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

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

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

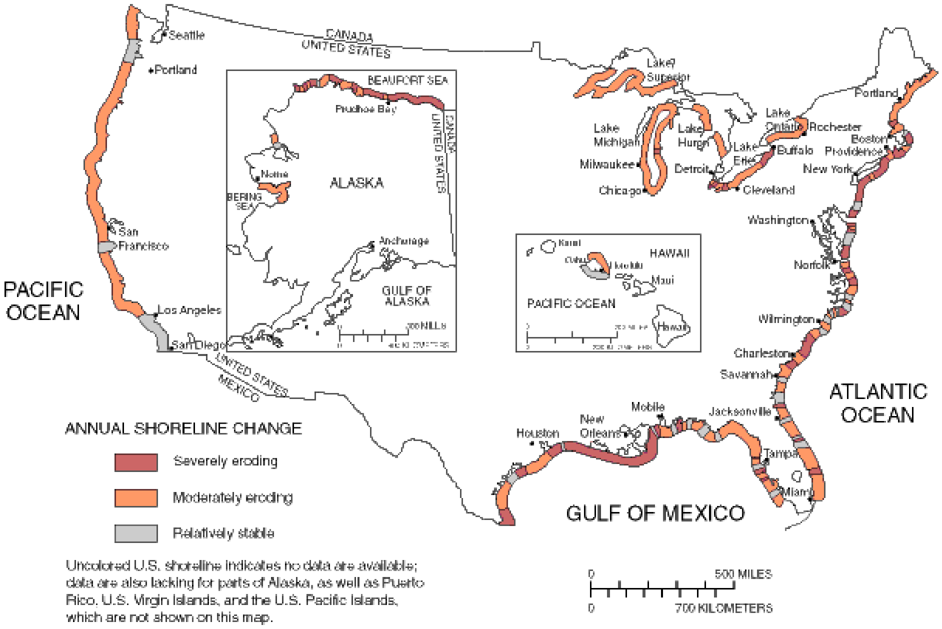

Figure V.1 Map of historic annual ocean shoreline change around the U.S. All 30 coastal states are undergoing erosion at highly variable rates due to natural and human factors (USGS National Atlas, 1985).

V.1 TYPES OF COASTS

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

V.1.1 Cliff and Bluff Shorelines

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

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

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

V.1.3 Coastal Wetlands

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

V.1.4 Coral Reef Coasts

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

V.1.5 Mudflat Shores

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

V.2 SHORELINE SETTINGS AROUND THE UNITED STATES

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

V.2.1 Atlantic Coast

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

V.2.2 Gulf of Mexico Coast

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

V.2.3 Pacific Coast

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

V.3 PREDICTING FUTURE SHORELINE CHANGE

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

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

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

V.3.1 Coastal Vulnerability to Sea-Level Rise

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

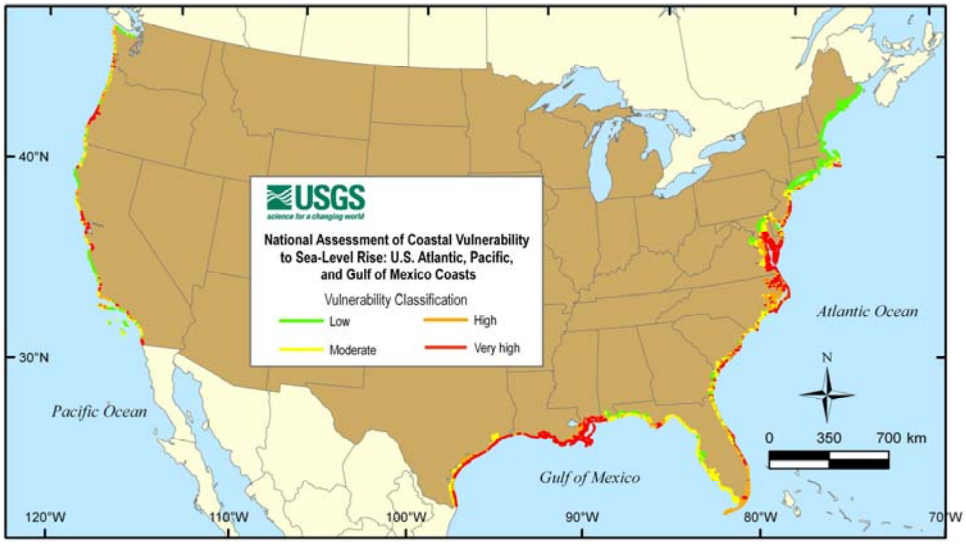

Figure V.2 Map of the Coastal Vulnerability Index (CVI) for the U.S. showing the relative vulnerability of the ocean coast to changes due to future rises in sea level. Segments of the coast are assigned a ranking from low to very high based on the analysis of geologic and oceanographic variables that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

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

V.3.2 Potential for Future Shoreline Change

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

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

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

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

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

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

V.4 PREVIOUS SEA-LEVEL RISE IMPACT ASSESSMENTS

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

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

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

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

V.5 AREA OF LAND VULNERABLE TO TIDAL INUNDATION

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

V.5.1 Early Cost Estimates of Shore Protection

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

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[45] The study excluded Alaska and Hawaii.

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

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

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

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

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

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

V.5.2 Coastal Wetlands

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

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

V.6 CONCLUSIONS

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

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