management*, **19(2)**, 171-204.

UK Environment Agency, 2007: *Managed Realignment Electronic Platform.* Version 1.0. <http://www.intertidalmanagement.co.uk/>

USACE (U.S. Army Corps of Engineers), 1995: *Engineering and Design: Design of Coastal Revetments, Seawalls, and Bulkheads.* Engineer manual no. 1110-2-1614. U.S. Army Corps of Engineers, Washington, DC.

USACE (U.S. Army Corps of Engineers), 1998. Shoreline and Channel Erosion Protection: Overview of Alternatives. WRP technical note HS-RS-4.1. U.S. Army Corps of Engineers Wetlands Research Program, [Vicksburg, MS], 8 pp. http://el.erdc.usace.army.mil/elpubs/pdf/hsrs4-1.pdf

USACE (U.S. Army Corps of Engineers), 2002: *Coastal Engineering Manual*. Engineer manual 1110-2-1100. U.S. Army Corps of Engineers, Washington, DC, (in 6 volumes issued between 2002 and 2006).

* **USACE** (U.S. Army Corps of Engineers), 2008a: *Corps of Engineers Public Interest Review Results in Permit Denial for Winthrop Beach*. News Release April 23,

2008. <http://www.nae.usace.army.mil/news/2008-041.htm>

USACE (U.S. Army Corps of Engineers), 2008b: *Project Factsheet: New Jersey Alternative Long-Term Nourishment RSM (Regional Sediment Management) Study*. USACE Philadelphia District, 2 pp. <http://www.nap.usace.army.mil/cenap-dp/projects/factsheets/NJ/NJ%20Alt%20LT%20Nourishment.pdf>

USCOP (U.S. Commission on Ocean Policy), 2004: *An Ocean Blueprint for the 21st Century*. U.S. Commission on Ocean Policy, Washington DC. <http://www.oceancommission.gov>

U.S. EPA (Environmental Protection Agency), 1989: *The Potential Effects of Global Climate Change on the United States. Appendix: B, Sea Level Rise*. EPA 230-05-89-052. U.S. Environmental Protection Agency, Washington, DC. <http://epa.gov/climatechange/effects/coastal/appB.html>

* **USFWS** (United States Fish and Wildlife Service), 2008: *Blackwater National Wildlife Refuge: Wetland Restoration*. [web site] <http://www.fws.gov/blackwater/restore.html>

Weggel, J.R., S. Brown, J.C. Escajadillo, P. Breen, and E.L. Doheny, 1989: The cost of defending developed shorelines along sheltered waters of the United States from a two meter rise in mean sea level. In: *The Potential Effects of Global Climate Change on the United States. Appendix: B, Sea Level Rise*. EPA 230-05-89-052. U.S. Environmental Protection Agency, Washington, DC, pp. 3-1 to 3-90. <http://epa.gov/climatechange/effects/coastal/appB.html>

Weiss, N.E., 2006: *Rebuilding Housing after Hurricane Katrina: Lessons Learned and Unresolved Issues*. Congressional Research Service, Washington, DC, 13 pp. <http://assets.opencrs.com/rpts/RL33761_20061219.pdf>

Wilcoxen, P.J., 1986: Coastal erosion and sea level rise: implications for Ocean Beach and San Francisco's Westside Transport Project. *Coastal Zone Management*

Journal, **14(3)**, 173-192.

Yohe, G. and J.E. Neumann, 1997: Planning for sea level rise and shore protection under climate uncertainty. *Climatic Change*, **37(1)**, 243-270.

Yohe, G., J.E. Neumann, P. Marshall, and H. Ameden, 1996: The economic cost of greenhouse induced sea level rise in the United States. *Climatic Change*, **32(4)**, 387-410.

Yzermans, C.J., G.A. Donker, J.J. Kerssens, A.J.E Dirkzwager, R.J.H. Soeteman, and P.M.H. ten Veen, 2005: Health problems of victims before and after disaster: a longitudinal study in general practice. *International Journal of Epidemiology*, **34(4)**, 820-826.

Zimmerman, R. and M. Cusker, 2001: Institutional decision-making. In: *Climate Change and a Global City: The Potential Consequences of Climate Variability and Change. Metro East Coast* [Rosenzweig, C. and W.D. Solecki (eds.)]. Columbia Earth Institute and Goddard Institute of Space Studies, New York, pp. 9-1 to 9-25; A11-A17.

Chapter 7. Population, Land Use, and Infrastructure

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KEY FINDINGS

- The comprehensive high-resolution and precise analyses of the spatial distributions of population and infrastructure vulnerable to sea-level rise in the Mid-Atlantic required for planning and response do not exist at the present time. Existing studies do not have the required underlying land elevation data with the degree of confidence necessary for local and regional decision-making (see Chapter 2 of this Product).
- Existing generalized data can only support a range of estimates. For instance, in the Mid-Atlantic, between approximately 900,000 and 3,400,000 people (between 3 and 10 percent of the total population in the mid-Atlantic coastal region) live on parcels of land or city blocks with at least some land less than 1 meter above monthly highest tides. Approximately 40 percent of this population is located along the Atlantic Ocean shoreline or small adjacent inlets and coastal bays (as opposed to along the interior shorelines of the large estuaries, such as Delaware Bay and Chesapeake Bay).

- Agriculture lands, forests, wetlands, and developed lands in lower elevation areas are likely to be most impacted by a 1-meter sea-level rise for the Mid-Atlantic.
- The coupling of sea-level rise with storm surge is one of the most important considerations for assessing impacts of sea-level rise on infrastructure. Sea-level rise poses a risk to transportation in ensuring reliable and sustained transportation services.

7.1 INTRODUCTION

Coastal areas in the United States have competing interests of population growth (accompanied by building of the necessary supporting infrastructure), the preservation of natural coastal wetlands and creation of buffer zones. Increasing sea level will put increasing stress on the ability to manage these competing interests effectively and in a sustained manner. This Chapter examines the current population, infrastructure, and socioeconomic activity that may potentially be affected by sea-level rise.

7.2 POPULATION STUDY ASSESSMENT

The population assessment for the Mid-Atlantic can be put into a regional perspective by first examining some recent national statistics and trends that illustrate the relative socioeconomic stress on our coasts:

- Using an analysis of coastal counties defined to have a coastline bordering the ocean or associated water bodies, or those containing special velocity zones (V Zones) defined by the Federal Emergency Management Administration (FEMA), Crowell *et al.* (2007) estimate that 37 percent of the total U.S. population is found in 364 coastal counties, including the Great Lakes. Excluding the Great Lakes counties, 30 percent of the total U.S. population is found in 281 coastal counties.

- Using an analysis with a broader definition of a coastal county to include those found in coastal watersheds in addition to those bordering the ocean and associated water bodies, the National Oceanic and Atmospheric Administration (NOAA) estimates that U.S. coastal counties, including the Great Lakes and excluding Alaska, contain 53 percent of the nation's population, yet account for only 17 percent of the total U.S. land area (Crossett *et al.*, 2004)
- Twenty-three of the 25 most densely populated U.S. counties are coastal counties. From 1980 to 2003, population density (defined as persons per unit area) increased in coastal counties by 28 percent and was expected to increase another 4 percent by 2008 (Crossett *et al*., 2004).
- Construction permits can be used to indicate economic growth and urban sprawl. More than 1,540 single family housing units are permitted for construction every day in coastal counties across the United States. From 1999 to 2003, 2.8 million building permits were issued for single family housing units (43 percent of U.S. total) and 1.0 million building permits were issued for multi-family housing units (51 percent of the U.S. total) (Crossett *et al*., 2004).
- In 2000, there were approximately 2.1 million seasonal or vacation homes in coastal counties (54 percent of the U.S. total) (Crossett *et al*., 2004).

Regional trends for the Mid-Atlantic can also be summarized, based on Crossett *et al.* (2004). This Product includes the mid-Atlantic states, defined in the Product to include the area from New York to Virginia, as part of their defined Northeast region, with North Carolina included in the Southeast region. The statistics serve to illustrate the relative vulnerability of the coastal socioeconomic infrastructure, either directly or indirectly, to sea-level rise.

- Of the 10 largest metropolitan areas in the United States, three (New York, Washington, D.C., and Philadelphia) are located in the coastal zone of the mid-Atlantic region.
- The coastal population in the Northeast (Maine to Virginia) is expected to increase by 1.7 million people from 2003 to 2008, and this increase will occur mostly in counties near or in major metropolitan centers. Six of the counties near metropolitan areas with the largest expected population increases are in the New York City area and four are in the Washington, D.C. area.
- The greatest percent population changes from 2003 to 2008 in the U.S. Northeast are expected to occur in Maryland and Virginia. Eight of the 10 coastal counties with the greatest expected percent population increases are located in Virginia and two are located in Maryland.
- North Carolina coastal counties rank among the highest in the U.S. Southeast for expected percent population change from 2003 to 2008. For instance, Brunswick County is expected to have the greatest percent increase, at 17 percent.

Crossett *et al*. (2004), show the mid-Atlantic states in context with the larger Atlantic Coast region. By presenting total land area and coastal land area, as well as total and coastal county population statistics, both in absolute numbers and in population density, the NOAA report quantifies the socioeconomic stressor of population change on the coastal region. As pointed out by Crowell *et al*. (2007), the coastal counties used in the NOAA study represent counties in a broader watershed area that include more than those counties that border the land-water interface and that detailed analyses and summary statistics for populations at direct risk for inundation due to sea-level rise must use only that subset of coastal counties subject to potential inundation. The analyses and statistics discussed in subsequent sections of this Product use those subsets. Crossett *et al*. (2004) is used simply to illustrate the increasing stress on coastal areas in general. The mid-Atlantic coastal counties are among the most developed and densely populated coastal areas in the nation. It is this environment that coastal managers must plan strategies for addressing impacts of climate change, including global sea-level rise.

Several regionally focused reports on examining populations at risk to sea-level rise in the Mid-Atlantic are found in the literature. For example Gornitz *et al*. (2001) includes a general discussion of population densities and flood risk zones in the New York metropolitan region and examines impacts of sea-level rise on this area. In this report, the authors also consider that low-lying areas will be more at risk to episodic flooding from storm events because storm tide elevations for a given storm will be higher with sea-level rise than without. They suggest that the overall effect for any given location will be a reduction in the return period of the 100-year storm flooding event. A similar analysis was performed for the Hampton Roads, Virginia area by Kleinosky *et al.* (2006) that attempts to take into account increased population scenarios by 2100.

Bin *et al.* (2007) studied the socioeconomic impacts of sea-level rise in coastal North Carolina, focusing on four representative coastal counties (New Hanover, Dare, Carteret, and Bertie) that range from high-development to rural, and from marine to estuarine shoreline. Their socioeconomic analyses studied impacts of sea-level rise on the coastal real estate market, on coastal recreation and tourism, and the impacts of tropical storms and hurricanes on business activity using a baseline year of 2004.

Comprehensive assessments of impacts of sea-level rise on transportation and infrastructure are found in the CCSP Synthesis and Assessment Product (SAP) 4.7 (CCSP, 2008), which focuses on the Gulf of Mexico, but provides a general overview of the scope of the impacts on transportation and infrastructure. In the Mid-Atlantic, focused assessments on the effects of sea-level rise to infrastructure in the New York City area are available in Jacob *et al*. (2007).

Some of the recent regional population and infrastructure assessments typically use the best available information layers (described in the following section), gridded elevation data, gridded or mapped population distributions, and transportation infrastructure maps to qualitatively depict areas at risk and vulnerability (Gornitz *et al*., 2001). The interpretation of the results from these assessments is limited by the vertical and horizontal resolution of the various data layers, the difference in resolution and matching of the fundamental digital-layer data cells, and the lack of spatial resolution of the population density and other data layers within the fundamental area blocks used (see Chapter 2 for further discussion). As discussed in Chapter 2, the available elevation data for the entire mid-Atlantic region do not support inundation modeling for sea-level rise scenarios of 1 meter or less. Therefore, the results reported in this Chapter should not be considered as reliable quantitative findings, and they serve only as demonstrations of the types of analyses that should be done when high-accuracy elevation data become available.

7.3 MID-ATLANTIC POPULATION ANALYSIS

In this Chapter, the methodology for addressing population and land use utilizes a Geographic Information Systems (GIS) analysis approach, creating data layer overlays and joining of data tables to provide useful summary information. GIS data are typically organized in themes as data layers. Data can then be input as separate themes and overlaid based on user requirements. Essentially, the GIS analysis is a vertical layering of the characteristics of the Earth's surface and is used to logically order and analyze data in most GIS software. Data layers can be expressed visually as map layers with underlying tabular information of the data being depicted. The analysis uses data layers of information and integrates them to obtain the desired output and estimated uncertainties in the results. The GIS layers used here are population statistics, land use information, and land elevation data.

The population and land use statistics tabulated in the regional summary tables (Tables 7.1 through 7.6) use an area-adjusted system that defines regions and subregions for analysis such that they are (1) higher than the zero reference contour (Spring High Water) used in a vertical datum-adjusted elevation model, and (2) not considered a wetland or open water, according to the state and National Wetlands Inventory wetlands data compiled by the U.S. Fish and Wildlife Service (USFWS, 2007). Uncertainties are expressed in the tables in terms of low and high statistical estimates (a range of values) in each case to account for the varying quality of topographic information and the varying spatial resolution of the other data layers. The estimated elevation of spring high water is used as a boundary that distinguishes between normal inundation that would occur due to the normal monthly highest tides and the added inundation due to a 1-meter (m) rise in sea level (Titus and Cacela, 2008) .

Census block statistics determined for the estimated area and the percent of a block affected by sea-level rise and the estimated number of people and households affected by sea-level rise are based on two methods: (1) a uniform distribution throughout the block and (2) a best estimate based on assumptions concerning elevation and population density. For instance, there is an uncertainty regarding where the population resides within the census block, and the relationship between the portion of a block's area that is lost to sea-level rise and the portion of the population residing in the vulnerable area is also uncertain. Analysis estimates of vulnerable population are based on the percentage of a census block that is inundated. Homes are not necessarily distributed uniformly throughout a census block. In addition, the differences in grid sizes between the census blocks and the elevation layers results in various blocks straddling differing elevation grids and adds to the uncertainty of the process.

Discussion on coastal elevations and mapping limitations and uncertainties as applied for inundation purposes is provided in Chapter 2. Given these limitations and uncertainties, the population and land use analyses presented here are only demonstrations of techniques using a 1-meter (m) sea-level rise scenario. More precise quantitative estimates require high-resolution elevation data and population data with better horizontal resolution.

Figure 7.1 illustrates the three GIS data layers used in the population and land use analysis: the elevation layer (Titus and Wang, 2008), a census layer (GeoLytics, 2001), and a land-use layer (USGS, 2001).

Figures 7.2, 7.3, and 7.4 show the fundamental underlying layers used in this study, using Delaware Bay as an example. The GIS layers used here are:

- *Elevation data*: The elevation data is the driving parameter in the population analysis. The elevation data is gridded into 30-m pixels throughout the region. All other input datasets are gridded to this system from their source format (Titus and Wang, 2008). The elevations are adjusted such that the zero-contour line is set relative to the Spring High Water vertical datum, which is interpolated from point sources derived from NOAA tide station data (Titus and Cacela, 2008).

- *Census data*: Census 2000 dataset (GeoLytics, 2001) is used in the analysis. Block boundaries are the finest-scale data available, and are the fundamental units of area of the census analysis. Tract, county, and state boundaries are derived from appropriate aggregations from their defining blocks. The census tract boundaries are the smallest census unit that contains property and tax values. Tract and county boundaries also extend fully into water bodies. For this analysis, these boundaries are cropped back to the sea-level boundary, but source census data remain intact.
- *Land use data*: The National Land Cover Data (NLCD) (USGS, 2001) dataset is used in this analysis. It consists of a 30-m pixel classification from circa 2001 satellite imagery and is consistently derived across the region. The caveat with the product is that pixels are classified as "wetland" and "open water" in places that are not classified as such by the wetland layer. Wetland layers are derived from state wetlands data (Titus and Wang, 2008). Usually, the NLCD Wetland class turns out to be forested land and the water tends to be edge effects (or uncertainty due to lack of resolution) along the shore or near farm ponds. This analysis folds the NLCD wetland pixels into forested land.

Figure 7.2 is an example of the county overlay, and Figure 7.3 is an example of the census tract overlay. A census tract is a small, relatively permanent statistical subdivision of a county used for presenting census data. Census tract boundaries normally follow visible features such as roads and rivers, but may follow governmental unit boundaries and other non-visible features in some instances; they are always contained within counties. Census tracts are designed to be relatively homogeneous units with respect to population characteristics, economic status, and living conditions at the time of establishment, and they average about 4,000 inhabitants. The tracts may be split by any sub-county geographic entity.

Figure 7.4 provides an example of the census block overlay. A census block is a subdivision of a census tract (or, prior to 2000, a block numbering area). A block is the smallest geographic unit for which the Census Bureau tabulates data. Many blocks correspond to individual city blocks bounded by streets; however, blocks–especially in rural areas—may include many square kilometers and due to lack of roads, may have some boundaries that are other features such as rivers and streams. The Census Bureau established blocks covering the entire nation for the first time in 1990. Previous censuses back to 1940 had blocks established only for part of the United States. More than 8 million blocks were identified for Census 2000 (U.S. Census Bureau, 2007).

The Digital Elevation Model (DEM) (Titus and Wang, 2008) was the base for this analysis. The areas of various land use, counties, tracts, and blocks are rasterized (converted in a vector graphics format [shapes]) into a gridded raster image (pixels or dots) to the DEM base. This ensures a standard projection (an equal-area projection), pixel size (30 m), grid system (so pixels overlay exactly), and geographic extent. A GIS data layer intersection was completed for each of the geographic reporting units (land use, county, tract, and block) with elevation ranges to produce a table of unique combinations.

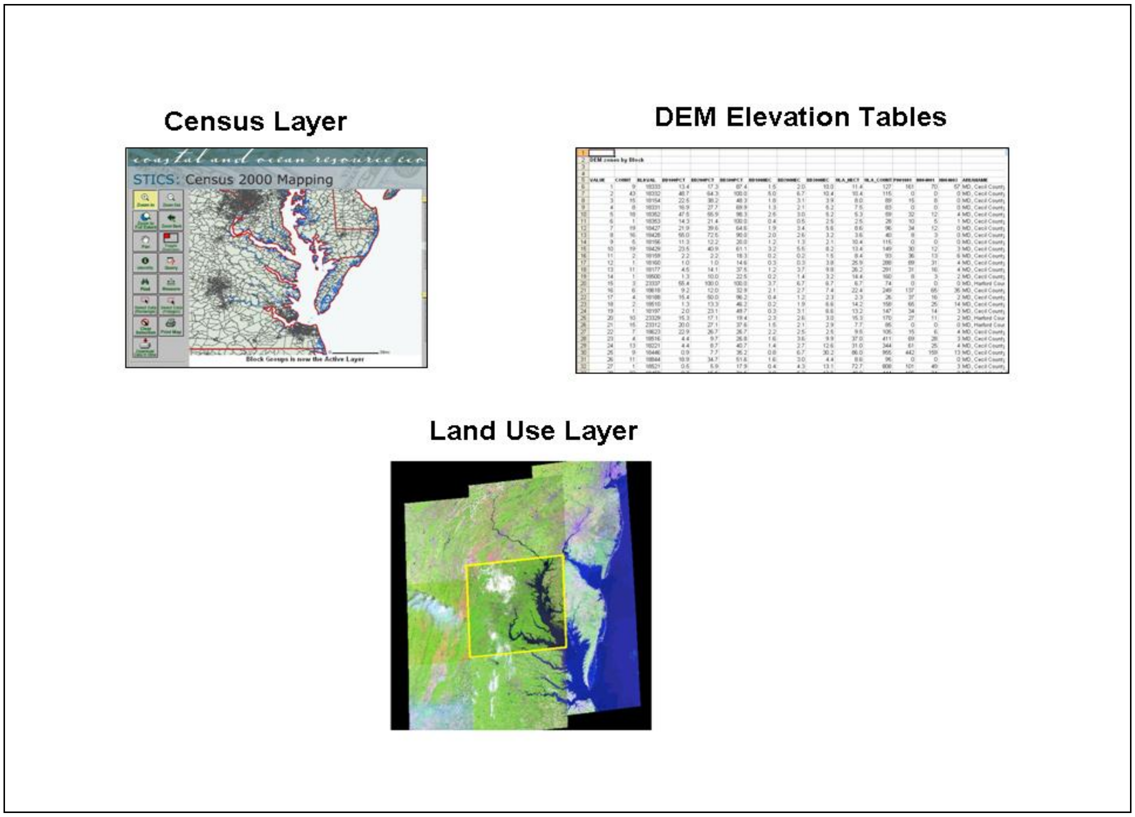

Figure 7.1 The three input data layers to the GIS analysis.

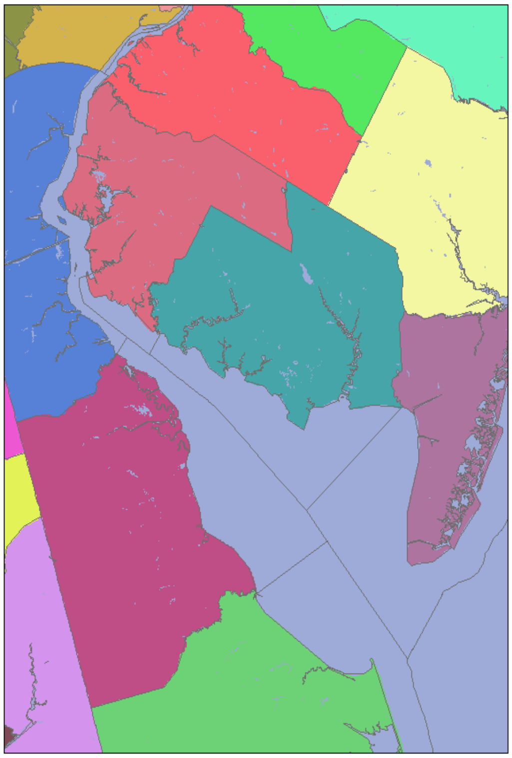

Figure 7.2 The county overlay example for Delaware Bay with each colored area depicting a county.

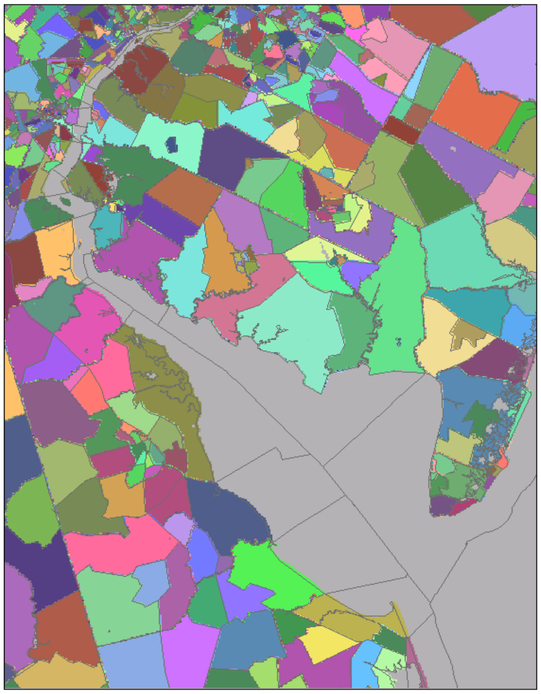

Figure 7.3 The census tract overlay example for Delaware Bay with each colored area depicting a census tract.

Figure 7.4 The census block overlay example for Delaware Bay with gray lines outlining individual areas of a census block.

This Chapter examines the mid-Atlantic region and makes some inferences on the populations that may be affected by sea-level rise. This assessment divides the mid-Atlantic region into sub-regions defined by watersheds (Crossett *et al*., 2004), as shown in Figure 7.5. The general populations within the various watersheds, although sometimes in more than one state, have to address common problems driven by common topographies, and natural hydrological regimes. Most of the watershed boundaries are clear, for instance the Potomac River and Chesapeake Bay. The watershed boundaries used do not include the upland portions of the watershed located in upland mountains and hills; those portions are not required for the analyses of the low-lying areas. The Atlantic Ocean watershed is the most complex because it is not defined by a discrete estuarine river watershed boundary, but by exposure to the outer coastline, and it has components in several states.

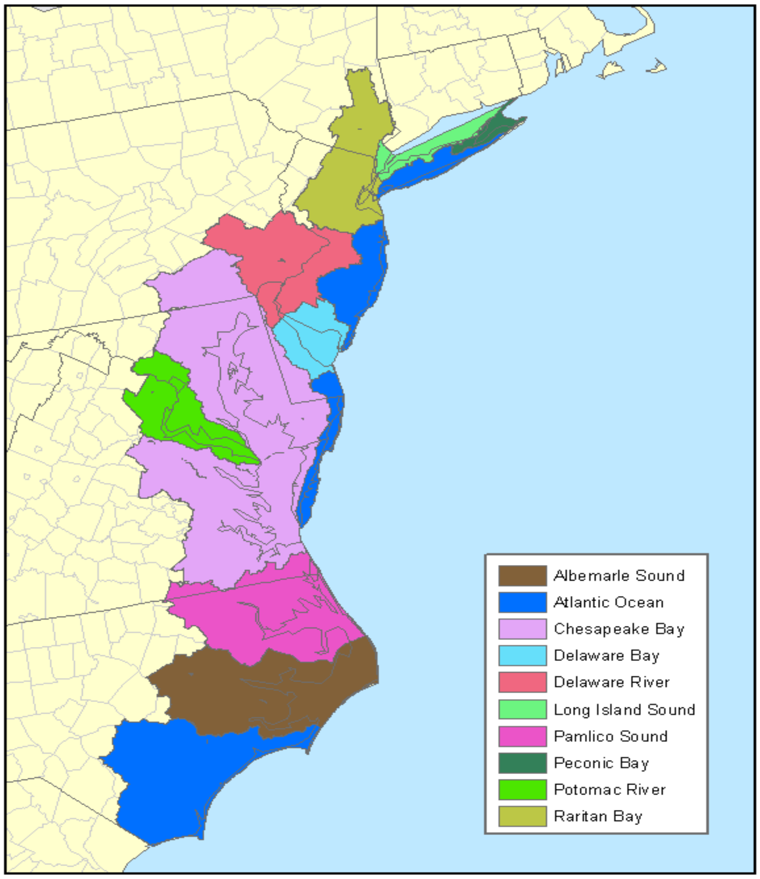

Figure 7.5 The mid-Atlantic region generalized watersheds.

7.3.1 Example Population Analysis Results

Not everyone who resides in a watershed lives in a low-lying area that may be at risk to the effects of sea-level rise. Table 7.1 provides a summary analysis of those populations in each watershed at potential risk for a 1-m sea-level rise. The low and high estimates in Table 7.1 provide the range of uncertainty by using the low and high DEMs (Titus and Wang, 2008; Titus and Cacela, 2008). The high elevation is equal to the best estimate plus the vertical error of the elevation data; the low elevation estimate is equal to the best estimate minus the vertical error. The high vulnerability estimate uses the low elevation estimate because if elevations are lower than expected a greater population is vulnerable. Similarly, the low vulnerability estimate uses the high end of the uncertainty range of elevation estimates. These DEMs are required to express the uncertainty in the numerical results because of the varying scales and resolutions of the data in the various overlays (for instance, the census block boundaries may not line up with specific elevation contours being used and interpolation algorithms must be used to derive population statistics within certain contour intervals. As previously mentioned, this analysis is also limited by the assumption that population has uniform density within the inhabited portion of particular census block. The census data provide no information where the population resides within a particular block.

The uncertainty in how much of a particular census tract or block may be inundated must also be addressed by listing high and low estimates. Table 7.1 is a maximum estimate of the potential populations because it is for census blocks that could have any inundation at all and thus includes a maximum count. Similarly, it should be noted that Table 7.3 also provides maximum estimates for the Chesapeake Bay and the Atlantic Ocean.

Table 7.1 Estimated mid-Atlantic low and high population estimates by watershed for a 1-meter sea-level rise (population is based on Census [2000] data). The reported numbers are subject to the caveat given at the end of Section 7.2.

Population count			
		1m Sea level Rise	
Watershed		Low Estimate	High Estimate
Long Island Sound		1,640	191,210
Peconic Bay		7,870	29,140
NHY-Raritan Bay		35,960	678,670
Delaware Bay		22,660	62,770
Delaware River		19,380	239,480
Chesapeake Bay		326,830	807,720
Potomac River		0	124,510

Albemarle Sound	61,140	75,830
Pamlico Sound	69,720	147,290
Atlantic Ocean	362,800	1,109,280
All Watersheds	908,020	3,465,940

To illustrate the nature of using the various sets of data and layers for analyses, and the uncertainty in the population distributions within a census block, a second type of analysis is useful. Because there is an uncertainty regarding where the population resides within the census block, the relationship between the portion of a block's area that is lost to sea-level rise and the portion of the population residing in the vulnerable area is also uncertain. Analysis estimates of vulnerable population are based on the percentage of a census block that is inundated. For instance, the total 2000 population low and high estimated counts for a 1-m sea-level rise for all watersheds are 908,020 and 3,465,940 for "any inundation" of census block (see Table 7.1). However, homes are not necessarily distributed uniformly throughout a census block. If 10 percent of a block is very low, for example, that land may be part of a ravine, or below a bluff, or simply the low part of a large parcel of land. Therefore, the assumption of uniform density would often overstate the vulnerable population. Table 7.2 provides estimates that assume distributions other than uniform density regarding the percentage of a block that must be vulnerable before one assumes that homes are at risk. (This table presents the results by state rather than by subregion.) If it is assumed that 90 percent of a block must be lost before homes are at risk, and that the population is uniformly distributed across the highest 10 percent of the block, then between 26,000 and 959,000 people live less than one meter above the elevation spring high water (see NOAA, 2000 and Titus and Wang, 2008), allowing for low and high elevation estimates. The estimated elevation of spring high water is used as a boundary that distinguishes between normal inundation that would occur due to the normal monthly highest tides and the added inundation due to a 1-m rise in sea level. The spread of these estimated numbers depending upon the underlying assumptions listed at the end of Table 7.2 underscore the uncertainty inherent in making population assessments based in limited elevation data. As reported in Chapter 2, the disaggregation of population density data into a more realistic spatial distribution would be to use a Dasymetric mapping technique (Mennis, 2003) which holds promise for better analysis of population, or other socioeconomic data, and to report statistical summaries of sea-level rise impacts within vulnerable zones.

The census information also allows further analysis of the population, broken down by owner and renter-occupied residences. This information gives a sense of the characterization of permanent home owners *versus* the more transient rental properties that could translate to infrastructure and local economy at risk as well. The estimated number of owner- and renter-occupied housing units in each watershed are shown in Tables 7.3 and 7.4. Similar to the estimates in Table 7.1, these are high estimates for which any portion of a particular census block is inundated.

Table 7.2 Low and High estimates of population living on land within one meter above spring high water (Using assumptions other than uniform population density about how much of the land must be lost before homes are lost). The reported numbers are subject to the caveat given at the end of Section 7.2.

	Percentage of census block within 1 m above spring high water							
	99[1]		90[2]		50[3]		0[4]	
State	Low	High	Low	High	Low	High	Low	High

NY	780	421,900	780	470,900	2,610	685,500	42,320	1,126,290
NJ	12,540	302,800	15,770	352,510	41,260	498,650	177,500	834,440
DE	480	7,200	810	9,230	2,040	16,650	44,290	85,480
PA	640	7,830	640	8,940	1,530	15,090	10,360	43,450
VA	950	59,310	1,020	84,360	5,190	173,950	232,120	662,400
MD	610	4,840	1,890	8,040	4,380	17,710	46,890	137,490
DC	0	0	0	0	0	40	0	9,590
NC	1,920	14,140	5,320	25,090	17,450	60,090	283,590	345,530
Total	17,920	818,020	26,230	959,070	74,460	1,467,680	837,070	3,244,670

[1] Population estimates in this column assume that no homes are vulnerable unless 99 percent of the dry land in census block is within 1 m above spring high water.
[2] Population estimates in this column assume that no homes are vulnerable unless 90 percent of the dry land in census block is within 1 m above spring high water.
[3] Population estimates in this column assume that no homes are vulnerable unless 50 percent of the dry land in census block is within 1 m above spring high water.
[4] Assumes uniform population distribution.

The actual coastal population potentially affected by sea-level rise also includes hotel guests and those temporarily staying at vacation properties. Population census data on coastal areas are rarely able to fully reflect the population and resultant economic activity. The analysis presented in this Product does not include vacant properties used for seasonal, recreational, or occasional use nor does it characterize the "transient" population, who make up a large portion of the people found in areas close to sea level in the Mid-Atlantic during at least part of the year. These temporary residents include the owners of second homes. A significant portion of coastal homes are likely to be second homes occupied for part of the year by owners or renters who list an inland location as their permanent residence for purposes of census data. In many areas, permanent populations are expected to increase as retirees occupy their seasonal homes for longer portions of the year.

Table 7.3 Low and high estimates of number of owner occupied residences in each watershed region for a 1- meter sea-level rise scenario. The reported numbers are subject to the caveat given at the end of Section 7.2.

Number of owner occupied residences	1- meter rise in sea level	
Watershed		
	Low Estimate	High Estimate
Long Island Sound	0	0
Peconic Bay	3,400	11,650
NYH-Raritan Bay	13,440	269,420
Delaware Bay	8,720	23,610
Delaware River	6,010	89,710
Chesapeake Bay	120,790	299,550
Potomac River	0	46,070
Albemarle Sound	22,760	28,720
Pamlico Sound	26,730	52,450
Atlantic Ocean	140,670	423,540
All Watersheds	342,520	1,244,720

Table 7.4 Low and high estimates of the number of renter occupied housing units by watershed for a 1-meter sea-level rise scenario. The reported numbers are subject to the caveat given at the end of Section 7.2.

Number of renter occupied residences		
	1- meter rise in sea level	
Watershed	Low Estimate	High Estimate
Long Island Sound	70	31,010
Peconic Bay	520	2,460
NYH-Raritan Bay	4,270	178,790
Delaware Bay	2,630	5,880
Delaware River	2,110	32,760
Chesapeake Bay	35,880	84,630
Potomac River	0	17,470
Albemarle Sound	5,260	6,830
Pamlico Sound	6,000	10,660
Atlantic Ocean	40,220	154,500

All Watersheds	96,960	524,990

7.4 LAND USE

The National Land Cover Database (USGS, 2001) is used to overlay land use onto the DEMs for a 1-m scenario of sea-level rise. Major land-use categories used for this analysis include: agriculture, barren land, developed land, forest, grassland, shrub-scrub, water, and wetland. An estimate of the area of land categorized by land use for all watersheds for the Mid-Atlantic is listed in Table 7.5. In the land-use tables, ranges of uncertainty are provided by showing the low and high estimated size of the areas for the 1-m sea-level rise scenario. The high and low estimates show significant differences in area and express the uncertainty in using this type of data layer integration.

Table 7.5 Mid-Atlantic All Watersheds Summary by Land Use category, depicting low and high estimates of areas affected by a 1-meter sea-level rise (in hectares; 1 hectare is equal to 2.47 acres). The reported numbers are subject to the caveat given at the end of Section 7.2.

Area (in hectares)	1-meter rise in sea level	
Land Use Category	Low Estimate	High estimate
Agriculture	43,180	141,800
Barren Land	5,040	14,750
Developed	11,970	92,950
Forest	27,050	94,280
Grassland	7,640	14,200
Shrub-scrub	3,790	7,720
Water	1,960	4,110
Wetland	34,720	66,590

The developed land-use acreage dominates northeast watersheds such as Long Island Sound and New York Harbor, as well as the Atlantic Coast watershed. This is in contrast to the Chesapeake Bay watershed that is dominated by agriculture and forest.

Table 7.6 Low and high area estimates by land use category for the mid-Atlantic for a 1-meter sea-level rise scenario (in hectares). The reported numbers are subject to the caveat given at the end of Section 7.2.

Area (in hectares)	For a 1-meter rise in sea level		
Watershed	Land Use Category	Low Estimate	High Estimate
Long Island Sound	Agriculture	0	20
	Barren Land	0	180
	Developed	90	3,280
	Forest	0	210
	Grassland	0	100
	Shrub-scrub	0	60
	Water	0	90
	Wetland	0	530
Peconic Bay	Agriculture	20	360
	Barren Land	20	340
	Developed	100	1,580
	Forest	50	760
	Grassland	0	170
	Shrub-scrub	0	70
	Water	10	150
	Wetland	70	770
NYH-Raritan Bay	Agriculture	30	870
	Barren Land	40	340
	Developed	330	21,090
	Forest	40	720
	Grassland	0	10
	Shrub-scrub	0	10
	Water	9	230
	Wetland	140	2,600
Delaware Bay	Agriculture	950	9,590
	Barren Land	280	1,040
	Developed	210	1,760
	Forest	590	4,280
	Water	80	130
	Wetland	900	2,420
Delaware River	Agriculture	310	8,190
	Barren Land	20	560
	Developed	430	10,960
	Forest	90	2,130
	Water	20	200
	Wetland	330	3,010

Table 7.6 (continued) Low and high area estimates by land use category for the mid-Atlantic for a 1-meter sea-level rise scenario (in hectares). The reported numbers are subject to the caveat given at the end of Section 7.2.

Area (in hectares)	For a 1- meter rise in sea level		
Watershed	Land Use Category	Low Estimate	High Estimate
Chesapeake Bay	Agriculture	11,180	40,460
	Barren Land	2,070	4,650
	Developed	2,220	13,180
	Forest	9,100	38,370
	Water	160	660
	Wetland	5,010	14,280
Potomac River	Agriculture	0	490
	Barren Land	0	460
	Developed	0	1,830
	Forest	0	4,630
	Water	0	130
	Wetland	0	1,120
Albemarle Sound	Agriculture	16,440	12,810
	Barren Land	320	5,900
	Developed	2,460	8,270
	Forest	8,680	4,950
	Grassland	4,790	44,720
	Shrub-scrub	2,720	10
	Water	750	8,440
	Wetland	14,480	920
Pamlico Sound	Agriculture	1,3130	3,9670
	Barren Land	470	1,327
	Developed	1,620	4,583
	Forest	5,490	1,380
	Grassland	2,010	3,570
	Shrub-scrub	670	1,430
	Water	210	290
	Wetland	8,500	12,070
Atlantic Ocean	Agriculture	1,090	8,220
	Barren Land	1,800	5,410
	Developed	4,470	29,210
	Forest	2,980	11,540
	Grassland	820	2,010
	Shrub-scrub	380	1,360
	Water	690	1,210
	Wetland	5,260	10,870

7.5 TRANSPORTATION INFRASTRUCTURE

7.5.1 General Considerations

The coupling of sea-level rise with storm surge is one of the most important considerations for assessing impacts of sea-level rise on infrastructure. Sea-level rise poses a risk to transportation in ensuring reliable and sustained transportation services. Transportation facilities serve as the life-line to communities, and inundation of even the smallest component of an intermodal system can result in a much larger system shut-down. For instance, even though a port facility or a railway terminal may not be affected, the access roads to the port and railways could be, thus forcing the terminal to cease or curtail operation.

Sea-level rise will reduce the 100-year flood return periods and will lower the current minimum critical elevations of infrastructure such as airports, tunnels, and ship terminals (Jacob *et al*., 2007). Some low-lying railroads, tunnels, ports, runways, and roads are already vulnerable to flooding and a rising sea level will only exacerbate the situation by causing more frequent and more serious disruption of transportation services. It will also introduce problems to infrastructure not previously affected by these factors.

The CCSP SAP 4.7 (Kafalenos *et al.,* 2008) discusses impacts of sea-level rise on transportation infrastructure by addressing the impacts generally on highways, transit systems, freight and passenger rail, marine facilities and waterways, aviation, pipelines, and implications for transportation emergency management and also specifically for the

U.S. Gulf Coast region. Each of these transportation modes also apply to the mid-Atlantic region.

One impact of sea-level rise not generally mentioned is the decreased clearance under bridges. Even with precise timing of the stage of tide and passage under fixed bridges, sea-level rise will affect the number of low water windows available for the large vessels now being built. Bridge clearance has already become an operational issue for major ports, as evidenced by the installation of real-time reporting air gap/bridge clearance sensors in the NOAA Physical Oceanographic Real-Time System (PORTS) (NOAA, 2005). Clearance under bridges has become important because the largest vessels need to synchronize passage with the stage of tide and with high waters due to weather effects and high river flows. To provide pilots with this critical information, air gap sensors in the Mid-Atlantic have been deployed at the Verrazano Narrows Bridge at the entrance to New York Harbor, the Chesapeake Bay Bridge located in mid-Chesapeake Bay, and on bridges at both ends of the Chesapeake and Delaware Canal connecting the upper Chesapeake Bay with mid-Delaware Bay (NOAA, 2008).

There are other potential navigation system effects as well because of sea-level rise. Estuarine navigation channels may need to be extended landward from where they terminate now to provide access to a retreating shoreline. The corollary benefit is that less dredging will be required in deeper water because a rising water elevation will provide extra clearance.

This discussion is limited in scope to transportation infrastructure. Complete infrastructure assessments need to include other at-risk engineering and water control structures such as spillways, dams, levees and locks, with assessments of their locations and design capacities.

7.5.2 Recent U.S. Department of Transportation Studies

The U.S. Department of Transportation (US DOT) studied the impacts of sea-level rise on transportation, as discussed in US DOT (2002). The study addresses the impacts of sea-level rise on navigation, aviation, railways and tunnels, and roads, and describes various options to address those impacts, such as elevating land and structures, protecting low-lying infrastructure with dikes, and applying retreat and accommodation strategies.

The US DOT has recently completed an update of the first phase of a study, "The Potential Impacts of Global Sea Level Rise on Transportation Infrastructure" (US DOT, 2008). The study covers the mid-Atlantic region and is being implemented in two phases: Phase 1 focuses on North Carolina, Virginia, Washington, D.C., and Maryland. Phase 2 focuses on New York, New Jersey, Pennsylvania, Delaware, South Carolina, Georgia, and the Atlantic Coast of Florida. This second phase is expected to be completed by the end of 2008. This study was designed to produce rough quantitative estimates of how future climate change, specifically sea-level rise and storm surge, might affect transportation infrastructure on a portion of the East Coast of the United States. The major purpose of the study is to aid policy makers responsible for transportation infrastructure including roads, rails, airports, and ports in incorporating potential impacts of sea-level rise in planning and design of new infrastructure and in maintenance and upgrade of existing infrastructure.

The report considers that the rising sea level, combined with the possibility of an increase in the number of hurricanes and other severe weather related incidents, could cause increased inundation and more frequent flooding of roads, railroads, and airports, and could have major consequences for port facilities and coastal shipping.

The GIS approach (US DOT, 2008) produces maps and statistics that demonstrate the location and quantity of transportation infrastructure that could be regularly inundated by sea-level rise and at risk to storm surge under a range of potential sea-level rise scenarios. The elevation data for the transportation facilities is the estimated elevation of the land upon which the highway or rail line is built.)

The three basic steps involved in the US DOT analysis help identify areas expected to be regularly inundated or that are at-risk of periodic flooding due to storm surge:

- Digital Elevation Models were used to evaluate the elevation in the coastal areas and to create tidal surfaces in order to describe the current and future predicted sea water levels.
- Land was identified that, without protection, will regularly be inundated by the ocean or is at risk of inundation due to storm surge under each sea-level rise scenario.

- Transportation infrastructure was identified that, without protection, will regularly be inundated by the ocean or be at risk of inundation due to storm surge under the given sea-level rise scenario.

The US DOT study compares current conditions (for 2000) to estimates of future conditions resulting from increases in sea level. The study examines the effects of a range of potential increases in sea level up to 59 centimeters (cm). The estimates of increases in sea level are based upon two sources: (1) the range of averages of the Atmosphere-Ocean General Circulation Models for all 35 SRES (Special Report on Emission Scenarios), as reported in Figure 11.12[18] from the IPCC Third Assessment Report and (2) the highest scenario (59 cm) that corresponds with the highest emission scenario modeled by the IPCC Fourth Assessment Report (Meehl *et al.*, 2007).

As noted above, the US DOT study was not intended to create a new estimate of future sea levels or to provide a detailed view of a particular area under a given scenario; similarly, the results should not be viewed as predicting the specific timing of any changes in sea levels. The inherent value of this study is the broad view of the subject and the overall estimates identified. Due to the overview aspect of the US DOT study, and systematic and value uncertainties in the involved models, this US DOT analysis appropriately considered sea-level rise estimates from the IPCC reports as uniform sea-level rise estimates, rather than estimates for a particular geographic location. The confidence stated by IPCC in the regional distribution of sea-level change is *low*, due to

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

significant variations in the included models; thus, it would be inappropriate to use the IPCC model series to estimate local changes. Local variations, whether caused by erosion, subsidence (sinking of land) or uplift, local steric (volumetric increase in water due to thermal expansion) factors or even coastline protection, were not considered in this study[19]. Given the analysis and cautionary statements presented in Chapter 2 regarding using the USGS National Elevation Data (NED) with small increments of sea-level rise as used in this US DOT study, only representative statistical estimations are presented here for just the largest 59-cm scenario. Because the 59-cm sea-level rise scenario is within the statistical uncertainty of the elevation data, the statistics are representative of the types of analyses that could be done if accurate elevation data were available.

The study first estimates the areas that would be regularly inundated or at risk during storm conditions, given nine potential scenarios of sea-level rise. It defines regularly inundated areas or base sea level as NOAA’s mean higher high water (MHHW) for 2000. The regularly inundated areas examined are the regions of the coast that fall between MHHW in 2000 and the adjusted MHHW levels (MHHW in 2000 plus for several scenarios up to 59 cm). For at-risk areas or areas that could be affected by storm conditions, the study uses a base level of NOAA’s highest observed water levels (HOWL) for 2000, and adjusts this upwards based on the nine sea-level rise scenarios. The at-risk areas examined are those areas falling between the adjusted MHHW levels and the adjusted HOWL levels.

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[19] It is recognized that protection such as bulkheads, seawalls or other protective measures may exist or be built that could protect specific land areas but, due to the overview nature of this study, they were not included in the analysis.

A sample of output tables from the US DOT study are shown in Table 7.7, which covers the state of Virginia. The numerical values for length and area in Tables 7.7 and 7.8 have been rounded down to the nearest whole number to be conservative in the estimates for lengths and areas at risk. This was done to avoid overstating the estimates as there are no estimates of uncertainty or error in the numbers presented.

Table 7.7 A representative output table for Virginia showing estimates of regularly inundated and at-risk areas and lengths under the 59 centimeter (cm) scenario, the highest level examined in the U.S. Department of Transportation (US DOT) study. The percent affected represent the proportion for the entire state, not only coastal areas (From US DOT, 2008). The reported numbers are subject to the caveat given at the end of Section 7.2.

State of Virginia Statistics	For a 59-cm rise in sea level					
	Regularly Inundated		At-Risk to Storm Surge		Total	
By Length in Kilometers (km)	Length (km)	Percent Affected	Length (km)	Percent Affected	Length (km)	Percent Affected
Interstates	7	0%	16	1%	23	1%
Non-Interstate Principal Arterials	12	0%	62	1%	74	2%
NHS Minor Arterials	2	0%	9	0%	11	0%
National Highway System (NHS)	22	0%	64	1%	86	2%
Rails	19	0%	64	1%	83	1%
By Area in Hectares	Area (Hectares)	Percent Affected	Area (Hectares)	Percent Affected	Area (Hectares)	Percent Affected
Ports	60	11%	132	24%	192	35%
Airport Property	277	2%	365	3%	642	4%
Airport Runways	29	2%	37	3%	66	5%
Total Land Area Affected	68,632	1%	120,996	1%	189,628	2%

Table 7.7 indicates there is some transportation infrastructure at risk under the 59-cm sea level rise scenario. Less than 1 percent (7 kilometers [km] of interstates, 12 km of non-interstate principal arterials) of the Virginia highways examined in the US DOT study would be regularly inundated, while an additional 1 percent (16 km of interstates, 62 km

of non-interstate principal arterials) could be affected by storm conditions. It should be noted that these percentages are given as a percentage of the total for each state, not only for coastal counties.

Table 7.8 provides the areas and percent of total areas affected of the various regularly inundated and at-risk transportation categories for the US DOT (2008) 59-cm sea-level rise scenario for Washington, D.C., Virginia, Maryland, and North Carolina.

Table 7.8 Summary of estimated areas and lengths for the total of regularly inundated and at risk infrastructure combined for a 59 centimeters (cm) increase in sea-level rise (based on US DOT, 2008). The reported numbers are subject to the caveat given at the end of Section 7.2.

Total, Regularly Inundated and At Risk								
For a 59-cm increase in sea level	Washington, D.C.		Virginia		Maryland		North Carolina	
By Length in Kilometers(km)	Length (km)	% Affected	Length (km)	% Affected	Length (km)	% Affected	Length (km)	% Affected
Interstates	1	5%	25	1%	2	0%	1	0%
Non-Interstate Principal Arterials	7	4%	75	2%	21	1%	130	2%
Minor Arterials	0	0%	11	0%	66	4%	209	4%
National Highway System (NHS)	7	5%	87	2%	19	1%	305	4%
Rails	3	5%	84	1%	44	2%	105	1%
By Area in hectares	Hectares	% Affected	Hectares	% Affected	Hectares	% Affected	Hectares	% Affected
Ports	n/a	n/a	192	35%	120	32%	88	47%
Airport Property	n/a	n/a	642	4%	59	1%	434	3%
Airport Runways	n/a	n/a	66	5%	1	0%	27	2%
Total Land Area Affected	968	6%	189,628	2%	192,044	8%	743,029	6%

Based on the small percentage (1 to 5 percent) statistics in Table 6.8, the combination of rising sea level and storm surge appears to have the potential to affect only a small portion of highways and roads across the region. However, because these transportation systems are basically networks, just a small disruption in one portion could often be sufficient to have far-reaching effects, analogous to when a storm causes local closure of a major airport, producing ripple effects nation-wide due to scheduling and flight connections and delays. Local flooding could have similar ripple effects in a specific transportation sector.

North Carolina appears slightly more vulnerable to regular inundation due to sea-level rise, both in absolute terms and as a percentage of the state highways: less than 1 percent of interstates (0.3 km), 1 percent of non-interstate principal arterials (59 km) and 2 percent of National Highway System (NHS) minor arterials (93 km) in the state would be regularly inundated given a sea-level rise of 59 cm. This US DOT study focuses on larger roads but there are many miles of local roads and collectors that could also be affected. In general, areas at risk to storm surge are limited. Washington, D.C. shows the greatest vulnerability on a percentage basis for both interstates and NHS roads for all sea-level rise scenarios examined.

Please refer to the US DOT study for complete results, at:
<http://climate.dot.gov/publications/potential_impacts_of_global_sea_level_rise/index.html>

CHAPTER 7 REFERENCES

Bin, P., C. Dumas, B. Poulter, and J. Whitehead, 2007: *Measuring the Impacts of Climate Change on North Carolina Coastal Resources.* Department of Economics, Appalachian State University, Boone, NC, 91 pp. <http://econ.appstate.edu/climate/ >

CCSP (Climate Change Science Program), 2008: *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I.* [Savonis, M.J., V.R. Burkett and J.R. Potter (eds.)]. Climate Change Science Program Synthesis and Assessment Product 4.7. U.S. Department of Transportation, Washington DC, 445 pp.

Crossett, K.M., T.J. Culliton, P.C. Wiley, and T.R. Goodspeed, 2004: *Population Trends along the Coastal United States 1980-2008*. NOAA National Ocean Service, Special Projects Office, [Silver Spring, MD], 47 pp.

Crowell, M., S. Edelman, K. Coulton, and S. McAfee, 2007: How many people live in coastal areas? *Journal of Coastal Research*, **23(5)**, iii-vi.

GeoLytics, 2001: *CensusCD 2000.* Version 1.1. GeoLytics, Inc., East Brunswick, NJ.

Gornitz, V., S. Couch, and E.K. Hartig, 2001: Impacts of sea level rise in the New York City metropolitan area. *Global and Planetary Change*, **32(1)**, 61-88.

Jacob, K., V. Gornitz, and C. Rosenzweig, 2007: Vulnerability of the New York City metropolitan area to coastal hazards, including sea-level rise: Inferences for urban coastal risk management and adaptation policies. In: *Managing Coastal Vulnerability*. [McFadden, L., R.J. Nicholls, and E.C. Penning-Rowsell (eds.)]. Elsevier, Amsterdam and Oxford, pp. 139-156.

Kafalenos, R.S., K.J. Leonard, D.M. Beagan, V.R. Burkett, B.D. Keim, A. Meyers, D.T. Hunt, R.C. Hyman, M.K. Maynard, B. Fritsche, R.H. Henk, E.J. Seymour, L.E. Olson, J.R. Potter, and M.J. Savonis, 2008: What are the implications of climate change and variability for Gulf Coast transportation? In: *Impacts of Climate*

Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I. [Savonis, M.J., V.R. Burkett, and J.R. Potter (eds.)]. Climate Change Science Program Synthesis and Assessment Product 4.7. U.S. Department of Transportation, Washington DC, [104 pp.]

Kleinosky, L.R., B. Yarnal, and A. Fisher, 2006: Vulnerability of Hampton Roads, Virginia to storm-surge flooding and sea level rise. *Natural Hazards,***40(1)**, 43-70.

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.)]. Cambridge University Press, Cambridge, UK, and New York, pp. 747-845.

Mennis, J., 2003: Generating surface models of population using dasymetric mapping. *Professional Geographer*, **55(1)**, 31-42.

NOAA (National Oceanic and Atmospheric Administration), 2000: *Tide and Current Glossary*. NOAA National Ocean Service, Silver Spring, MD, 29 pp. <http://tidesandcurrents.noaa.gov/publications/glossary2.pdf>

NOAA (National Oceanic and Atmospheric Administration), 2005: *Microwave Air Gap-Bridge Clearance Sensor Test, Evaluation, and Implementation Report*. NOAA technical report NOS CO-OPS 042. NOAA National Ocean Service Ocean Systems Test and Evaluation Program, Silver Spring, MD, 111 pp.

NOAA (National Oceanic and Atmospheric Administration), 2008: *The Physical Oceanographic Real-Time System (PORTS).* [Website] <http://tidesandcurrents.noaa.gov/ports.html>

Titus, J.G. and P. Cacela, 2008: Uncertainty ranges associated with EPA's estimates of the area of land close to sea level. Section 1.3b in: *Background Documents Supporting Climate Change Science Program Synthesis and Assessment Product 4.1: Coastal Elevations and Sensitivity to Sea Level Rise* [Titus, J.G. and E.M. Strange (eds.)]. EPA 430R07004. U.S. Environmental Protection Agency, Washington, DC, pp. 69-133. <http://epa.gov/climatechange/effects/coastal/background.html>

Titus, J.G. and J. 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. Section 1.1 in: *Background Documents Supporting Climate Change Science Program Synthesis and Assessment Product 4.1: Coastal Elevations and Sensitivity to Sea Level Rise* [Titus, J.G. and E.M. Strange (eds.)]. EPA 430R07004. U.S. Environmental Protection Agency, Washington, DC, pp. 2-44.

U.S. Census Bureau, 2000: *United States Census 2000*. [Website] U.S. Census Bureau, Washington, DC. <http://www.census.gov/main/www/cen2000.html>

U.S. Census Bureau, 2007: *American FactFinder Glossary*. [U.S. Census Bureau, Washington, DC.] <http://factfinder.census.gov/home/en/epss/glossary_a.html>

US DOT (Department of Transportation), 2002**:** *The Potential Impacts of Climate Change on Transportation*, Workshop Proceedings; J. Titus: Does Sea Level Rise matter to Transportation along the Atlantic Coast? October 1-2, 2002, Summary and Discussion Papers. <http://www.epa.gov/climatechange/effects/downloads/Transportation_Paper.pdf >

US DOT, 2008: *The Potential Impacts of Global Sea Level Rise on Transportation Infrastructure, Phase 1 - Final Report: the District of Columbia, Maryland, North Carolina and Virginia*. Center for Climate Change and Environmental Forecasting, U.S. Department of Transportation, Washington DC.

USFWS (U.S. Fish and Wildlife Service), 2007: *National Wetlands Inventory*. [web site] U.S Fish and Wildlife Service, Arlington, VA. <http://www.fws.gov/nwi/>

USGS (U.S. Geological Survey), 2001: *National Land Cover Database 2001*. U.S. Geological Survey, Sioux Falls, SD. <http://www.mrlc.gov/mrlc2k_nlcd.asp>

Chapter 8. Public Access

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KEY FINDINGS

- The Public Trust Doctrine provides access along the shore below mean high water, but it does not include the right to cross private property to reach the shore. Therefore, access *to* the shore varies greatly, depending on the availability of roads and public paths to the shore.
- Rising sea level alone does not have a significant impact on either access to the shore or access along the shore; however, responses to sea-level rise can decrease or increase access.
- Shoreline armoring generally eliminates access along estuarine shores, by eliminating the intertidal zone along which the public has access. New Jersey has regulatory provisions requiring shorefront property owners in some urban areas to provide alternative access inland of new shore protection structures. Other mid-Atlantic states lack similar provisions to preserve public access.
- Beach nourishment has minimal impact in areas with ample access; however, it can increase access in areas where public access is restricted. Federal and state policies generally require public access to and along a shore before providing subsidized beach nourishment. In several communities, property owners have assigned public access easements in return for beach nourishment.

Responses based on allowing shores to retreat generally have minimal impact on public access to and along the shore.

8.1 INTRODUCTION

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

This Chapter examines the impacts of sea-level rise on public access to the shore and describes existing public access to the shore (Section 8.2), the likely impacts of shoreline changes (Section 8.3), and how responses to sea-level rise might change public access (Section 8.4) The focus of this Chapter is on the public's legal right to access the shore, not on the transportation and other infrastructure that facilitates such access[20].

8.2 EXISTING PUBLIC ACCESS AND THE PUBLIC TRUST DOCTRINE

The right to access tidal waters and shores is well established. Both access to and ownership of tidal wetlands and beaches is defined by the "Public Trust Doctrine", which is part of the common law of all the mid-Atlantic states. According to the Public Trust

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[20] Chapter 7 discusses impacts on transportation infrastructure.

Doctrine, navigable waters and the underlying lands were publicly owned at the time of statehood and remain so today.

The Public Trust Doctrine is so well established that it often overrides specific governmental actions that seem to transfer ownership to private parties (Lazarus, 1986; Rose, 1986). Many courts have invalidated state actions that extinguished public ownership or access to the shore (*Illinois Central R.R. v. Illinois; Arnold v. Mundy*; see also Slade, 1990*)*. Even if a land deed states that someone's property extends into the water, the Public Trust Doctrine usually overrides that language and the public still owns the shore[21]. In those cases when government agencies do transfer ownership of coastal land to private owners, the public still has the right to access along the shore for fishing, hunting, and navigation, unless the state explicitly indicates an intent to extinguish the public trust (Lazarus, 1986; Slade, 1990).

Figure 8.1 illustrates some key terminology used in this Chapter. Along sandy shores with few waves, the wet beach lies between *mean high water* and *mean low water*. (Along shores with substantial waves, the beach at high tide is wet inland from the mean high water mark, as waves run up the beach.) The *dry beach* extends from approximately mean high water inland to the seaward edge of the dune grass or other terrestrial plant life, sometimes called the *vegetation line* (Slade, 1990). The dune grass generally extends inland from the point where a storm in the previous year struck with sufficient force to erode the vegetation (Pilkey, 1984), which is well above mean high water. Along marshy

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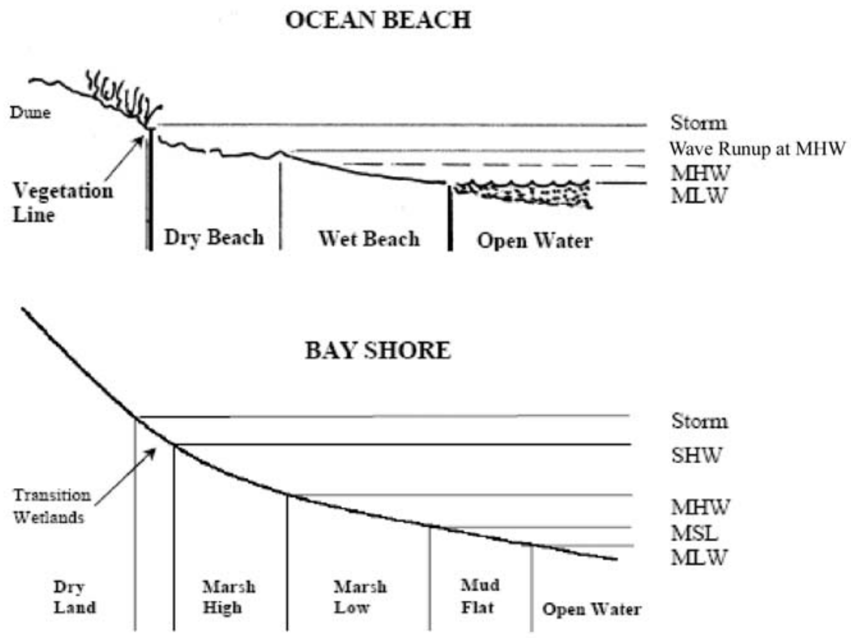
[21] The "mean low water states" (i.e., Virginia, Delaware, and Pennsylvania), are an exception. See Figure 8.2.

shores, mudflats are found between mean low water and mean sea level, *low marsh* is found between mean sea level and mean high water, and *high marsh* extends from mean high water to *spring high water*. Collectively, the lands between mean high water and mean low water (mudflats, low marsh, and wet beaches) are commonly known as *tidelands*.



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

Figure 8.1 Legal and geological tideland zonation. The area below mean high water is usually publicly owned, and in all cases is subject to public access for fishing and navigation. Along the ocean, the dry beach above mean high water may be privately owned; however, in several states the public has an easement. Along the bay, the high marsh above mean high water is also privately owned, but wetland protection laws generally prohibit or discourage development.

The Public Trust Doctrine includes these wetlands and beaches because of the needs associated with hunting, fishing, transportation along the shore, and landing boats for rest or repairs (Figure 8.2). In most states, the public owns all land below the high water mark (Slade, 1990) which is generally construed as mean high water. The precise boundary varies in subtle ways from state to state. The portion of the wet beach inland of mean high water resulting from wave runup has also been part of the public trust lands in some cases (see *e.g.*, *State v. Ibbison* and Freedman and Higgins [undated]). Thus, in general, the public trust includes mudflats, low marsh, and wet beach, while private parties own the high marsh and dry beach (Figure 8.3). Nevertheless, Figure 8.4.shows that there are some exceptions. In Pennsylvania, Delaware, and Virginia, the publicly owned land extends only up to the low water mark (Slade, 1990). In New York, by contrast, the inland extent of the public trust varies; in some areas the public owns the dry beach as well[22]. The public has also obtained ownership to some beaches through government purchase, land dedication by a developer, or other means (see Slade 1990; Figure 8.5).

Figure 8.2. Traditional purposes of the Public Trust Doctrine include fishing and transportation along the shore. (a) New Jersey side of Delaware River, below Delaware Memorial Bridge (March 2003). (b) Beach provided primary access to homes along the beach at Surfside, Texas (May 2003).

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

Figure 8.3. Privately owned dunes adjacent to publicly owned intertidal beach. Southold, New York. (September 2006).

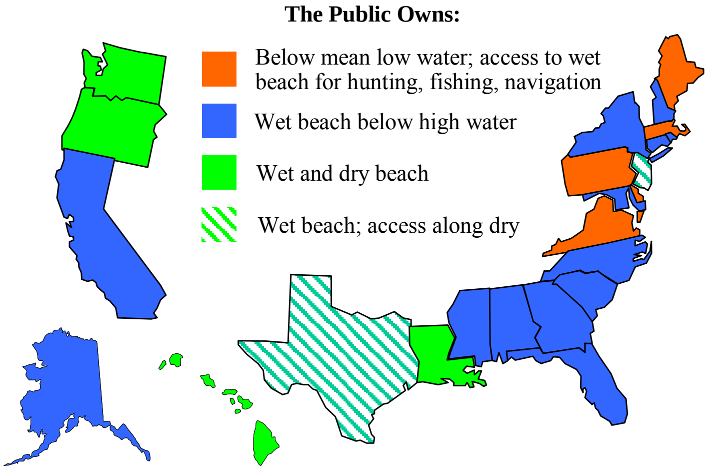


Figure 8.4 The public's common law interest in the shores of various coastal states. Source: Titus (1998)

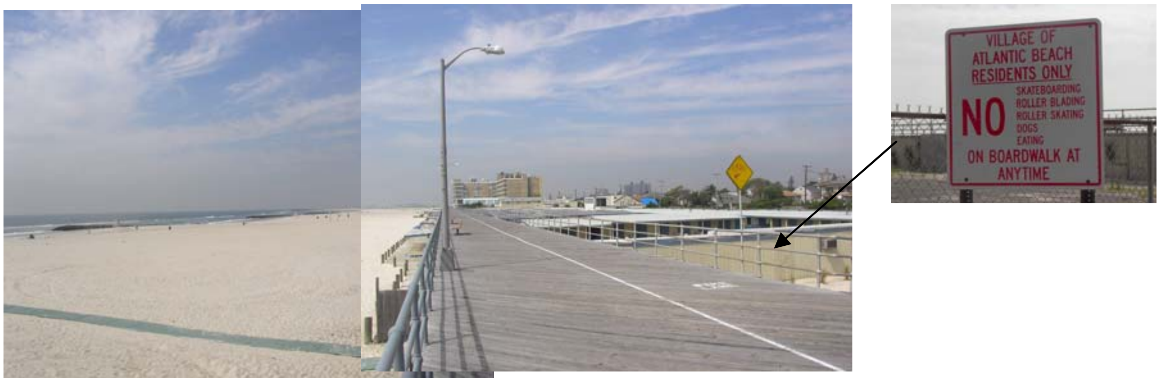


Figure 8.5 Public beach owned by local government. Beaches that are owned by local governments sometimes have access restrictions for nonresidents. Atlantic Beach, New York (September, 2006).

Ownership, however, is only part of the picture. In Pennsylvania, Delaware, and Virginia, the Public Trust Doctrine provides an easement along the tidelands for hunting, fishing, and navigation. In New Jersey, the Public Trust Doctrine includes access along the *dry* part of the beach for recreation, as well as the traditional public trust purposes (*Matthews v. Bay Head*). Other states have gradually obtained easements for access along some dry beaches either through purchases or voluntary assignment by the property owners in return for proposed beach nourishment. The federal policy precludes funding for beach nourishment unless the public has access (USACE, 1996). Some state laws specify that any land created with beach nourishment belong to the state (*e.g.*, MD. CODE ANN., NAT. RES. II 8-1103 [1990]).

The right to access *along* the shore does not mean that the public has a right to cross private land to get *to* the shore. Unless there is a public road or path to the shore, access along the shore is thus only useful to those who either reach the shore from the water or have permission to cross private land. Although the public has easy access to most ocean beaches and large embayments like Long Island Sound and Delaware Bay, the access points to the shores along most small estuaries are widely dispersed (*e.g.*, Titus, 1998). However, New Jersey is an exception: its Public Trust Doctrine recognizes access *to* the shore in some cases (*Matthews v. Bay Head*); and state regulations require new developments with more than three units along all tidal waters to include public access to the shore (NJAC 7:7E-8.11 [d-f]). Given the federal policy promoting access, the lack of access to the shore has delayed several beach nourishment projects. To secure the funding, many communities have improved public access to the shore, not only with more access ways to the beach, but also by upgrading availability of parking, restrooms, and other amenities (*e.g.*, New Jersey, 2006).

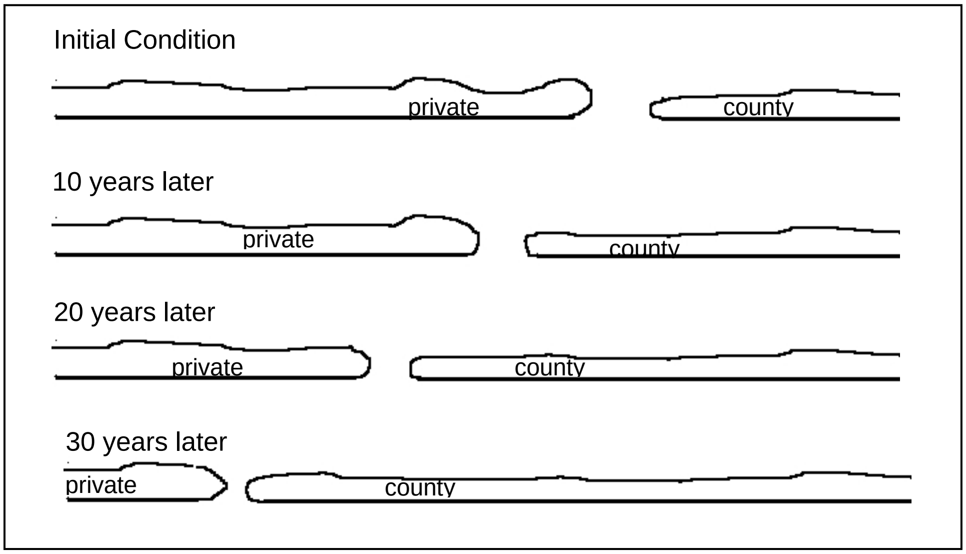
8.3 IMPACT OF SHORE EROSION ON PUBLIC ACCESS

The rule that property lines retreat whenever shores erode gradually has been part of the common law for over one thousand years (*County of St. Clair v. Lovingston*; *DNR v. Ocean City*), assuming that the shoreline change is natural. Therefore, as beaches migrate landward, the public's access rights to tidal wetlands and beaches do not change, they simply migrate landward along with the wetlands and beaches. Nevertheless, the area to which the public has access may increase or decrease, if sea-level rise changes the area of wetlands or beaches.

When riparian landowners caused the shorelines to advance seaward, the common law did not vest owners with title to land reclaimed from the sea, although legislatures sometimes have (ALR, 1941). If beach nourishment or a federal navigation jetty artificially creates new land, a majority of states (*e.g.*, MD. CODE ANN., ENVIR. 16-201) award the new land to the riparian owner if he or she is not responsible for creating the land (Slade, 1990); a minority of states (*e.g.*, *Garrett v. State of New Jersey;* N.C. Gen Stat §146-6[f]) vest the state public trust with the new land. Although these two approaches were established before sea-level rise was widely recognized, legal scholars have evaluated the existing rules in the analogous context of shore erosion (*e.g.*, Slade, 1990). Awarding artificially created land to the riparian owner has two practical advantages over awarding it to the state. First, determining what portion of a shoreline change resulted from some artificial causes, (*e.g.*, sedimentation from a jetty or a river diversion) is much more difficult than determining how much the shoreline changed when the owner filled some wetlands. Second, this approach prevents the state from depriving shorefront owners of their riparian access by pumping sand onto the beach and creating new land (*e.g.*, *Board of Public Works v. Larmar Corp*). A key disadvantage is that federal and state laws generally prevent the use of public funds to create land that accrues to private parties. Therefore, part of the administrative requirements of a beach nourishment project is to obtain easements or title to the newly created land. Obtaining those rights can take time, and significantly delayed a beach nourishment project at Ocean City, Maryland (Titus, 1998).

Sea-level rise causes shores to retreat both through inundation and erosion. Although the case law generally assumes that the shore is moving as a result of sediment being transported, inundation and shore erosion are legally indistinguishable. Among the causes of natural shoreline change, the major legal distinction has been between gradual and imperceptible shifts, and sudden shifts that leave land intact but on the other side of a body of water, often known as "avulsion". Shoreline erosion changes ownership; avulsion does not. If an inlet formed 200 meters (m) west of one's home during a storm after which an existing inlet 200 m east of the home closed, an owner would still own her home because this shoreline change is considered to be avulsion. But if the inlet gradually migrated 400 m west, entirely eroding the property but later creating land in the same location, all of the newly created land will belong to the owner to the east (see Figure 8.6). The public trust has the same rights of access to beaches created through avulsion as to beaches migrating by gradual erosion in New York (*People v. Steeplechase Park Co.*) and North Carolina (Kalo, 2005). In other states, the law is less clear (Slade, 1990).

Gradual inlet migration



Inlet breech followed by inlet closing

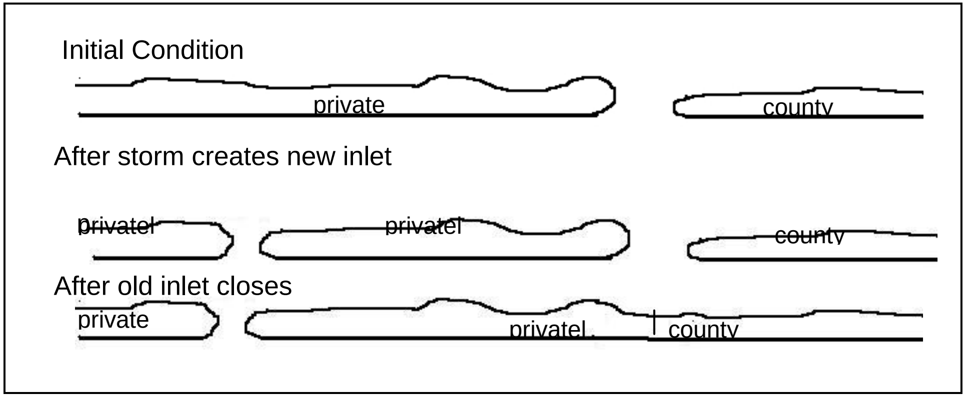


Figure 8.6 Impact of inlet migration and inlet breech on land ownership. In this example, the island to the west is privately owned while the island to the east is a county park.

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

8.4 IMPACT OF RESPONSES TO SEA-LEVEL RISE ON PUBLIC ACCESS

Although sea-level rise appears to have a small direct effect on public access to the shore, responses to sea-level rise can have a significant impact, especially in developed areas. Along developed bay beaches, by contrast, public access along the shore can be eliminated if the shorefront property owner erects a bulkhead, because the beach is eventually eliminated. A number of options are available for state governments that wish to preserve public access along armored shores, such as public purchases of the shorefront (Figure 8.7) and protecting public access in permits for shore protection structures. New Jersey requires pathways to be at least 5 m (16 feet [ft]) wide between the shore and new developments with more than three units along urban tidal rivers (NJAC 7.7E-8.11[e]; see also Section A1.D.2 in Appendix 1) and some other areas, and has a more general requirement to preserve public access elsewhere. (NJAC 7.7E-8.11 [d] [1]). However, single-family homes are generally exempt (NJAC 7.7E-8.11[f] [7])—and other mid-Atlantic states have no such requirements. Therefore, sea-level rise has reduced public access along many estuarine shores and is likely to do so in the future as well.

Figure 8.7 Public access along a bulkheaded shore. In North Beach, Maryland, one block of Atlantic Avenue is a walkway along Chesapeake Bay (May,2006).

Government policies related to beach nourishment, by contrast, set a minimum standard for public access (USACE, 1996), which often increases public access along the shore. Along the ocean shore from New York to North Carolina, the public does not have access along the dry beach under the Public Trust Doctrine (except in New Jersey)[23]. However, once a federal beach nourishment project takes place, the public gains access. Beach nourishment projects have increased public access *along* the shore in Ocean City, Maryland and Sandbridge (Virginia Beach), Virginia, where property owners had to provide easements to the newly created beach before the projects began (Titus, 1998; Virginia Marine Resources Commission, 1988).

Areas where public access *to* the beach is currently limited by a small number of access points include the area along the Outer Banks from Southern Shores to Corolla, North Carolina (NC DENR, 2008); northern Long Beach Township, New Jersey (USACE,

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[23] In some places, the public has obtained access through government purchase, land dedication by a developer, or other means. See Slade (1990).

1999); and portions of East Hampton, South Hampton, Brookhaven, and Islip along the South Shore of Long Island, New York (Section A1.A.2 in Appendix 1). In West Hampton, landowners had to provide six easements for perpendicular access from the street to the beach in order to meet the New York state requirement of public access every one-half mile (see Section A1.A.2 in Appendix 1). A planned $71 million beach restoration project for Long Beach Island has been stalled (Urgo, 2006), pending compliance with the New Jersey state requirement of perpendicular access every one-quarter mile (USACE, 1999). An additional 200 parking spaces for beachgoers must also be created in Northern Long Beach Township (USACE, 1999). Private communities along Delaware Bay have granted public access to the beaches in return for state assistance for beach protection (Beaches 2000 Planning Group, 1988).

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

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

CHAPTER 8 REFERENCES

* Indicates non-peer reviewed literature; available upon request

ALR, 1941: Annotation: Waters: rights in respect of changes by accretion or reliction due to artificial conditions. *American Law Review*, **134**, 467-472.

Arnold v. Mundy, 6 N.J.L. 1 (1821)

Beaches 2000 Planning Group, 1988: Beaches 2000: Report to the Governor [Delaware], June 21, 1988.

Board of Pub. Works v. Larmar Corp., 277 A.2d 427, 436 (Md. 1971)

County of St. Clair v. Lovingston, 90 U.S. (23 Wall.) 46, 66-69 (1874) (quoting the Institutes of Justinian, Code Napoleon, and Blackstone for the universal rule that a boundary shifts with the shore)

DNR (Department of Natural Resources) **v. Ocean City,** 332 A.2d 630-638 (Md. 1975)

Freedman, J. and M. Higgins, Undated: *What Do You Mean by High Tide? The Public Trust Doctrine in Rhode Island.* Rhode Island Coastal Resources Management Council, Wakefield, 5 pp. <http://www.crmc.state.ri.us/presentations/presentations/wdymbht.pdf>

Garrett v. State [of New Jersey]. *118 N.J. Super. 594 (Ch. Div. 1972),* 289 A.2d 542 (N.J. Super 1972).

Illinois Central R.R. v. Illinois, 146 U.S. 387 (1982)

Kalo, J.J., 2005: North Carolina oceanfront property and public waters and beaches: the rights of littoral owners in the twenty-first century. *North Carolina Law Review*, **83**, 1427-1506.

Lazarus, R.J., 1986: Changing conceptions of property and sovereignty in natural resources: questioning the Public Trust Doctrine. *Iowa Law Review*, **71**, 631.

Matthews v. Bay Head Improvement Association, 471 A.2d 355-358 (N.J. 1984)

New Jersey, 2006: *Highlights of the Public Access Proposal*. New Jersey Department of Environmental Protection Coastal Management Program, 4 pp. <http://www.nj.gov/dep/cmp/access/pa_rule_highlights.pdf>

NC DENR (North Carolina Department of Environment and Natural Resources), 2008: *Public Beach & Waterfront Access Interactive Mapping.* <http://dcm2.enr.state.nc.us/Access/sites.htm>

NRC (National Research Council), 2007: *Mitigating Shore Erosion Along Sheltered Coasts*. National Academies Press, Washington DC, 188 pp.

People v. Steeplechase Park Co., 82 Misc 247, 255-256; 143, N.Y.S. 503, 509

Pilkey, O.H., Jr. (ed.), 1984: *Living with the East Florida Shore*. Duke University Press, Durham, NC, 259 pp.

Rhode Island CRMC (Coastal Resources Management Council), 2007: Coastal Resources Management Program, as Amended (a.k.a. the "Red Book"). State of Rhode Island Coastal Resources Management Council, Providence, RI. <http://www.crmc.state.ri.us/regulations/programs/redbook.html>

Rose, C., 1986: The comedy of the commons: custom, commerce, and inherently public property. *University of Chicago Law Review*, **53**, 711, 715-723.

Slade, D.C., 1990: Lands, waters and living resources subject to the Public Trust Doctrine. In: *Putting the Public Trust Doctrine to Work*. Coastal States Organization, Washington, DC, pp. 13, 59.

State v. Ibbison. 448 A.2d 728 (Rhode Island, 1982).**Titus**, J.G., 1998: Rising seas, coastal erosion, and the takings clause: how to save wetlands and beaches without hurting property owners. *Maryland Law Review*, **57(4)**, 1277-1399.

Titus, J.G., 1998: Rising seas, coastal erosion and the taking clause: how to save wetlands and beaches without hurting property owners. *Maryland Law Review*, **57(4)**, 1277-1399.

* **Urgo**, J.L., 2006: A standoff over sand: A state beach project requires more public access, but in Loveladies and North Beach, it's meeting some resistance. *Philadelphia Inquirer*, June 11, 2006.

USACE (U.S. Army Corps of Engineers), 1996: *Digest of Water Resources Policies and Authorities 14-1: Shore Protection*. EP 1165-2-1, U.S. Army Corps of Engineers, Washington, DC.

USACE (U.S. Army Corps of Engineers), 1999: *Barnegat Inlet to Little Egg Inlet*. Final Feasibility Report and Integrated Final Environmental Impact Statement.

USACE (U.S. Army Corps of Engineers), and New Jersey Department of Environmental Protection, 1999: *Barnegat Inlet to Little Egg Inlet, Final Feasibility and Integrated Final Environmental Impact Statement*.

Virginia Marine Resources Commission, 1988: *Criteria for the Placement of Sandy Dredged Material along Beaches in the Commonwealth*. Regulation VAC 20-400-10 et seq. <http://www.mrc.virginia.gov/regulations/fr400.shtm>

Chapter 9. Coastal Flooding, Floodplains and Coastal Zone Management Issues

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KEY FINDINGS

- Rising sea level increases the vulnerability of coastal areas to flooding. The higher sea level provides a higher base for storm surges to build upon. It also diminishes the rate at which low-lying areas drain, thereby increasing the risk of flooding from rainstorms. Increased shore erosion can further increase flood damages by removing protective dunes, beaches, and wetlands, thus leaving previously protected properties closer to the water's edge. In addition to flood damages, many other effects, responses, and decisions are likely to occur during or in the immediate aftermath of severe storms. Beach erosion and wetlands loss often occur during storms, and the rebuilding phase after a severe storm often presents the best opportunity for developed areas to adapt to future sea-level rise.
- Coastal storms could have higher flooding potential in the future due to higher sea levels relative to the land.
- The most recent Federal Emergency Management Agency (FEMA) study on the potential effects of sea-level rise on the Nation’s flood insurance program was

published in 1991. Because of the uncertainties in the projections of potential changes in sea level at the time and the ability of the rating system to respond easily to a 0.3 meter rise in sea level, the 1991 FEMA study (FEMA, 1991) concluded that no immediate program changes were needed.

- The mid-Atlantic coastal zone management community is increasingly recognizing that sea-level rise is a high-risk coastal hazard as evidenced by the recent comprehensive analyses and studies needed to make recommendations for state policy formulation performed by Maryland.

9.1 INTRODUCTION

This Chapter examines the effects of sea-level rise on coastal floodplains and on coastal flooding management issues confronting the U.S. Federal Emergency Management Agency (FEMA), the floodplain management community, the coastal zone management community, coastal resource managers, and the public, including private industry. Sea-level rise is just one of numerous complex scientific and societal issues these groups face. There is also uncertainty in the local rate of sea-level change, which needs to be taken into account along with the interplay with extreme storm events (see Chapter 1). In addition, impacts of increased flooding frequency and extent on coastal areas can be significant for marine ecosystem health and human health in those areas (Boesch *et al.*, 2000). This Chapter provides a discussion of the current state of knowledge and provides assessments for a range of actions being taken by many state and federal agencies and other groups related to coastal flooding.

9.2 PHYSICAL CHARACTERISTICS

9.2.1 Floodplain

In general, a floodplain is any normally dry land surrounding a natural water body that holds the overflow of water during a flood. Because they border water bodies, floodplains have been popular sites to establish settlements, which subsequently become susceptible to flood-related disasters. Most management and regulatory definitions of floodplains apply to rivers; however, open-coast floodplains characterized by beach, dunes, and shrub-forest are also important since much of the problematic development and infrastructure is concentrated in these areas (see Chapter 3 for a detailed description of this environment).

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

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

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

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

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

Floodplains can support particularly rich ecosystems, both in quantity and diversity. These regions are called riparian zones or systems. Wetting of the floodplain soil releases an immediate surge of nutrients, both those left over from the last flood and those from the rapid decomposition of organic matter that accumulated since the last flood. Microscopic organisms thrive and larger species enter a rapid breeding cycle. Opportunistic feeders (particularly birds) move in to take advantage of these abundant populations. The production of nutrients peaks and then declines quickly; however, the surge of new growth endures for some time, thus making floodplains particularly valuable for agriculture. Markedly different species grow within floodplains compared to surrounding regions. For instance, certain riparian trees species (that grow in floodplains near river banks) tend to be very tolerant of root disturbance and thus tend to grow quickly, compared to different tree species growing in a floodplain some distance from a river.

9.3 POTENTIAL IMPACTS OF SEA-LEVEL RISE ON COASTAL FLOODPLAINS

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

With no human intervention, the hydrologic and hydraulic characteristics of coastal and river floodplain interactions will change with sea-level rise. Fundamentally, the floodplains will become increasingly vulnerable to inundation. In tidal areas, the tidal inundation characteristics of the floodplain may change with the range of tide and associated tidal currents increasing with sea-level rise. With this inundation, floodplains will be vulnerable to increased coastal erosion from waves, river and tidal currents, storm-induced flooding, and tidal flooding. Upland floodplain boundaries will be vulnerable to horizontal movement. Coastal marshes could be vulnerable to vertical buildup or inundation (see Chapter 4 for further discussion).

In a study for the state of Maine (Slovinsky and Dickson, 2006), the impacts of sea-level rise on coastal floodplains were characterized by marsh habitat changes and flooding implications. The coast of Maine has a significant spring tidal range of 2.6 to 6.7 meters (m) (8.6 to 22.0 feet [ft]), such that impacts of flooding are coupled with the timing of storms and the highest astronomical tides on top of sea-level rise. The study found that there was increasing susceptibility to inlet and barrier island breaches where existing breach areas were historically found, increased stress on existing flood-prevention infrastructure (levees, dikes, roads), and a gradual incursion of low marsh into high marsh with development of a steeper bank topography. On the outer coast, impacts included increased overwash and erosion.

In addition, the effects of significant local or regional subsidence of the land will add to the effects of sea-level rise on coastal floodplains. Regional areas with significant subsidence include the Mississippi River Delta region (AGU, 2006), the area around the entrance to the Chesapeake Bay (Poag, 1997), and local areas such as the Blackwater National Wildlife Refuge on the Eastern Shore of Maryland (Larsen *et al.*, 2004).

9.4 POTENTIAL EFFECTS OF SEA-LEVEL RISE ON THE IMPACTS OF COASTAL STORMS

The potential interaction among increased sea levels, storm surges, and upstream rivers is complex. The storm surge of any individual storm is a function of storm intensity defined by storm strength and structure, forward speed, landfall location, angle of approach, and local bathymetry and topography. However, the absolute elevation of the maximum water levels observed relative to the land during a storm (operationally defined as storm tides) are a combination of the storm surge defined above, plus the non-storm-related background water level elevations due to the stage of tide, the time of year (sea level varies seasonally), river flow, local shelf circulation patterns (such as the Gulf Loop Current/eddies and the El Niño-Southern Oscillation [especially on the west coast]). Storm surge "rides” on top of these other variations, including sea level rise (NOAA, 2008). Storm surge can travel several hundred kilometers up rivers at more than 40 kilometers (km) (25 miles [mi]) per hour, as on the Mississippi River, where storm surge generated by land-falling hurricanes in the Gulf of Mexico can be detected on stream gauges upstream of Baton Rouge, Louisiana, more than 480 km (300 mi) from the mouth of the river (Reed and Stucky, 2005).

Both NWS (for flood forecasting) and FEMA (for insurance purposes and land use planning) recognize the complexity of the interactions among sea-level rise, storm surge, and river flooding. For instance, NWS uses both a hurricane storm surge model (the Sea, Lakes, and Overland Surge from Hurricanes [SLOSH] model, Jelesnianski *et al.*, 1992) and a riverine hydraulic model (the Operational Dynamic Wave Model) to forecast effects of storm surge on river stages on the Mississippi River. The two models are coupled such that the output of the storm surge model is used as the downstream boundary of the river model. This type of model coupling is needed to determine the effects of sea-level rise and storm surge on riverine systems. Other modeling efforts are starting to take into account river and coastal physical process interactions, such as use of the two-dimensional hydrodynamic model (the Advanced Circulation Model or ADCIRC; Luettich *et al.*, 1992) on the Wacammaw River in South Carolina to predict effects of storm surge on river stages as far inland as Conway, 80 km (50 mi) from the Atlantic Ocean (Hagen *et al.*, 2004). These model coupling routines are becoming increasingly more common and have been identified as future research needs by such agencies as NOAA and the U.S. Geological Survey (USGS), as scientists strive to model the complex interactions between coastal and riverine processes. As sea level rises, these interactions will become ever more important to the way the coastal and riverine floodplains respond (Pietrafesa *et al.*, 2006).

9.4.1 Historical Comparison at Tide Stations

There is the potential for higher elevations of coastal flooding from coastal storms over time as sea level rises relative to the land. Looking at storms in historical context and accounting for sea level change is one way to estimate maximum potential storm water levels. For example, this assessment can be made by analyzing the historical record of flooding elevations observed at NOAA tide stations in the Chesapeake Bay. The following analysis compares the elevation of the storm tides for a particular storm at a particular tide station; that is from when it occurred historically to as if the same exact storm occurred today under the exact same conditions, but adjusted for relative sea level rise at that station. These comparisons are enabled because NOAA carefully tabulates water level elevations over time relative to a common reference datum that is connected to the local land elevations at each tide station. From this, relative sea level trends can be determined and maximum water level elevations recorded during coastal storms can be directly compared over the time period of record (Zervas, 2001). The relative sea level trend provides the numerical adjustment needed depending on the date of each storm.

The NOAA post-hurricane report (Hovis, 2004) on the observed storm tides of Hurricane Isabel assessed the potential effects of sea-level rise on maximum observed storm tides for four long-term tide stations in the Chesapeake Bay. Prior to Hurricane Isabel, the highest water levels reached at the NOAA tide stations at Baltimore, Maryland; Annapolis, Maryland; Washington, D.C.; and Sewells Point, Virginia occurred during the passage of an unnamed hurricane in August, 1933. At the Washington, D.C. station, the 1933 hurricane caused the third highest recorded water level, surpassed only by river floods in October 1942 and March 1936. Hurricane Isabel caused water levels to exceed the August 1933 levels at Baltimore, Annapolis and Washington, D.C. by 0.14, 0.31, and 0.06 meters (m), respectively. At Sewells Point, the highest water level from Hurricane Isabel was only 0.04 m below the level reached in August 1933. Zervas (2001) calculated sea-level rise trends for Baltimore, Annapolis, Washington, and Sewells Point of 3.12, 3.53, 3.13, and 4.42 millimeters (mm) per year, respectively. Using these rates, the time series of monthly highest water level were adjusted for the subsequent sea-level rise up to the year 2003. The resulting time series, summarized in Tables 9.1, 9.2, 9.3, and 9.4, indicate the highest level reached by each storm as if it had taken place in 2003 under the same conditions, thus allowing an unbiased comparison of storms. The purpose of Tables 9.1 through 9.4 is to show that the relative ranking of the flooding elevations from particular storm events changes at any given station once the adjustment for sea level trend is taken into account. The 1933 hurricane, especially, moves up in ranking at Baltimore and Washington, DC once adjusted for the local sea level trend. Hurricane Hazel moved up in ranking at Annapolis. If the 1933 hurricane occurred today under the same conditions, it would have had the highest water level of record at Baltimore, not Hurricane Isabel. Elevations are relative to the tidal datum of mean higher high water (MHHW). Noting the earlier discussion in this section on the operational difference between storm surge and the actual observed storm tide elevation, the tables suggest that, while not affecting intensity of storms and the resulting amplitude of storm surges, sea-level rise could increasingly add to the potential maximum water level elevations observed relative to the land during coastal storms.

Table 9.1 Five highest water levels for Baltimore, Maryland in meters above mean higher high water. Ranked first by absolute elevation and then ranked again after adjustment for sea level rise.

Absolute water level			Corrected for sea-level rise to 2003		
Event	Date	Elevation (m)	Event	Date	Elevation (m)
Hurricane Isabel	Sep 2003	1.98	Hurricane	Aug 1933	2.06
Hurricane	Aug 1933	1.84	Hurricane Isabel	Sep 2003	1.98
Hurricane Connie	Aug 1955	1.44	Hurricane Connie	Aug 1955	1.59
Hurricane Hazel	Oct 1954	1.17	Hurricane	Aug 1915	1.38
Hurricane	Aug 1915	1.11	Hur. Hazel	Oct 1954	1.32

Table 9.2 Five highest water levels for Annapolis, Maryland in meters above mean higher high water. Ranked first by absolute elevation and then ranked again after adjustment for sea level rise.

Absolute water level.			Corrected for sea-level rise to 2003		
Event	Date	Elevation (m)	Event	Date	Elevation (m)
Hurricane Isabel	Sep 2003	1.76	Hurricane Isabel	Sep 2003	1.76
Hurricane	Aug 1933	1.45	Hurricane	Aug 1933	1.69
Hurricane Connie	Aug 1955	1.08	Hurricane Connie	Aug 1955	1.25
Hurricane Fran	Sep 1996	1.04	Hurricane Hazel	Oct 1954	1.19
Hurricane Hazel	Oct 1954	1.02	Hurricane Fran	Sep 1996	1.06

Table 9.3 Five highest water levels for Washington, D.C. in meters above mean higher high water. Ranked first by absolute elevation and then ranked again after adjustment for sea level rise.

Absolute water level			Corrected for sea-level rise to 2003		
Event	Date	Elevation (m)	Event	Date	Elevation (m)
Flood	Oct 1942	2.40	Flood	Oct 1942	2.59
Flood	Mar 1936	2.25	Flood	Mar 1936	2.46
Hurricane Isabel	Sep 2003	2.19	Hurricane	Aug 1933	2.35
Hurricane	Aug 1933	2.13	Hurricane Isabel	Sep 2003	2.19
Flood	Apr 1937	1.70	Flood	Apr 1937	1.91

Table 9.4 Five highest water levels for Sewells Point, Virginia in meters above mean higher high water. Ranked first by absolute elevation and then ranked again after adjustment for sea level rise.

Absolute water level			Corrected for sea-level rise to 2003		
Event	Date	Elevation (m)	Event	Date	Elevation (m)
Hurricane	Aug 1933	1.60	Hurricane	Aug 1933	1.91

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

9.4.2 Typical 100-Year Storm Surge Elevations Relative to Mean Higher High Water within the Mid-Atlantic Region

A useful application of long-term tide gauge data is a return frequency analysis of the monthly and annual highest and lowest observed water levels. This type of analysis provides information on how often extreme water levels can be expected to occur (*e.g.*, once every 100 years, once every 50 years, once every 10 years?) On the East Coast and in the Gulf of Mexico, hurricanes and winter storms interact with the wide, shallow, continental shelf to produce large extreme storm tides. A generalized extreme value distribution can be derived for each station after correcting the values for the long-term sea-level trend (Zervas, 2005). Theoretical exceedance probability statistics give the 99-percent, 50-percent, 10-percent, and 1-percent annual exceedance probability levels. These levels correspond to average storm tide return periods of 1, 2, 10, and 100 years. The generalized extreme value analyses are run on the historical data from each tide station. Interpolating exceedance probability results away from the tide station location is not recommended as elevations of tidal datums and the extremes are highly localized. Figures 9.1 and 9.2 show the variations in these statistics along the mid-Atlantic coast. Figure 9.1 shows exceedance elevations above local mean sea level (LMSL) at mid-Atlantic stations relative to the 1983 to 2001 National Tidal Datum Epoch (NTDE).

Figure 9.2 shows the same exceedance elevations, except the elevations are relative to mean higher high water (MHHW) computed for the same 1983 to 2001 NTDE.

In Figure 9.1, the elevations relative to LMSL are highly correlated with the range of tide at each station (Willets Point, New York has a very high range of tide, 2.2 m), except for the 1-percent level at Washington D.C., which is susceptible to high flows of the Potomac River. Due to their varying locations, the 1-percent elevation level varies the most among the stations. Figure 9.2 shows a slightly geographically decreasing trend in the elevations from north to south.

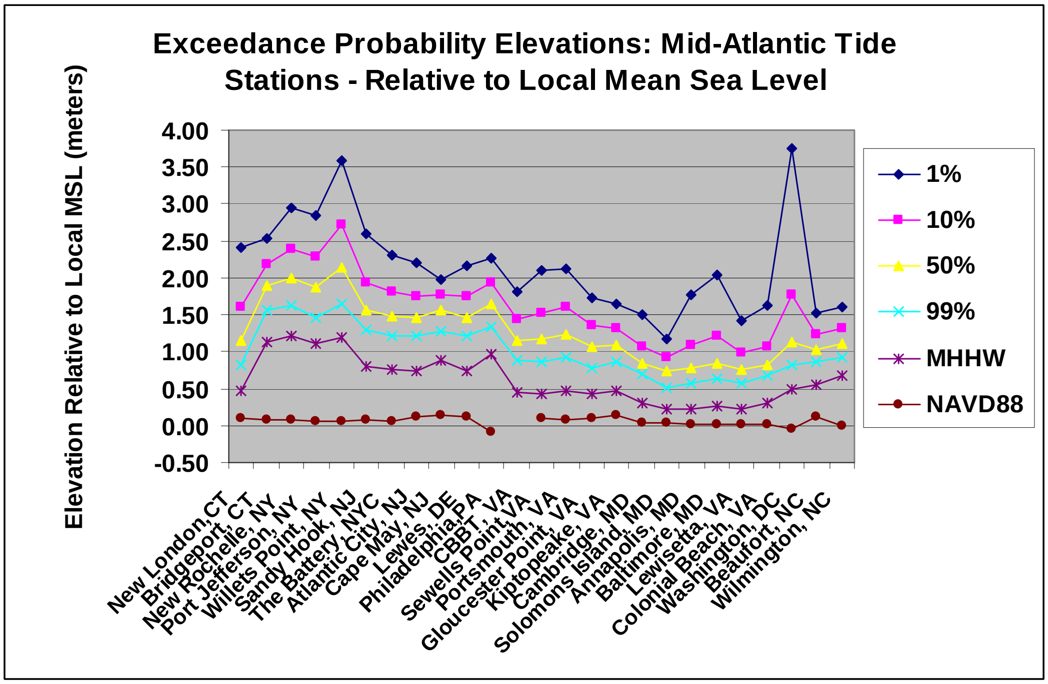


Figure 9.1 Exceedance probabilities for mid-Atlantic tide stations relative to local mean sea level.

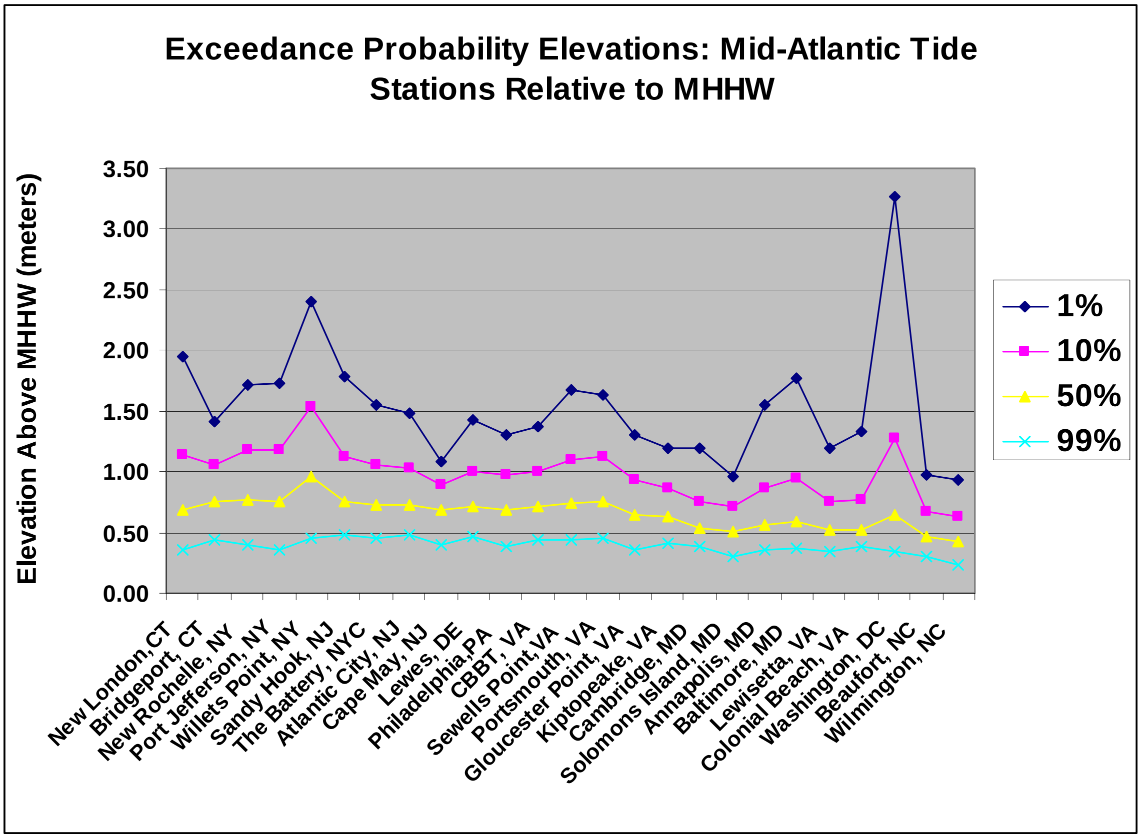


Figure 9.2 Exceedance probabilities at mid-Atlantic tide stations relative to mean higher high water.

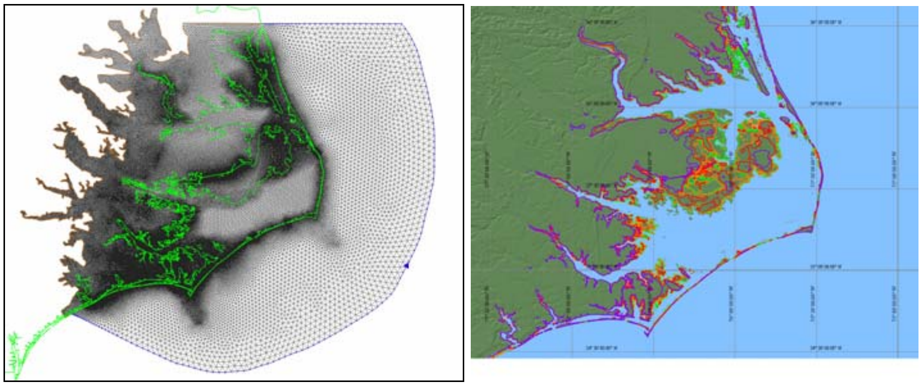
Examining the effects of sea-level rise on the highest water level during a hurricane or coastal storm does not provide a complete picture because the impacts of sea-level rise on the duration of the inundation can be as important as the maximum height. Sea-level rise, coupled with any increased frequency of extra-tropical storms (nor'easters), may also increase the durations of inundation from extra-tropical storms (NOAA, 1992). For instance, some of the most severe impacts of nor'easters are generally felt in bays where water can get in but not out for several days as the storms slowly transit parallel to the coast.

Other federal agencies, such as NOAA, have been sponsoring applied research programs to bring an integrated approach to understanding the effects of sea-level rise into operations. One such study on the ecological effects of sea-level rise is discussed in Box 9.1 (NOAA, 2007), which is due to come out with a final report in 2009.

Box 9.1 Ecological Effects of Sea Level Rise–NOAA North Carolina Study

An ongoing National Oceanic and Atmospheric Administration (NOAA)-sponsored study on the ecological effects of sea-level rise is just one example of the type of integrated applied research that will be required to fully describe the effects of sea-level rise in the coming century. The study incorporates and integrates features including high resolution data of the littoral zone, geography, ecology, biology, and coastal process studies in a region of concern. A complete overview of the NOAA program can be found at: <http://www.cop.noaa.gov/stressors/climatechange/current/sea_level_rise.html>

The North Carolina pilot study demonstrates the ability to design a meaningful product for regional coastal managers that integrates capabilities in vertical reference frames, mapping, and modeling, with targeted applied research led by the local academic marine science research community. The applied research program is designed to help coastal managers and planners better prepare for changes in coastal ecosystems due to land subsidence and sea-level rise. Starting with the southern Pamlico Sound, the approach is to simulate projected sea-level rise using a coastal flooding model that combines a hydrodynamic model (see Figure 9.1 [a]) of water levels with a high resolution digital elevation model (DEM). When completed, the coastal flooding model will be used to simulate long-term rises in water levels (see Figure 9.1 [b]). Sub-models will then be developed to forecast ecological changes in coastal wetland and forested areas, and will be integrated with the coastal flooding model. The final goal of the program is to produce mapping and modeling tools that allow managers and planners to see projected shoreline changes and to display predictions of ecosystem impacts. Using these ecological forecasts, proactive mitigation will be possible.



Box Figure 9.1 (a) The Coastal Flooding Model grid and (b) one preliminary result of shoreline change due to various sea-level rise scenarios.

9.5 FLOODPLAIN MAPPING AND SEA-LEVEL RISE

A nationwide study was performed by FEMA (1991) (see Box 9.2) in which costs for remapping floodplains were estimated at $150,000 per county (in 1991 dollars) or $1,500 per map panel (the standard map presentation used by FEMA). With an estimated 283 counties (5,050 map panels) potentially in need of remapping, the total cost of restudies and remapping was estimated at $30 million (in 1991). Based on this study and assuming that the maps are revised on a regular basis, such an undertaking today would cost about $46.5 million. The 1991 study concluded that "there are no immediate program changes needed" (FEMA, 1991).

At present, FEMA periodically revises Flood Insurance Rate Maps (FIRMs) to reflect new engineering, scientific, and imagery data. In addition, under their Map Modernization and post-Map Modernization Programs, FEMA intends to assess the integrity of the flood hazard data by reviewing the flood map inventory every five years. Where the review indicates the flood data integrity has degraded the flood maps (due to outdated data and known changes in hydrology and floodplain elevation since the last maps were issued), updates will be provided or new studies will be performed. Whenever an update or remap of coastal areas is made, changes that had occurred in the interim due to sea-level rise will be accounted for. An upcoming Impact of Climate Change on the National Flood Insurance Program study (scheduled to begin at the end of fiscal year 2008 and last 1.5 years) may come up with different conclusions than the 1991 study and cause FEMA to rethink the issue.

The primary floodplain management adjustment for sea-level rise is the local increase in required base flood elevation (BFE) for new construction. Elevating a building's lowest floor above predicted flood elevations by a small additional height, generally 0.3 to 0.9 meters above National Flood Insurance Program (NFIP) minimum height requirements, is termed a freeboard addition. Freeboard additions are generally justified for other more immediate purposes including the lack of safety factor in the 1-percent flood and uncertainties in prediction and modeling. FEMA encourages freeboard adoptions through the Community Rating System, which offers community-wide flood insurance premium discounts for higher local standards and for individuals through premium discounts for higher than minimum elevation on higher risk buildings. Velocity flood zones, known as V Zones or coastal high hazard areas, have been identified by FEMA as areas "where wave action and/or high velocity water can cause structural damage in the 100-year flood", a flood with a 1 percent chance of occurring or being exceeded in a given year. FEMA also defines A Zones as areas inundated in a 100-year storm event that experience conditions of less severity, for example, wave heights less than 1 m, than conditions experienced in V Zones. Accurate determination of the spatial extent of these zones is vital to understanding the level of risk for a particular property or activity.

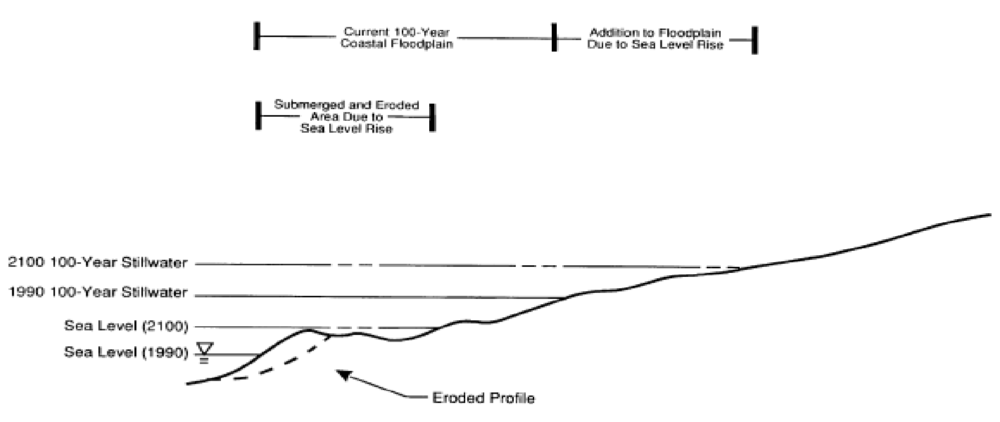
A recent historical overview of FEMA's Coastal Risk Assessment process is found in Crowell *et al.* (2007), and includes overviews of the FEMA Map Modernization Program, revised coastal guidelines, and FEMA's response to recommendations of a Heinz Center report, *Evaluation of Erosion Hazards* (Heinz Center, 2000).

Box 9.2 1991 FEMA Study: Projected Impact of Relative Sea-Level Rise on the National Flood Insurance Program

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

In the 1991 study, FEMA used both a 0.3 and 0.9 meter (1 and 3 feet) projected increase in relative sea level by 2100, based on previous studies (Titus and Green, 1989; IPCC, 1990). For both scenarios it was assumed that the current 100-year floodplain would increase by the exact amount as the change in sea level. This assumption was made to simplify some of the hydrodynamic interactions such as the effect of the increased water depth due to sea-level rise on storm surge, and how sea-level rise will propagate up tidally affected rivers to a point where sea-level rise will no longer affect water flood levels. The study did not attempt to model the effects of sea-level rise in upstream river areas, a task that would have required site-specific hydraulic calculations.

For each coastal county, a still water flood level (SWFL) was estimated, as were the V Zone flood level (V Zones are coastal high hazard areas where wave action and/or high velocity water can cause structural damage in the 100-year flood), the estimated area covered by the Special Flood Hazard Area (SFHA), and the fraction for which coastal V Zones were estimated. The equation divides the amount of sea-level rise by the SWFL and multiplies the result by the current floodplain area. Another assumption was that shoreline erosion and inundation due to sea-level rise, causing an overall loss in floodplain, would cancel out the overall gain in floodplain associated with rising flood levels. Box Figure 9.2 shows this relationship. Using this method, coastal areas where shore protection measures such as beach nourishment and construction of groins, levees, bulkheads, and sea walls are used would reduce the amount of land lost to sea-level rise and thus cause some overestimation in the amount of floodplain lost due to rising sea levels (Titus, 1990).



Box Figure 9.2 Schematic illustrating the effect of sea-level rise on the 100-year coastal floodplain (FEMA, 1991).

The study notes that these numbers differ slightly from a previous sea-level rise study (Titus and Green, 1989) but supports the conclusion from both studies that the size of the floodplain will not increase as sea level rises because of the balancing of land lost through submergence. Box Tables 9.2a and 9.2b show the breakdown of impacted land areas for 0.3 meter (m) rise and 0.9 m rise by regions in A Zones *versus* V Zones (A Zones are areas inundated in a 100-year storm event that experience conditions of less severity than conditions experienced in V Zones).

Box Table 9.2a Area affected by a 0.3 meter rise in sea level by 2100 (in square kilometers).

Area	Floodplain 1990			Additional Area Affected Due to Sea level rise		
	A Zone	V Zone	Total	A Zone	V Zone	Total
Entire U.S.	41,854	8,637	50,491	4,677	937	5,614
Mid-Atlantic	10,782	891	11,673	1,411	114	1,525

Box Table 9.2b Area affected by a 0.9 meter rise in sea level by 2100 (in square miles).

Area	Floodplain 1990			Additional Area Affected Due to Sea level rise		
	A Zone	V Zone	Total	A Zone	V Zone	Total
Entire U.S.	41,854	8,637	50,491	14,045	2,800	16,845
Mid-Atlantic	10,782	891	11,673	4,229	347	4,756

The total land area nationwide estimated by the study to be in a floodplain was close to 50,491 square kilometers (sq km), with approximately 5,614 sq km added to the floodplain for a 0.3 m rise scenario and an additional 16,845 added for a 0.9 m rise. These numbers do not account for subsidence rates in the Louisiana region. For the mid-Atlantic region the floodplain was estimated to be about 11,673 sq km, with 15,250 sq km added to the floodplain for a 0.3 m rise and 4,576 sq km added for a 0.9 m rise.

The study also estimates the number of households in the coastal floodplain. Based on the 1990 Census, 2.7 million households were currently in the 100-year floodplain, including 624,000 in the mid-Atlantic region. For the 0.3 m and 0.9 m rise scenarios, respectively, 5.6 million and 6.6 million households would be in the floodplain, with 1.1 million and 1.3 million in the mid-Atlantic region.

This projected rise in population, in combination with the sea-level rise scenarios, would increase the expected annual flood damage by 2100 for an average NFIP insured property by 36 to 58 percent for a 10.3 m rise and 102 to 200 percent for a 0.9 m rise. This would lead to actuarial increases in insurance premiums for building subject to sea-level rise of 58 percent for a 0.3 m rise and 200 percent for a 0.9 m rise. The study estimated that a 0.3 m would gradually increase the expected annual NFIP flood losses by $150 million by 2100. Similarly, a 0.9 m rise would gradually increase expected losses by about $600 million by 2100. Per policy holder, this increase would equate to $60 more than in 1990 for the 0.3 m rise and $200 more for the 0.9 m rise.

The study concludes that based on the aspects of flood insurance rates that already account for the possibility of increasing risk and the tendency of new construction to be built more than 0.3 m above the base flood elevation, the NFIP would not be significantly impacted under a 0.3 m rise in sea level by the year 2100. For a high projection of a 0.9 m rise, the incremental increase of the first 0.3 m would not be expected until the year 2050. The study concludes that the 60-year timeframe over which this gradual change would occur provides the opportunity for the NFIP to consider alternative approaches to the loss control and insurance mechanisms. Because of the present uncertainties in the projections of potential changes in sea level and the ability of the rating system to respond easily to a 0.3 m rise in sea level, the study concluded that there were no immediate program changes needed.

9.6 STUDIES OF FUTURE COASTAL CONDITIONS AND FLOODPLAIN MAPPING

9.6.1 FEMA Coastal Studies

Currently, communities can opt to use future conditions (projected) hydrology for mapping according to FEMA rules established in December 2001[24]. Showing future conditions flood boundaries has been provided at the request of some communities in Flood Map Modernization, but it is not a routine product. As outlined in those rules, showing a future condition boundary in addition to the other boundaries normally shown on a FIRM is acceptable. FEMA shows future condition boundaries for informational purposes only and carries with it no additional requirements for floodplain management. Insurance would not be rated using a future condition boundary. The benefits showing future condition flood boundaries relate to the fact that future increases in flood risk can lead to significant increases in both calculated and experienced flood heights, resulting in serious flood losses (structural damage and economic) as well as loss of levee certification and loss of flood protection for compliant post-FIRM structures. Providing this information to communities may lead to coordinated watershed-wide actions to manage for, or otherwise mitigate, these future risks.

A recent increase in losses from coastal storms has been recognized by FEMA. In 2005, Hurricane Katrina clearly illustrated this, reporting the most losses of any U.S. natural disaster to date. This fact, coupled with the facts that new developments in modeling and mapping technology have allowed for more accurate flood hazard assessment over the

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[24] Input to author team during CCSP SAP 4.1 Federal Advisory Committee review, Mark Crowell, FEMA.

past few years and that populations at risk are growing in coastal areas, has caused FEMA to develop a new national coastal strategy. This strategy consists of assessing coastal Flood Insurance Studies on a national scale and developing a nationwide plan for improved coastal flood hazard identification. The assessment will prioritize regional studies, look at funding allocations, and develop timelines for coastal study updates.

River models that are affected by tides and storm surge require the downstream boundary starting water surface elevation to be the “1-percent-annual-chance” base flood elevation (BFE) from an adjacent coastal study. If the coastal study BFE is raised by 0.3 m or even 0.9 m because of sea-level rise, the river study flood profile will be changed as well and this will ultimately affect the resulting FIRMs that are published. This is a complicated issue and points out the fact that simply raising the coastal BFEs to estimate a new 1-percent-annual-chance floodplain is not taking into account the more complex hydraulics that will have undetermined effects on the upstream 1-percent-annual-chance floodplains as well. The 1991 study does not factor in the complexity of different tidal regimes that would be occurring because of an increased sea level and how those regimes would affect the geomorphology of the floodplains. This is because FEMA is restricted in what it can and cannot do in the regulated NFIP process.

Maryland has completed a comprehensive state strategy document in response to sea-level rise (Johnson, 2000). The Maryland Department of Natural Resources (Johnson, 2000) requires all communities to adopt standards that call for all structures in the non-tidal floodplain to be elevated 0.3 m (1 ft) above the 100-year floodplain elevation, and all coastal counties except Worcester, Somerset, and Dorchester (the three most vulnerable to exacerbated flooding due to sea-level rise) have adopted the 1-ft freeboard standard. Although 1 foot of freeboard provides an added cushion of protection to guard against uncertainty in floodplain projections, it may not be enough in the event of 0.6 to 0.9 m (2 to 3 ft) of sea-level rise, as Johnson (2000) points out.

Crowell *et al*. (2007) identified a need for a tide-gauge analysis for FEMA Region III, which encompasses the mid-Atlantic states, similar to new studies being done currently on Chesapeake Bay by the state of Maryland. Each coastal FEMA region has been evaluated and new guidelines and specifications have been developed by FEMA for future coastal restudies, the first of which was for the Pacific Coast region. These guidelines outline new coastal storm surge modeling and mapping procedures and allow for new flooding and wave models to be used for generating coastal BFEs.

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

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

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

9.6.2 Mapping Potential Impacts of Sea-Level Rise on Coastal Floodplains

Floodplain management regulations are intended to minimize damage as a result of flooding disasters, in conjunction with other local land-use requirements and building codes. Meeting only these minimum requirements will not guarantee protection from storm damages. Management activities that focus on mitigating a single, short-term hazard can result in structures that are built only to withstand the hazards as they are identified today, with no easy way to accommodate an increased risk of damage in the coming decades (Honeycutt and Mauriello, 2005). The concept of going above and beyond current regulations to provide additional hazards information other than BFEs and the 1-percent-annual-chance flood (coastal erosion and storm surge inundation potential) has been advocated in some quarters with a No Adverse Impact (NAI) program (Larson and Plasencia, 2002). A NAI toolkit was developed that outlines a strategy for communities to implement a NAI approach to floodplain management (ASFPM, 2003, 2008).

The International Codes (FEMA, 2005) include freeboard (elevations above the BFE) and standards for coastal A Zones that are more stringent than the NFIP criteria. The International Codes also incorporate criteria from the national consensus document ASCE 24-05 *Flood Resistant Design and Construction Standard* (ASCE, 2006).

9.7 HOW COASTAL RESOURCE MANAGERS COPE WITH SEA-LEVEL RISE AND ISSUES THEY FACE

9.7.1 Studies by the Association of State Floodplain Managers

The Association of State Floodplain Mangers (ASFPM) recently completed a study that contains a broad spectrum of recommendations for improving the management of U.S. floodplains (ASFPM, 2007). In their study, ASFPM noted that changing climate was one of the major challenges for the significant changes in social, environmental, and political realities and their impact on floodplain management, and highlights the wide spread implications for flood protection.

9.7.2 The Response through Floodproofing

The U.S. Army Corps of Engineers heads the national floodproofing committee, established through the USACE’s floodplain management services program, to promote the development and use of proper floodproofing techniques throughout the United States (USACE, 1996). The USACE publication on floodproofing techniques, programs, and references gives an excellent overview of currently accepted flood mitigation practices from an individual structure perspective.

Mitigating flooding or “floodproofing” is a process for preventing or reducing flood damages to structures and/or to the contents of buildings located in flood hazard areas. It mainly involves altering or changing existing properties; however, it can also be incorporated into the design and construction of new buildings. There are three general approaches to floodproofing:

1. *Raising or moving the structure.* Raising or moving the structure such that floodwaters cannot reach damageable portions of it is an effective floodproofing approach.
2. *Constructing barriers to stop floodwater from entering the building*. Constructing barriers can be an effective approach used to stop floodwaters from reaching the damageable portions of structures. There are two techniques employed in constructing barriers. The first technique involves constructing free-standing barriers that are not attached to the structure. The three primary types of free-standing barriers used to reduce flood damages are berms, levees, or floodwalls. The second technique that can be used to construct a barrier against floodwaters is known as “dry floodproofing”. With this technique, a building is sealed such that floodwaters cannot get inside.

3. *Wet Floodproofing*. This approach to floodproofing involves modifying a structure to allow floodwaters inside, but ensuring that there is minimal damage to the building's structure and to its contents. Wet floodproofing is often used when dry floodproofing is not possible or is too costly. Wet floodproofing is generally appropriate in cases where an area is available above flood levels to which damageable items can be relocated or temporarily stored.

The recommended techniques of levees, berms, floodwalls and wet floodproofing are not allowed under the NFIP to protect new individual structures. These techniques may also have limited use in protecting older existing structures in coastal areas. Although dry floodproofing is allowed in A Zones (not V Zones), FEMA does not generally recommend its use for new non-residential structures in the coastal A Zones due to the potential flood forces. Under the NFIP, all new construction and substantial improvements of residential buildings in A Zones must have the lowest floor elevated to or above the BFE. All new construction and substantial improvement of non-residential buildings in A Zones must have either the lowest floor elevated to or above the BFE or the building must be dry floodproofed to the BFE. In V Zones, all new construction and substantial improvements must have the bottom of the lowest horizontal structural member of the lowest floor elevated to or above the BFE on a pile or column foundation. Although the NFIP allows dry floodproofing in coastal A Zone areas, FEMA does not recommend its use in the coastal A Zone because of the potential for severe flood hazards. While Base Flood Elevations in coastal A Zones contain a wave height of less than 3 feet, the severity of the hazard in coastal A Zones is often much greater than in non-coastal A Zones due to the combination of water velocity, wave action, and debris impacts that can occur in these areas. For existing, older structures in the coastal area, the best way to protect the structure is elevating or relocating the structure.

9.7.3 Coastal Zone Management Act

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

The U.S. Congress recognized the importance of meeting the challenge of continued growth in the coastal zone and responded by passing the Coastal Zone Management Act in 1972. The amended act (CZMA, 1996), administered by NOAA, provides for management of U.S. coastal resources, including the Great Lakes, and balances economic development with environmental conservation.

As a voluntary federal–state partnership, the CZMA is designed to encourage state-tailored coastal management programs. It outlines two national programs, the National Coastal Zone Management Program and the National Estuarine Research Reserve System, and aims to balance competing land and water issues in the coastal zone, while estuarine reserves serve as field laboratories to provide a greater understanding of estuaries and how humans impact them. The overall program objectives of CZMA remain balanced to "preserve, protect, develop, and where possible, to restore or enhance the resources of the nation's coastal zone" (CZMA, 1996).

9.7.4 The Coastal Zone Management Act and Sea-Level Rise Issues

The CZMA language (CZMA, 1996) refers specifically to sea-level rise issues (16 U.S.C. § 1451). Congressional findings (§ 302) calls for coastal states to anticipate and plan for sea-level rise and climate change impacts.

In 16 U.S.C. § 1452, Congressional declaration of policy (§ 303), the Congress finds and declares that it is the national policy to manage coastal development to minimize the loss of life and property caused by improper development in flood-prone, storm surge, geological hazard, and erosion-prone areas, and in areas likely to be affected by or vulnerable to sea-level rise, land subsidence, and saltwater intrusion, and by the destruction of natural protective features such as beaches, dunes, wetlands, and barrier islands; to study and develop plans for addressing the adverse effects upon the coastal zone of land subsidence and of sea-level rise; and to encourage the preparation of special area management plans which provide increased specificity in protecting significant natural resources, reasonable coastal-dependent economic growth, improved protection of life and property in hazardous areas, including those areas likely to be affected by land subsidence, sea-level rise, or fluctuating water levels of the Great Lakes, and improved predictability in governmental decision-making.

9.7.5 The Coastal Zone Enhancement Program

The reauthorization of CZMA in 1996 by the U.S. Congress led to the establishment of the Coastal Zone Enhancement Program (CZMA §309), which allows states to request additional funding to amend their coastal programs in order to support attainment of one or more coastal zone enhancement objectives. The program is designed to encourage states and territories to develop program changes in one or more of the following nine coastal zone enhancement areas of national significance: wetlands, coastal hazards, public access, marine debris, cumulative and secondary impacts, special area management plans, ocean/Great Lakes resources, energy and government facility citing, and aquaculture. The Coastal Zone Enhancement Grants (§ 309) defines a "Coastal zone enhancement objective" as "preventing or significantly reducing threats to life and destruction of property by eliminating development and redevelopment in high-hazard areas, managing development in other hazard areas, and anticipating and managing the effects of potential sea-level rise and Great Lakes level rise".

Through a self-assessment process, state coastal programs identify high-priority enhancement areas. In consultation with NOAA, state coastal programs then develop five-year strategies to achieve changes (enhancements) to their coastal management programs within these high-priority areas. Program changes often include developing or revising a law, regulation or administrative guideline, developing or revising a special area management plan, or creating a new program such as a coastal land acquisition or restoration program.

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

1. What is the general level or risk from specific coastal hazards (*i.e.*, hurricanes, storm surge, flooding, shoreline erosion, sea-level rise, Great Lakes level fluctuations, subsidence, and geological hazards) and risk to life and property due to inappropriate development in the state?
2. Have there been significant changes to the state's hazards protection programs (*e.g.*, changes to building setbacks/restrictions, methodologies for determining building setbacks, restriction of hard shoreline protection structures, beach/dune protection, inlet management plans, local hazard mitigation planning, or local post-disaster redevelopment plans, mapping/GIS/tracking of hazard areas)?
3. Does the state need to direct future public and private development and redevelopment away from hazardous areas, including the high hazard areas delineated as FEMA V Zones and areas vulnerable to inundation from sea- and Great Lakes level rise?
4. Does the state need to preserve and restore the protective functions of natural shoreline features such as beaches, dunes, and wetlands?

5. Does the state need to prevent or minimize threats to existing populations and property from both episodic and chronic coastal hazards?

Section 309 grants have benefited states such as Virginia in developing local conservation corridors that identify and prioritize habitat areas for conservation and restoration; and New Jersey for supporting new requirements for permittees to submit easements for land dedicated to public access, when such access is required as a development permit condition and is supporting a series of workshops on the Public Trust Doctrine and ways to enhance public access (see <http://coastalmanagement.noaa.gov/nationalsummary.html>).

9.7.6 Coastal States Strategies

Organizations such as the Coastal States Organization have recently become more proactive in how coastal zone management programs consider adaptation to climate change, including sea-level rise (Coastal States Organization, 2007) and are actively leveraging each other’s experiences and approaches as to how best obtain baseline elevation information and inundation maps, how to assess impacts of sea-level rise on social and economic resources and coastal habitats, and how to develop public policy. There have also been several individual state-wide studies on the impact of sea-level rise on local state coastal zones (*e.g.*, Johnson [2000] for Maryland; Cooper *et al*. [2005] for New Jersey). Many state coastal management websites show an active public education program with regards to providing information on impacts of sea-level rise:

New Jersey: <http://www.nj.gov/dep/njgs/enviroed/infocirc/sealevel.pdf>

Delaware:

<http://www.dnrec.delaware.gov/Climate+change+shoreline+erosion.htm>

Maryland: <http://www.dnr.state.md.us/Bay/czm/sea_level_rise.html>

9.7.6.1 Maryland's Strategy

The evaluation of sea-level rise response planning in Maryland and the resulting strategy document constituted the bulk of the state's CZMA §309 *Coastal Hazard Assessment and Strategy for 2000–2005* and in the 2006-2010 Assessment and Strategy (MD DNR, 2006). Other mid-Atlantic states mention sea-level rise as a concern in their assessments, but have not yet developed a comprehensive strategy.

The sea-level rise strategy is designed to achieve the desired outcome within a five-year time horizon. Implementation of the strategy is evolving over time and is crucial to Maryland's ability to achieve sustainable management of its coastal zone. The strategy states that planners and legislators should realize that the implementation of measures to mitigate impacts associated with erosion, flooding, and wetland inundation will also enhance Maryland's ability to protect coastal resources and communities whether sea level rises significantly or not.

Maryland has taken a proactive step towards addressing a growing problem by committing to implementation of this strategy and increasing awareness and consideration of sea-level rise issues in both public and governmental arenas. The strategy suggests that Maryland will achieve success in planning for sea-level rise by establishing effective response mechanisms at both the state and local levels. Sea-level rise response planning is crucial in order to ensure future survival of Maryland's diverse and invaluable coastal resources.

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

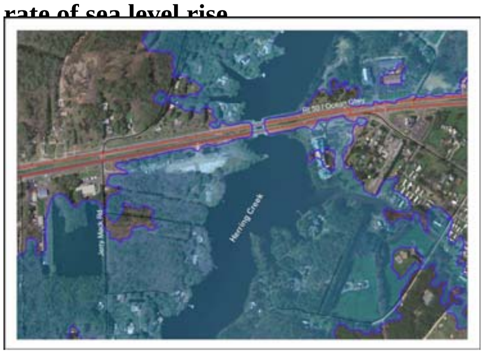
In April 2007, Maryland's Governor, Martin O'Malley, signed an Executive Order establishing a Commission on Climate Change (Maryland, 2007) that is charged with advising both the Governor and Maryland's General Assembly on matters related to climate change and is charged with developing a Plan of Action that will address climate

Box 9.3 A Maryland Case Study–Implications for Decision-makers: *Worcester County Sea Level Rise Inundation Modeling*

The Maryland Department of Natural Resources (MD DNR) and the U.S. Geological Survey (USGS) completed the development of a Worcester County Sea Level Rise Inundation Model in November 2006 (Johnson *et al*., 2006). Taking advantage of recent lidar coverage for the county, a Digital Elevation Model (DEM) was produced as the base layer on which to overlay various sea-level rise scenarios modeled for three time periods: 2025, 2050, and 2100. The three scenarios were the historic rate of regional sea-level rise estimated from tide station records (3.1 millimeters per year), the average accelerated rate of sea-level rise projected by the 2001 IPCC report, and the worst case scenario using the maximum projection of accelerated sea-level rise by the 2001 IPCC report (85 to 90 centimeters by 2100). The scenarios were applied to present day elevations of Mean Sea Level (MSL), Mean High Water (MHW), and Spring tides derived at local tide stations. Box Figures 9.3a and 9.3b below show a typical result for year 2100 using an accelerated rate of sea-level rise scenario from the IPCC 2001 Report. An agricultural block overlay depicts the potential loss of agricultural land to sea-level rise for Public Landing, Maryland.

Box Figure 9.3a Day Public landing.

Box Figure 9.3b Public landing at 2100 with current rate of sea level rise



Box Figure 9.3c Sea level rise in 2100 using present day sea-level trends coupled with a category 2 hurricane storm surge.

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

CHAPTER 9 REFERENCES

AGU (American Geophysical Union), 2006: *Hurricanes and the U.S. Gulf Coast: Science and Sustainable Rebuilding*. American Geophysical Union, [Washington, DC], 29 pp. <http://www.agu.org/report/hurricanes>

ASCE (American Society of Civil Engineers), 2006: *Flood Resistant Design and Construction.* ASCE/SEI 24-05. American Society of Civil Engineers, Reston, VA, 61 pp.

ASFPM (Association of State Floodplain Managers), 2003: *No Adverse Impact. A Toolkit for Common Sense Floodplain Management.* [Larson, L.A., M.J. Klitzke, and D.A Brown eds.]. Association of State Floodplain Managers, Madison, WI, 108 pp.

ASFPM (Association of State Floodplain Managers), 2007: *National Flood Programs and Policies in Review – 2007*. Association of State Floodplain Managers, Madison, WI, 92 pp.

ASFPM (Association of State Floodplain Managers), 2008: *Coastal No Adverse Impact Handbook*. Association of State Floodplain Managers, Madison, WI, 165 pp. <http://www.floods.org/CNAI/CNAI_Handbook.asp>

Boesch, D.F., J.C. Field, and D. Scavia, (eds.): 2000. *The Potential Consequences of Climate Variability and Change on Coastal Areas and Marine Resources: Report of the Coastal Areas and Marine Resources Sector Team, U.S. National Assessment of the Potential Consequences of Climate Variability and Change, U.S. Global Change Research Program*. NOAA Coastal Ocean Program decision analysis series no. 21. NOAA Coastal Ocean Program, Silver Spring, MD, 163 pp.

Coastal States Organization, 2007: *The Role of Coastal Zone Management Programs in Adaptation to Climate Change*. CSO Climate Change Work Group, Washington, DC, 27 pp.

<http://www.coastalstates.org/uploads/PDFs/CSO%20Climate%20Change%20Report%20-%20Final%2010-1-07.pdf>

Cooper, M.J.P., M.D. Beevers, and M. Oppenheimer, 2005: *Future Sea Level Rise And The New Jersey Coast: Assessing Potential Impacts and Opportunities.* Science, Technology and Environmental Policy Program, Woodrow Wilson School of Public and International Affairs, Princeton University, Princeton, NJ, 36 pp. <http://www.princeton.edu/~cmi/news/Future%20of%20Sea%20Level%20Rise%20and%20the%20New%20Jersey%20Coast.pdf>

Crowell, M., E. Hirsch, and T.L. Hayes, 2007: Improving FEMA's coastal risk assessment through the National Flood Insurance Program: an historical overview. *Marine Technology Science*, **41(1)**, 18-27.

CZMA (Coastal Zone Management Act)**,** 1996: The Coastal Zone Management Act of 1972, as amended through P.L. 104-150, The Coastal Zone Protection Act of 1996, 16 U.S.C. § 1451 through 16 U.S.C. § 1465.

FEMA (Federal Emergency Management Agency), 1991: *Projected Impact of Relative Sea-level Rise on the National Flood Insurance Program*. Federal Emergency Management Agency, Washington, DC, 61 pp.

FEMA (Federal Emergency Management Agency), 2002: *Guidelines and Specifications for Flood Hazard Mapping Partners Archive*. [web site] Federal Emergency Management Agency. <http://www.fema.gov/plan/prevent/fhm/gs_arch.shtm>

FEMA (Federal Emergency Management Agency), 2005: *Reducing Flood Losses Through the International Codes, Meeting the Requirements of the National Flood Insurance Program.* Federal Emergency Management Agency and International Code Council, [Washington, DC], 2nd edition, 156 pp.

FEMA (Federal Emergency Management Agency), 2008: *National Flood Insurance Program Definitions* [web page] <http://www.fema.gov/business/nfip/19def2.shtm>

Hagen, S.C., W. Quillian, and R. Garza, 2004: *A Demonstration of Real-time Tide and Hurricane Storm Surge Predictions for the National Weather Service River Forecast System.* Technical report, UCAR Contract No. S01-32794. CHAMPS Laboratory, University of Central Florida, Orlando.

Heinz Center, 2000: *Evaluation of Erosion Hazards.* The H. John Heinz III Center for Science, Economics and the Environment, Washington, DC, 203 pp.

Honeycutt, M.G. and M.N. Mauriello, 2005: Multi-hazard mitigation in the coastal zone: when meeting the minimum regulatory requirements isn't enough: In: *Solutions to Coastal Disasters 2005*, Proceedings of the conference, May 8-11, Charleston, SC. American Society of Civil Engineers, Reston VA, pp. 713-722.

Hovis, J., W. Popovich, C. Zervas, J. Hubbard, H.H. Shih, and P. Stone, 2004: *Effect of Hurricane Isabel on Water Levels: Data Report*. NOAA technical Report NOS CO-OPS 040. NOAA, Silver Spring, MD, 120 pp.

Jelesnianski, C.P., J. Chen, and W.A. Shaffer, 1992: *SLOSH: Sea, Lake, and Overland Surges from Hurricanes*. NOAA technical report NWS 48. National Weather Service, Silver Spring, MD, 71 pp.

Johnson, Z.P., 2000: *A Sea Level Response Strategy for the State of Maryland*. Maryland Department of Natural Resources, Coastal Zone Management Division, Annapolis, 49 pp.

Larsen, C., I. Clark, G.R. Guntenspergen, D.R. Cahoon, V. Caruso, C. Hupp, and T. Yanosky, 2004: *The Blackwater NWR Inundation Model. Rising Sea Level on a Low-lying Coast: Land Use Planning for Wetlands.* U.S. Geological Survey open file report 04-1302. U.S. Geological Survey, Reston, VA. <http://pubs.usgs.gov/of/2004/1302/>

Luettich, R.A., Jr., J.J. Westerink, and N.W. Scheffner, 1992: *ADCIRC: An Advanced Three-dimensional Circulation Model of Shelves, Coasts and Estuaries, Report 1: Theory and Methodology of ADCIRC-2DD1 and ADCIRC-3DL*. Technical report

DRP-92-6. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, 141 pp.

Maryland, 2007: Maryland Executive Order 01.01.2007.07, Commission on Climate Change. State of Maryland, Executive Department, [Annapolis].

Maryland, 2008: *Climate Action Plan*. Maryland Commission on Climate Change and Maryland Department of Environment, Baltimore, 356 pp. <http://www.mdclimatechange.us/>

MD DNR (Maryland Department of Natural Resources), Coastal Zone Management Program, 2006: Coastal Zone Management Assessment, Section 309, Assessment and Strategy.

NOAA (National Oceanic and Atmospheric Administration), 1992: *Effects of the Late October 1991 North Atlantic Extra-Tropical Storm on Water Levels: Data Report*. NOAA National Ocean Service, Rockville, MD, 46 pp.

NOAA (National Oceanic and Atmospheric Administration), 2007: *NOAA's Sea level Rise Research Program: North Carolina Managers Meetings Fact Sheet*. NOAA National Centers for Coastal Ocean Science, Silver Spring, MD, 2 pp. http://www.cop.noaa.gov/stressors/climatechange/current/slr/SLR_manager_handout.pdf

NOAA (National Oceanic and Atmospheric Administration), 2008: *Glossary of NHC Terms*. NOAA National Weather Service, National Hurricane Center, Miami, FL. See defintions for Storm Surge and for Storm Tide. <http://www.nhc.noaa.gov/aboutgloss.shtml>

Pietrafesa, L.J., E.B. Buckley, M. Peng, S. Bao, H. Liu, S. Peng, L. Xie, and D.A. Dickey, 2007: On coastal ocean systems, coupled model architectures, products and services: morphing from observations to operations and applications. *Marine Technology Societyl*, **41(1)**, 44-52.

Poag, C.W., 1997: Chesapeake Bay bolide impact: a convulsive event in Atlantic Coastal Plain evolution. *Sedimentary Geology*, **108(1-4)**, 45-90.

Reed, D.B. and B.E. Stucky, 2005: Forecasting storm surge on the Mississippi River. In: *Solutions to Coastal Disasters*, Proceedings of the conference, May 8-11, Charleston, SC. American Society of Civil Engineers, Reston, VA, pp. 52-60.

Slovinsky, P.A. and S.M. Dickson, 2006: *Impacts of Future Sea Level Rise on the Coastal Floodplain.* MGS open-file 06-14. Maine Geological Survey, Augusta, ME, [26 pp.] <http://www.maine.gov/doc/nrimc/mgs/explore/marine/sea-level/contents.htm>

USACE (U.S. Army Corps of Engineers), 1996: *Flood Proofing Techniques, Programs and References*. U.S. Army Corps of Engineers, Washington, DC, 25 pp.

Worcester County Planning Commission, 2006: *Comprehensive Plan, Worcester County Maryland.* Worcester County Commissioners, Snow Hill, MD, 96 pp. <http://www.co.worcester.md.us/cp/finalcomp31406.pdf>

Zervas, C.E., 2001: *Sea Level Variations for the Unites States 1854-1999.* NOAA technical report NOS CO-OPS 36. NOAA National Ocean Service, Silver Spring, MD, 186 pp. <http://tidesandcurrents.noaa.gov/publications/techrpt36doc.pdf>

Zervas, C.E., 2005: *Extreme Storm Tide Levels of the United States 1897-2004*. Poster paper presented at NOAA Climate Program Office, Office of Climate Observations Annual Meeting, Silver Spring, MD.