CHAPTER 7
SEA LEVEL RISE

by James G. Titus

FINDINGS

Global warming could cause sea level to rise 0.5 to 2 meters by 2100. Such a rise would inundate wetlands and lowlands, erode beaches, exacerbate coastal flooding, and increase the salinity of estuaries and aquifers.

- A 1-meter rise could drown approximately 25 to 80% of the U.S. coastal wetlands; ability to survive would depend largely on whether they could migrate inland or whether levees and bulkheads blocked their migration. Even current sea level trends threaten the wetlands of Louisiana.

- A 1-meter rise could inundate 5,000 to 10,000square miles of dryland if shores were not protected and 4,000 to 9,000 square miles of dryland if only developed areas were protected.

- Most coastal barrier island communities would probably respond to sea level rise by raising land with sand pumped from offshore. Wide and heavily urbanized islands may use levees, while communities on lightly developed islands may adjust to a gradual landward migration of the islands.

- Protecting developed areas against such inundation and erosion by building bulkheadsand levees, pumping sand, and raising barrier islands could cost $73 to $111 billion (cumulative capital costs in 1985 dollars) for a 1-meter rise by the year 2100 (compared with $6 to $11 billion under current sea level trends). Of this total, $50 to $75 billion would be spent (cumulative capital costs in 1985 dollars) to elevate beaches, houses, land, and roadways by the year 2100 to protect barrier islands (compared with $4 billion under current trends). Developed barrier islands would likely be protected from sea level rise because of their high property values.

- The Southeast would bear approximately 90% of the land loss and 66% of the shore protection costs.

Policy Implications

- Many of the necessary responses to sea level rise, such as rebuilding ports, constructing levees, and pumping sand onto beaches, need not be implemented until the rise is imminent. On the other hand, the cost of incorporating sea level rise into a wide variety of engineering and land use decisions would be negligible compared with the costs of not responding until sea level rises.

- Many wetland ecosystems are likely to survive sea level rise only if appropriate measures are implemented in the near future. At the state and local levels, these measures include land use planning, regulation, and redefinitions of property rights. The State of Maine has already issued regulations to enable wetlands to migrate landward by requiring that structures be removed as sea level rises.

- The coastal wetlands protected under Section 404 of the Clean Water Act will gradually be inundated. The act does not authorize measures to ensure survival of wetland ecosystems as sea level rises.

- The National Flood Insurance Program may wish to consider the implications of sea level rise on its future liabilities. A recent HUD authorization act requires this program to purchase property threatened with erosion. The act may imply a commitment by the federal government to compensate property owners for losses due to sea level rise.

- The need to take action is particularly urgent in coastal Louisiana, which is already losing 100 square kilometers per year.

CAUSES, EFFECTS, AND RESPONSES

Global warming from the greenhouse effect could raise sea level approximately 1 meter by expanding ocean water, melting mountain glaciers, and causing ice sheets in Greenland to melt or slide into the oceans. Such a rise would inundate coastal wetlands and lowlands, erode beaches, increase the risk of flooding, and increase the salinity of estuaries, aquifers, and wetlands.

In the last 5 years, many coastal communities throughout the world have started to prepare for the possibility of such a rise. In the United States, Maine has enacted a policy declaring that shorefront buildings will have to be moved to enable beaches and wetlands to migrate inland to higher ground. Maryland has shifted its shore-protection strategy from a technology that can not accommodate sea level rise to one that can. Seven coastal states have held large public meetings on how to prepare for a rising sea. Australia, the Netherlands, and the Republic of Maldives are beginning to undergo a similar process.

Causes

Ocean levels have always fluctuated with changes in global temperatures. During the ice ages when the earth was 5°C (9°F) colder than today, much of the ocean's water was frozen in glaciers and sea level often was more than 100 meters (300 feet) below the present level (Dorm et al., 1962; Kennett, 1982; Oldale, 1985). Conversely, during the last interglacial period (100,000 years ago) when the average temperature was about 1°C (2°F) warmer than today, sea level was approximately 20 feet higher than the current sea level (Mercer, 1968).

When considering shorter periods of time, worldwide sea level rise must be distinguished from relative sea level rise. Although climate change alters worldwide sea level, the rate of sea level rise relative to a particular coast has greater practical importance and is all that monitoring stations can measure. Because most coasts are sinking (and a few are rising), the range of relative sea level rise varies from more than 3 feet per century in Louisiana and parts of California and Texas to 1 foot per century along most of the Atlantic and gulf coasts, to a slight drop in much of the Pacific Northwest (Figure 7-1). Areas such as Louisiana provide natural laboratories for assessing the possible effects of future sea level rise (Lyle et al., 1987).

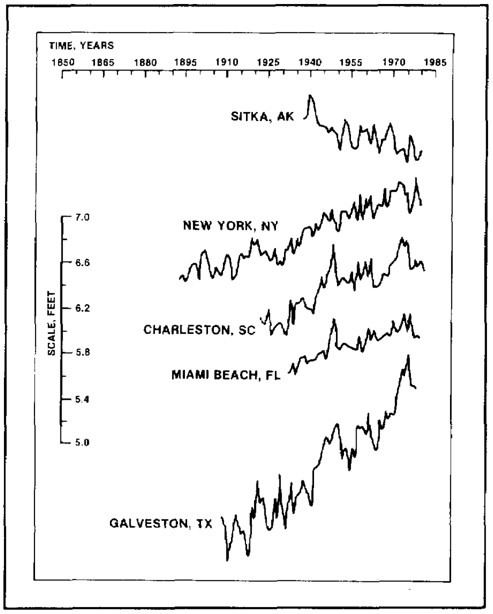

Figure 7-1. Time series graph of sea level trends for New York, Charleston, Miami, Galveston, and Siika (Lyle et al., 1987).

Global sea level trends have generally been estimated by combining the trends at tidal stations around the world. Studies combining these measurements suggest that during the last century, worldwide sea level has risen 10 to 15 centimeters (4 to 6 inches) (Barnett, 1984; Fairbridge and Krebs, 1962). Much of this rise has been attributed to the global warming that has occurred during the last century (Meier, 1984; Gornitz et al., 1982). Hughes (1983) and Bentley (1983) estimated that a complete disintegration of West Antarctica in response to global warming would require a 200- to 500-year period, and that such a disintegration would raise sea level 20 feet. Most recent assessments, however, have focused on the likely rise by the year 2100. Figure 7-2 illustrates recent estimates of sea level rise, which generally fall into the range of 50 io 200 centimeters.

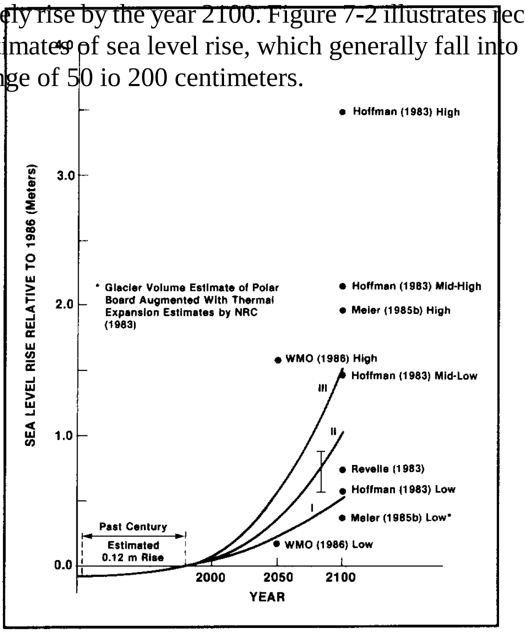

Figure 7-2. Estimates of future sea level rise (derived from Hoffman, 1983, 1986; Meier, 1985; Revelle, 1983).

Although most studies have focused on the impact of global warming on global sea level, the greenhouse effect would not necessarily raise sea level by the same amount everywhere. Removal of water from the world's ice sheets would move the earth's center of gravity away from Greenland and Antarctica and would thus redistribute the oceans' water toward the new center of gravity. Along the U.S. coast, this effect would generally increase sea level rise by less than 10%. Sea level could actually drop, however, at Cape Horn and along the coast of Iceland. Climate change could also affect local sea level by changing ocean currents, winds, and atmospheric pressure; no one has estimated these impacts.

Effects

In this section and in the following sections, the effects of and responses to sea level rise are presented separately. However, the distinction is largely academic and is solely for presentation purposes. In many cases, the responses to sea level rise are sufficiently well established and the probability of no response is sufficiently low that it would be misleading to discuss the potential effects without also discussing responses. For example, much of Manhattan Island is less than 2 meters above high tide; the effect of sea level rise would almost certainly be the increased use of coastal engineering structures and not the inundation of downtown New York.

A rise in sea level would inundate wetlands and lowlands, accelerate coastal erosion, exacerbate coastal flooding, threaten coastal structures, raise water tables, and increase the salinity of rivers, bays, and aquifers (Barth and Titus, 1984). Most of the wetlands and lowlands are found along the gulf coast and along the Atlantic coast south of central New Jersey, although a large area also exists around San Francisco Bay. Similarly, the areas vulnerable to erosion and flooding are also predominately in the Southeast; potential salinity problems are spread more evenly along the U.S. Atlantic coast. We now discuss some of the impacts that would result if no responses were initiated to address sea level rise.

Destruction of Coastal Wetlands

Coastal wetlands are generally found between the highest tide of the year and mean sea level. Wetlands have kept pace with the past rate of sea level rise because they collect sediment and produce peat upon which they can build; meanwhile, they expanded inland as lowlands were inundated (Figure 7-3). Wetlands accrete vertically and expand inland. Thus, as Figure 7-3 illustrates, the present area of wetlands is generally far greater than the area that would be available for new wetlands as sea level rises (Titus et al., 1984b; Titus, 1986). The potential loss would be the greatest in Louisiana (see Chapter 16: Southeast).

In many areas, people have built bulkheads just above the marsh. If sea level rises, the wetlands will be squeezed between the sea and the bulkheads (see Figure 7-3). Previous studies have estimated that if the development in coastal areas were removed to allow new wetlands to form inland, a 1.5- to 2-meter rise would destroy 30 to 70% of the U.S. coastal wetlands. If levees and bulkheads were erected to protect today's dryland, the loss could be 50 to 80% (Titus, 1988; Armentano et al., 1988).

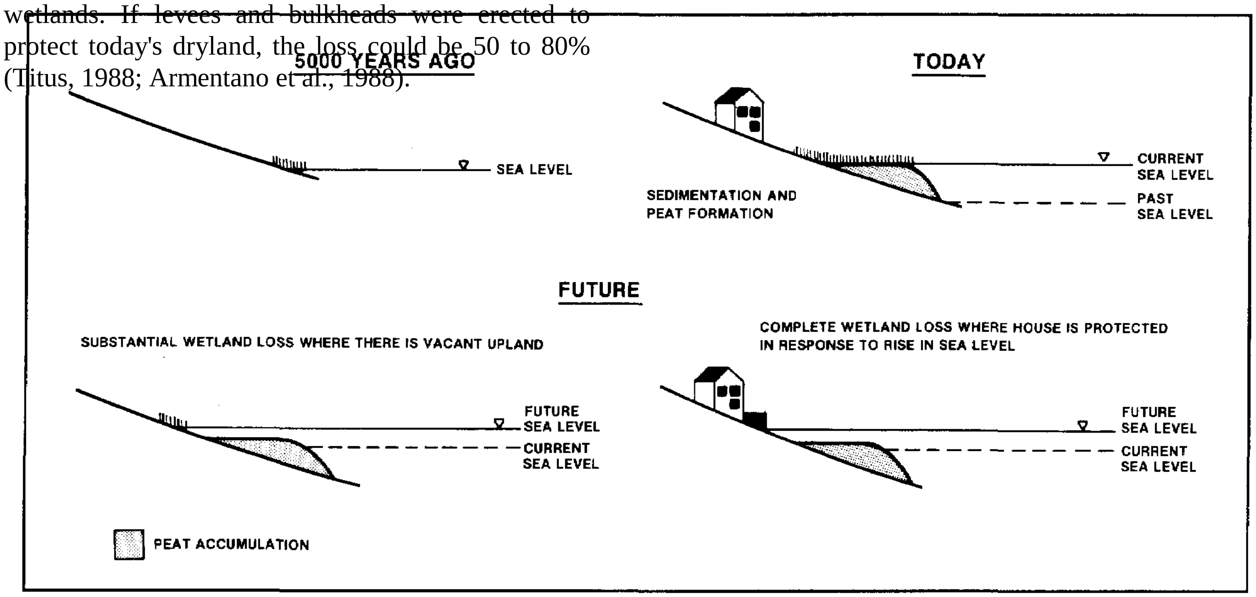

Figure 7-3. Evolution of marsh as sea rises. Coastal marshes have kept pace with the slow rate of sea level rise that has characterized the last several thousand years. Thus, the area of marsh has expanded over time as new lands have been inundated. If in the future, sea level rises faster than the ability of the marsh to keep pace, the marsh area will contract. Construction of bulkheads to protect economic development may prevent new marsh from forming and result in a total loss of marsh in some areas.

Such a loss would reduce the available habitat for birds and juvenile fish and would reduce the production of organic materials on which estuarine fish rely.

The dryland within 2 meters of high tide includes forests, farms, low parts of some port cities, cities that sank after they were built and are now protected with levees, and the bay sides of barrier islands. The low forests and farms are generally in the mid-Atlantic and Southeast regions; these would provide potential areas for new wetland formation. Major port cities with low areas include Boston, New York, Charleston, and Miami. New Orleans is generally 8 feet below sea level, and parts of Galveston, Texas City, and areas around the San Francisco Bay are also well below sea level. Because they are already protected by levees, these cities are more concerned with flooding than with inundation.

Inundation and Erosion of Beaches and Barrier Islands

Some of the most important vulnerable areas are the recreational barrier islands and spits (peninsulas) of the Atlantic and gulf coasts. Coastal barriers are generally long narrow islands and spits with the ocean on one side and a bay on the other. Typically, the oceanfront block of an island ranges from 5 to 10 feet above high tide, and the bay side is 2 to 3 feet above high water. Thus, even a 1meter sea level rise would threaten much of this valuable land with inundation.

Erosion threatens the high part of these islands and is generally viewed as a more immediate problem than the inundation of the bay sides. As Figure 7-4 shows, a rise in sea level can cause an ocean beach to retreat considerably more than it would from the effects of inundation alone. The visible part of the beach is much steeper than the underwater portion, which comprises most of the active "surf zone." While inundation alone is determined by the slope of the land just above the water, Bruun (1962) and others have shown that the total shoreline retreat from a sea level rise depends on the average slope of the entire beach profile.

Previous studies suggest that a 1-foot rise in sea level would generally cause beaches to erode 50 to 100 feet from the Northeast to Maryland (e.g., Kyper and Sorensen, 1985; Everts, 1985); 200 feet along the Carolinas (Kana et al., 1984); 100 to 1,000 feet along the Florida coast (Bruun, 1962); 200 to 400 feet along the California coast (Wilcoxen, 1986); and perhaps several miles in Louisiana. Because most U.S. recreational beaches are less than 100 feet wide at high tide, even a 1-foot rise in sea level would require a response. In many areas, undeveloped barrier islands could keep up with rising sea level by "over-washing" landward. In Louisiana, however, barrier islands are breaking up and exposing the wetlands behind them to gulf waves; consequently, the Louisiana barrier islands have rapidly eroded.

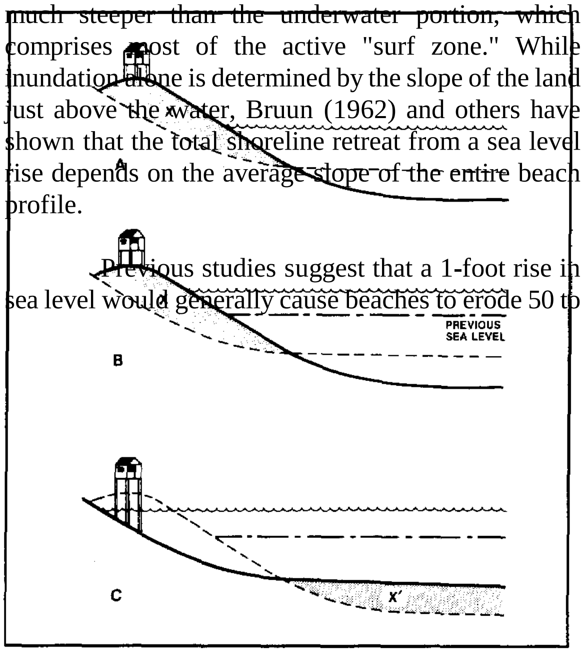

Figure 7-4. The Bruun Rule: (A) initial condition; (B) immediate inundation when sea level rises; (C) subsequent erosion due to sea level rise. A rise in sea level immediately results in shoreline retreat due to inundation, shown in the first two examples. However, a 1-meter rise in sea level implies that the offshore bottom must also rise 1 meter. The sand required to raise the bottom (X') can be supplied by beach nourishment. Otherwise, waves will erode the necessary sand (X) from upper part of the beach as shown in (C).

Flooding

If sea level rises, flooding would increase along the coast for four reasons: (1) A higher sea level provides a higher base for storm surges to build upon. A 1-meter sea level rise would enable a 15-year storm to flood many areas that today are flooded only by a 100-year storm (e.g., Kana et al., 1984; Leatherman, 1984). (2) Beach erosion also would leave oceanfront properties more vulnerable to storm waves. (3) Higher water levels would reduce coastal drainage and thus would increase flooding attributable to rainstorms. In artificially drained areas such as New Orleans, the increased need for pumping could exceed current capacities. (4) Finally, a rise in sea level would raise water tables and would flood basements, and in cases where the groundwater is just below the surface, perhaps raise it above the surface.

Saltwater Intrusion

A rise in sea level would enable saltwater to penetrate farther inland and upstream into rivers, bays, wetlands, and aquifers. Salinity increases would be harmful to some aquatic plants and animals, and would threaten human uses of water. For example, increased salinity already has been cited as a factor contributing to reduced oyster harvests in the Delaware and Chesapeake Bays, and to conversion of cypress swamps to open lakes in Louisiana. Moreover, New York, Philadelphia, and much of California's Central Valley obtain their water from areas located just upstream from areas where the water is salty during droughts. Farmers in central New Jersey and the city of Camden rely on the Potomac-Raritan-Magothy Aquifer, which could become salty if sea level rises (Hull and Titus, 1986). The South Florida Water Management District already spends millions of dollars every year to prevent Miami's Biscayne Aquifer from becoming contaminated with seawater.

Responses

The possible responses to inundation, erosion, and flooding fall broadly into three categories: erecting walls to hold back the sea, allowing the sea to advance and adapting to the advance, and raising the land. Both the slow rise in sea level over the last thousand years and the areas where land has been sinking more rapidly offer numerous historical examples of all three responses.

For over five centuries, the Dutch and others have used dikes and windmills to prevent inundation from the North Sea. By contrast, many cities have been rebuilt landward as structures have eroded; the town of Dunwich, England, has rebuilt its church seven times in the last seven centuries. More recently, rapidly subsiding communities (e.g., Galveston, Texas) have used fill to raise land elevations; the U.S. Army Corps of Engineers and coastal states regularly pump sand from offshore locations to counteract beach erosion. Venice, a hybrid of all three responses, has allowed the sea to advance into the canals, has raised some lowlands, and has erected storm protection barriers.

Most assessments in the United States have concluded that low-lying coastal cities would be protected with bulkheads, levees, and pumping systems, and that sparsely developed areas would adapt to a naturally retreating shoreline (e.g., Dean et al., 1987; Gibbs, 1984; Schelling, 1983). This conclusion has generally been based on estimates that the cost of structural protection would be far less than the value of the urban areas being protected but would be greater than the value of undeveloped land.

Studies on the possible responses of barrier islands and moderately developed mainland communities show less agreement but generally suggest that environmental factors would be as important as economics. Some have suggested that barrier islands should use seawalls and other "hard" engineering approaches (e.g., Kyper and Sorensen, 1985; Sorensen et al., 1984). Others have pointed to the esthetic problems associated with losing beaches and have advocated a gradual retreat from the shore (Howard et al., 1985). Noting that new houses on barrier islands are generally elevated on pilings, Titus (1986) suggested that communities could hold back the sea but keep a natural beach by extending the current practice of pumping sand onto beaches to raising entire islands in place.

Responses to erosion are more likely to have adverse environmental impacts along sheltered water than on the open coast (Titus, 1986). Because the beach generally is a barrier island's most important asset, economics would tend to encourage these communities to preserve their natural shorelines; actions that would prevent the island from breaking up also would protect the adjacent wetlands. However, along most mainland shorelines, economic self-interest would encourage property owners to erect bulkheads; these would prevent new wetland formation from offsetting the loss of wetlands that were inundated.

Most of the measures for counteracting saltwater intrusion attributable to sea level rise have also been employed to address current problems. For example, the Delaware River Basin Commission protects Philadelphia's freshwater intake on the river and New Jersey aquifers recharged by the river by storing water in reservoirs during the wet season and releasing it during droughts, thereby forcing the saltwater back toward the sea. Other communities have protected coastal aquifers by erecting underground barriers and by maintaining freshwater pressure through the use of impoundments and injection wells.

HOLDING BACK THE SEA: A NATIONAL ASSESSMENT

The studies referenced in the previous section have illustrated a wide variety of possible effects from and responses to a rise in sea level from the greenhouse effect. Although they have identified the implications of the risk of sea level rise for specific locations and decisions, these studies have not estimated the nationwide magnitude of the impacts. This report seeks to fill that void.

It was not possible to estimate the nationwide value of every impact of sea level rise. The studies thus far conducted suggest that the majority of the environmental and economic costs would be associated with shoreline retreat and measures to hold back the sea, which can be more easily assessed on a nationwide basis. Because the eventual impact will depend on what people actually do, a number of important questions can be addressed within this context:

- Would a gradual abandonment of moderately developed mainland areas significantly increase the amount of wetlands that survived a rise in sea level?

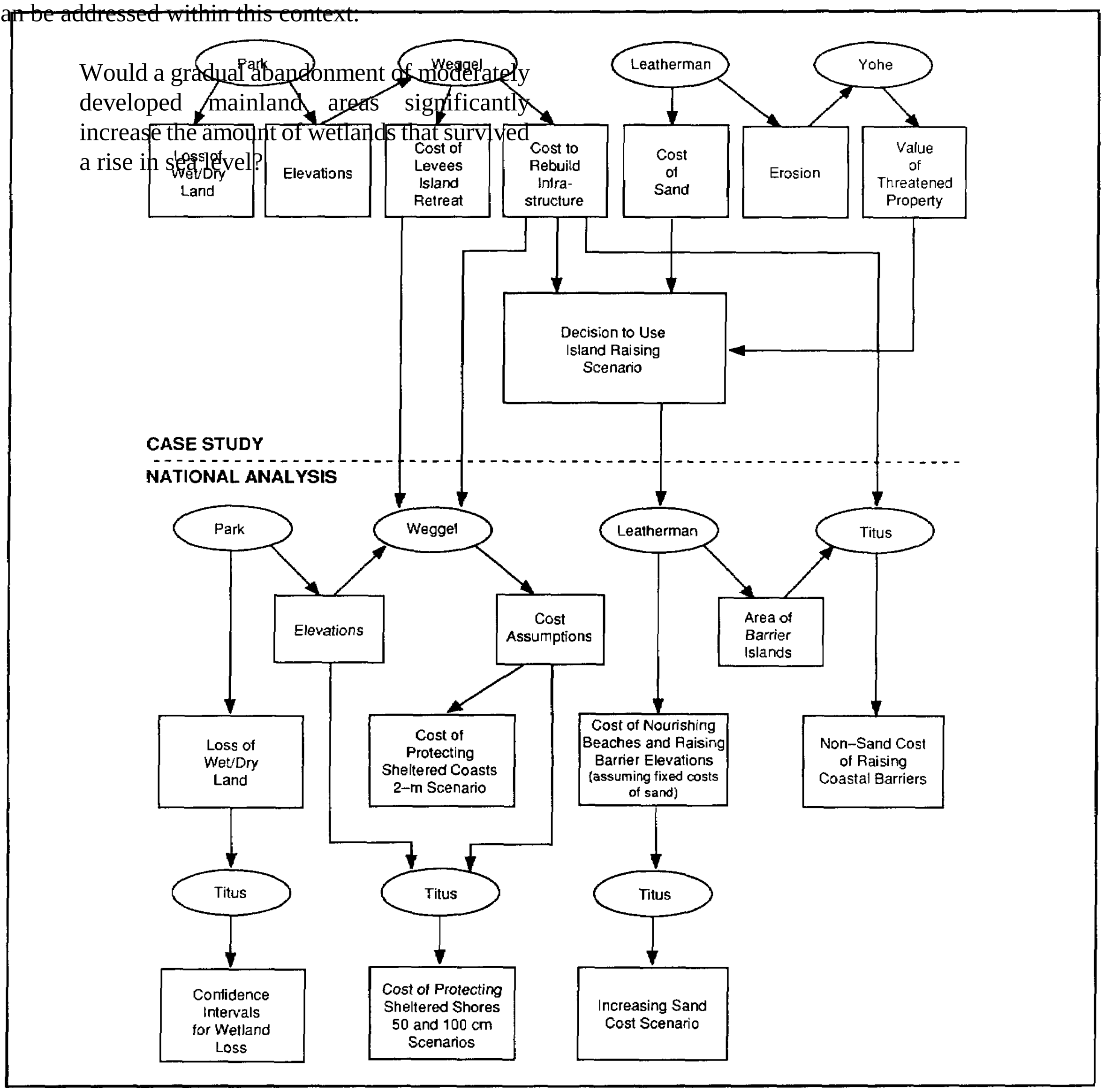

Figure 7-5. Overview of sea level rise studies and authors.

- Would the concave profiles of coastal areas ensure that more wetlands would be lost than gained, regardless of land-use decisions?

- Should barrier islands be raised in place by pumping sand and elevating structures and utilities?
- Would a landward migration of developed barrier islands or encircling them with dikes and levees be feasible alternatives?
- How much property would be lost if barrier islands were abandoned?

STRUCTURE OF STUDIES FOR THIS REPORT

A central theme underlying these questions is that the implications of sea level rise for a community depend greatly on whether people adjust to the natural impact of shoreline retreat or undertake efforts to hold back the sea. Because no one knows the extent to which each of these approaches would be applied, this study was designed to estimate the impacts of sea level rise for (1) holding back the sea, and (2) natural shoreline retreat.

The tasks were split into five discrete projects:

1. Park et al. estimated the loss of coastal wetlands and dryland.

2. Leatherman estimated the cost of pumping sand onto open coastal beaches and barrier islands.

3. Weggel et al. estimated the cost of protecting sheltered shores with levees and bulkheads.

4. Yohe began a national economic assessment by estimating the value of threatened property.

5. Titus and Greene synthesized the results of other studies to estimate ranges of the nationwide impacts.

Figure 7-5 illustrates the relationships between the various reports. (All of the sea level rise studies are in Volume B of the Appendices to this report.) As the top portion shows, the assessment began with a case study of Long Beach Island, New Jersey, which was necessary for evaluating methods and providing data for purposes of extrapolation. The Park and Leatherman studies performed the same calculations for the case study site that they would subsequently perform for the other sites in the nationwide analysis. However, Weggel and Yohe conducted more detailed assessments of the case study whose results were used in the Leatherman and Titus studies.

Because it would not be feasible for Leatherman to examine more than one option for the cost of protecting the open coast, Weggel estimated the cost of protecting Long Beach Island by three approaches: (1) raising the island in place; (2) gradually rebuilding the island landward; and (3) encircling the island with dikes and levees. Yohe estimated the value of threatened structures. Titus analyzed Weggel's and Yohe's results and concluded that raising barrier islands would be the most reasonable option for the Leatherman study and noted that the cost of this option would be considerably less than the resources that would be lost if the islands were not protected as shown in Figure 7-6.

Once the case study was complete, Park, Leatherman, and Weggel proceeded independently with their studies (although Park provided Weggel with elevation data). When those studies were complete, Titus synthesized their results, developing a nationwide estimate of the cost of holding back the sea and interpolating Weggel's 200-centimeter results for the 50- and 100centimeter scenarios.

In presenting results from the Park and Weggel studies, the sites were grouped into seven coastal regions, four of which are in the Southeast: New England, mid-Atlantic, south Atlantic, south Florida/gulf coast peninsula, Louisiana, other gulf (Texas, Mississippi, Alabama, Florida Panhandle), and the Pacific coast. Figure 7-7 illustrates these regions.

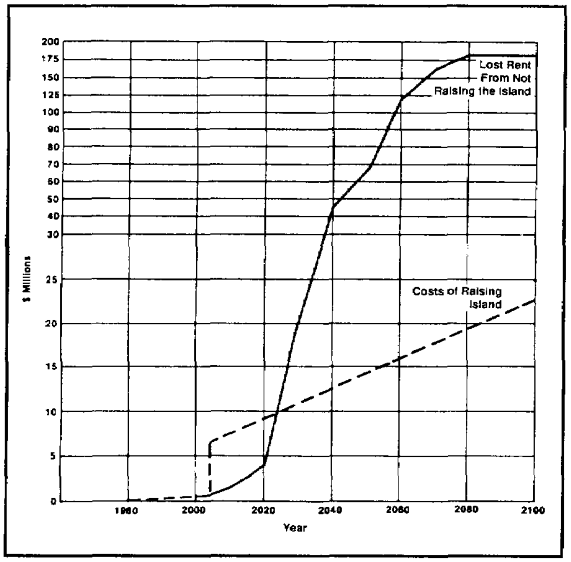

Figure 7-6. Annual cost of raising island versus annual costs (lost rent) from not protecting the island (in 1986 dollars) (Titus and Greene, Volume B).

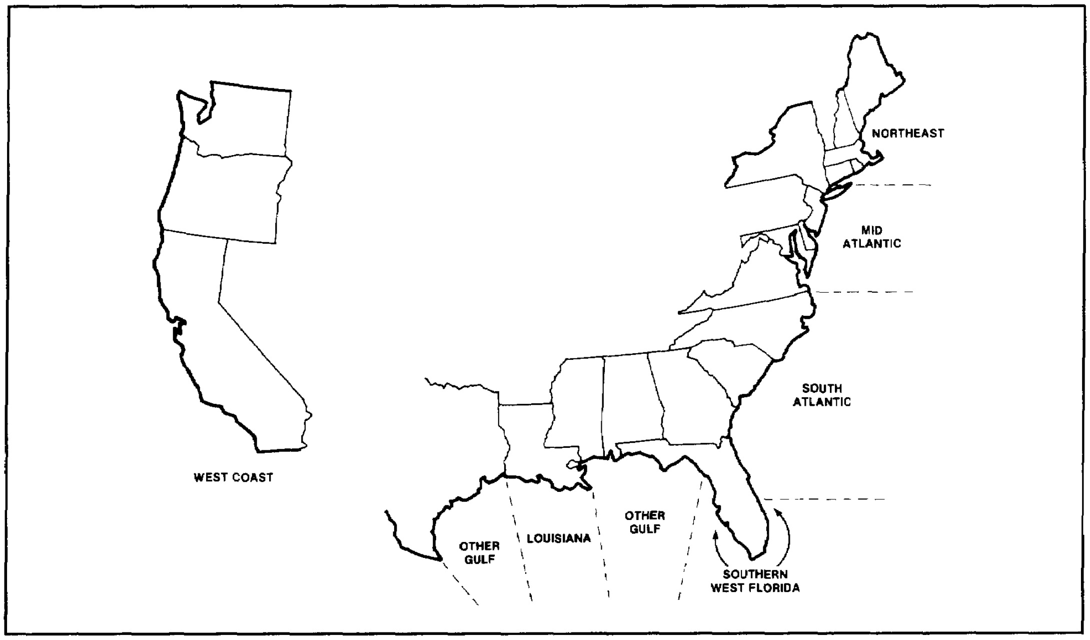

Figure 7-7. Costal regions used in this study.

SCENARIOS OF SEA LEVEL RISE

Although the researchers considered a variety of scenarios of future sea level rise, this report focuses on the impacts of three scenarios: rises of 50, 100, and 200 centimeters by the year 2100. All three of these scenarios are based on quantitative estimates of sea level rise. No probabilities were associated with these scenarios. Following the convention of a recent National Research Council report (Dean et al., 1987), the rise was interpolated throughout the 21st century using a quadratic (parabola). For each site, local subsidence was added to determine relative sea level rise. Figure 7-8 shows the scenarios for the coast of Florida where relative sea level rise will be typical of most of the U.S. coast. Sea level would rise 1 foot by 2025, 2040, and 2060 for the three scenarios and 2 feet by 2045, 2065, and 2100.

RESULTS OF SEA LEVEL STUDIES IN THIS REPORT

Loss of Coastal Wetlands and Dryland

Park (Volume B) sought to test a number of hypotheses presented in previous publications:

- A rise in sea level greater than the rate of vertical wetland accretion would result in a net loss of coastal wetlands.

- The loss of wetlands would be greatest if all developed areas were protected, less if shorelines retreated naturally, and least if barrier islands were protected while mainland shores retreated naturally.

- The loss of coastal wetlands would be greatest in the Southeast, particularly Louisiana.

Study Design

Park's study was based on a sample of 46 coastal sites that were selected at regular intervals. This guaranteed that particular regions would be represented in proportion to their total area in the coastal zone. The sites chosen accounted for 10% of the U.S. coastal zone excluding Alaska and Hawaii. To estimate the potential loss of wet and dry land, Park first had to characterize their elevations. For wetlands, he used satellite imagery to determine plant species for 60- by 80-meter parcels. Using estimates from the literature on the frequency of flooding that can be tolerated by various wetland plants, Park determined the percentage of time that particular parcels are currently under water.

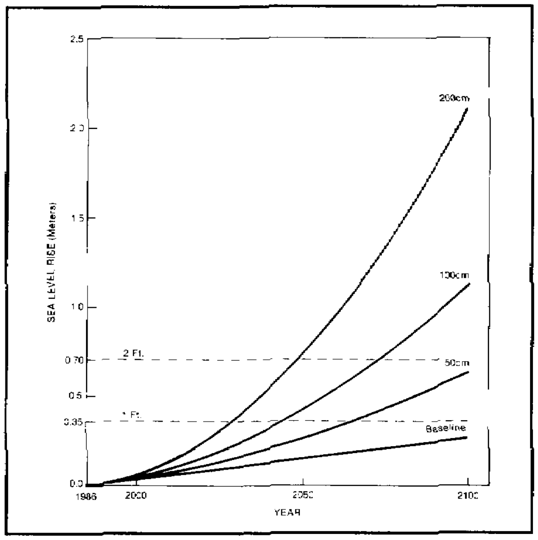

Figure 7-8. Sea level scenarios (Miami Beach).

From this, Park inferred wetland elevation based on the known tidal range. For dryland, he used spot elevation measurements to interpolate between contours on U.S. Geological Survey topographic maps.

Park estimated the net loss of wetlands and dryland for no protection, protection of developed areas, and protection of all shores. For the no-protection scenario, estimating the loss of dryland is straightforward. However, for calculating net wetland loss, Park had to estimate the loss of existing wetlands as well as the creation of new wetlands. For calculating losses, Park used published vertical accretion rates (see Armentano et al., 1988), although he allowed for some acceleration of vertical accretion in areas with ample supplies of sediment, such as tidal deltas. Park assumed that dryland would convert to wetlands within 5 years of being inundated.

For sites in the Southeast, Park also allowed for the gradual replacement of salt marshes by mangrove swamps. The upper limit for mangroves is around Fort Lauderdale. Park used the GISS transient scenario to determine the year particular sites would be as warm as Fort Lauderdale is today and assumed that mangroves would begin to replace marsh after that year.

Limitations

The greatest uncertainty in Park's analysis is a poor understanding of the potential rates of vertical accretion. Although this could substantially affect the results for low sea level rise scenarios, the practical significance is small for a rise of 1 meter because it is generally recognized that wetlands could not keep pace with the rise of 1 to 2 centimeters per year that such a scenario implies for the second half of the 21st century.

Errors can be made when determining vegetation type based on the use of infrared "signatures" that satellites receive. Park noted, for example, that in California the redwoods have a signature similar to that of marsh grass. For only a few sites, Park was able to corroborate his estimates of vegetation type.

Park's study did not consider the potential implications of alternative methods of managing riverflow. This limitation is particularly serious regarding application to Louisiana, where widely varying measures have been proposed to increase the amount of water and sediment delivered to the wetlands. Finally, the study makes no attempt to predict which undeveloped areas might be developed in the next century.

At the coarse (500-meter) scale Park used, the assumption of protecting only developed areas amounts to not protecting a number of mainland areas where the shoreline is developed but areas behind the shoreline are not. Therefore, Park's estimates for protecting developed areas should be interpreted as applying to the case where only densely developed areas are protected. Finally, Park's assumption that dryland would convert to vegetated wetlands within 5 years of being inundated probably led him to underestimate the net loss of wetlands due to sea level rise.

Results

Park's results supported the hypotheses suggested by previous studies. Figure 7-9 shows nationwide wetlands loss for various (0- to 3-meter) sea level rises for the three policy options investigated. For a 1-meter rise, 66% of all coastal wetlands would be lost if all shorelines were protected, 49% would be lost if only developed areas were protected, and 46% would be lost if shorelines retreated naturally.

As expected, the greatest losses of wetlands would be in the Southeast, which currently contains 85% of U.S. coastal wetlands (Figure 7-9). For a 1-meter sea level rise, 6,000 to 8,600 square miles (depending on which policy is implemented) of U.S. wetlands would be lost; 90 to 95% of this area would be in the Southeast, and 40 to 50% would be in Louisiana alone. By contrast, neither the Northeast nor the West would lose more than 10% of its wetlands if only currently developed areas are protected.

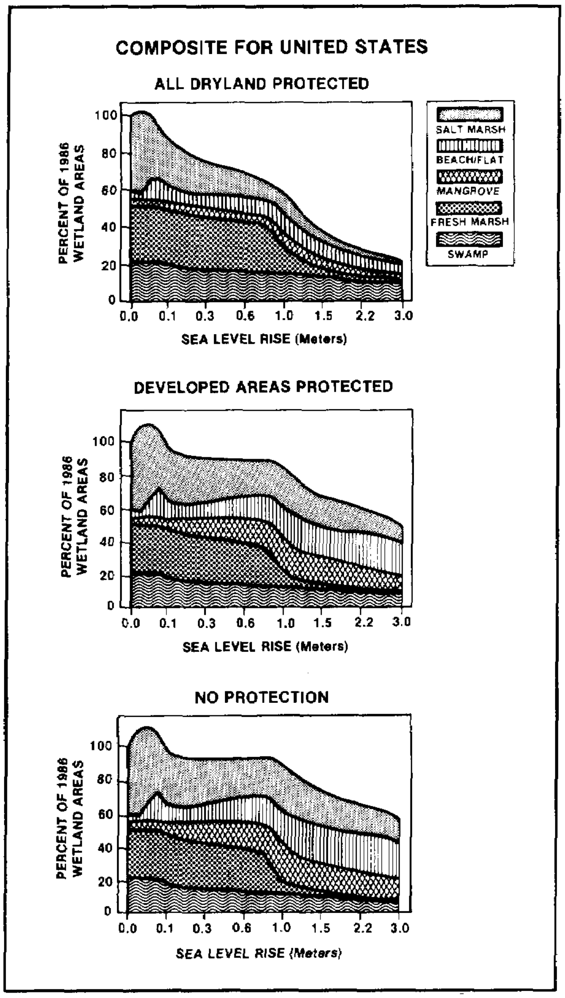

Figure 7-9. Nationwide wetlands loss for three shoreline-protection options. Note: These wetlands include beaches and flats that are not vegetated wetlands; however, results cited in the text refer to vegetated wetlands (Park, Volume B).

Figure 7-10 illustrates Park's estimates of the inundation of dryland for the seven coastal regions. If shorelines retreated naturally, a 1-meter rise would inundate 7,700 square miles of dryland, an area the size of Massachusetts. Rises of 50 and 200 centimeters would result in losses of 5,000 and 12,000 square miles, respectively. Approximately 70% of the dryland losses would occur in the Southeast, particularly Florida, Louisiana, and North Carolina. The eastern shores of the Chesapeake and Delaware Bays also would lose considerable acreage.

Costs of Defending Sheltered Shorelines

Study Design

This study began by examining Long Beach Island in depth. This site and five other sites were used to develop engineering rules of thumb for the cost of protecting coastal lowlands from inundation. Examining the costs of raising barrier islands required an assessment of two alternatives: (1) building a levee around the island; and (2) allowing the island to migrate landward.

After visiting Long Beach Island and the adjacent mainland, Weggel (Volume B) designed and estimated costs for an encirclement scheme consisting of a levee around the island and a drainage system that included pumping and underground retention of stormwater. For island migration, he used the Bruun Rule to estimate oceanside erosion and navigation charts to calculate the amount of sand necessary to fill the bay an equivalent distance landward. For island raising and island migration, Weggel used the literature to estimate the costs of elevating and moving houses and of rebuilding roads and utilities.

Weggel's approach for estimating the nationwide costs was to examine a number of index sites in depth and thereby develop generalized cost estimates for protecting different types of shorelines. He used the topographic information collected by Park for a sample of 95 sites to determine the area and shoreline length that had to be protected. He then applied the cost estimation factors to each site and extrapolated the sample to the entire coast.

After assessing Long Beach Island, Weggel conducted less detailed studies of the following areas:

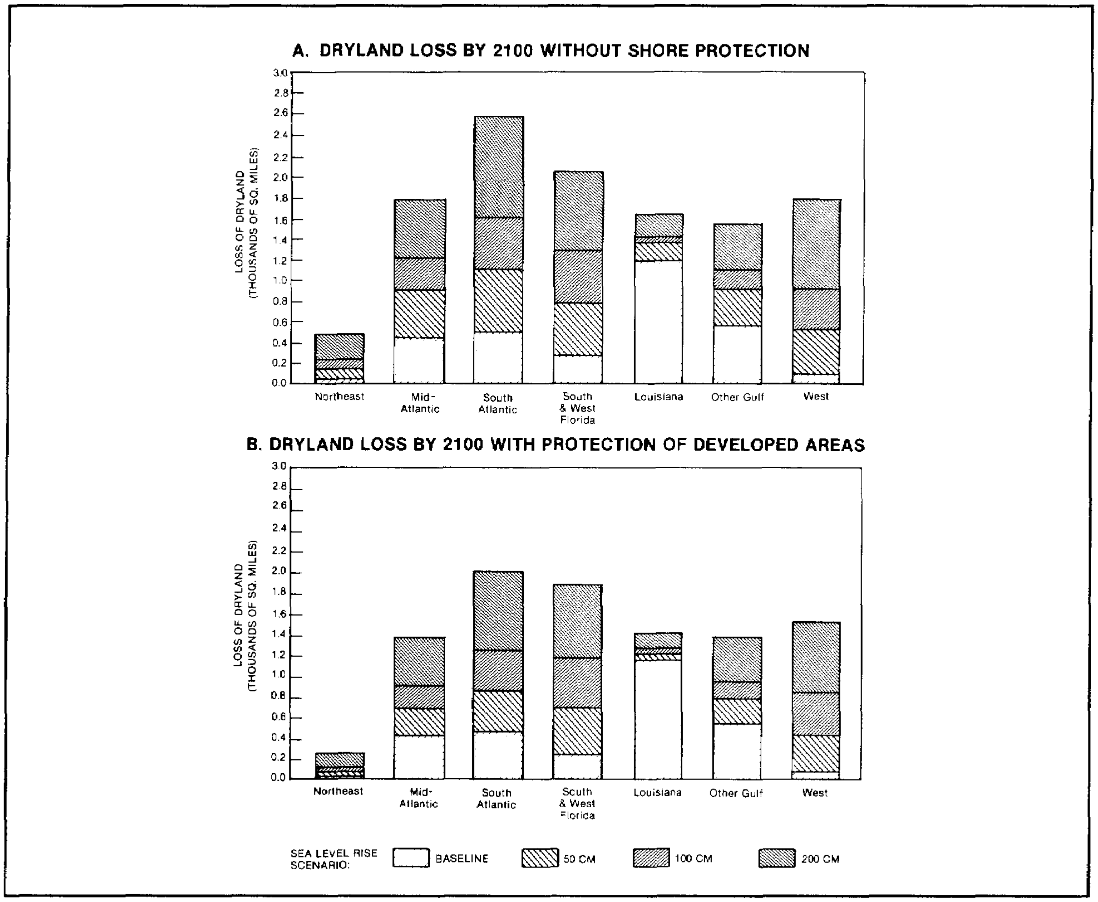

Figure 7-10. Loss of dryland by 2100: (A) if no areas are protected, and (B) if developed areas are protected with levees (derived from Park, Volume B; see also Titus and Greene, Volume B).

metropolitan New York; Dividing Creek, New Jersey; Miami and Miami Beach; the area around Corpus Christi, Texas; and parts of San Francisco Bay.

Limitations

The most serious limitation of the Weggel study is that cruder methods are used for the national assessment than for the index sites. Even for the index sites, the cost estimates are based on the literature, not on site-specific designs that take into consideration wave data for bulkheads and potential savings from tolerating substandard roads. Weggel did not estimate the cost of pumping rainwater out of areas protected by levees.

Finally, Weggel was able to examine only one scenario: a 2-meter rise by 2100. This scenario was chosen over the more likely 1-meter scenario because an interpolation from 2 meters to 1 meter would be more reliable than an extrapolation from 1 meter to 2 meters. (See the discussion of Titus and Greene for results of the interpolation.)

Results

Case Study of Long Beach Island

Weggel's cumulative cost estimates clearly indicate that raising Long Beach Island would be much less expensive ($1.7 billion) than allowing it to migrate landward ($7.7 billion). Although the cost of building a levee around the island ($800 million) would be less, the "present value" would be greater. Weggel concluded that the levee would have to be built in the 2020s, whereas the island could be raised gradually between 2020 and 2100. Thus, the (discounted) present value of the levee cost would be greater, and raising the necessary capital for a levee at any one time could be more difficult than gradually rebuilding the roads and elevating houses as the island was raised. Moreover, a levee would eliminate the waterfront view. A final disadvantage of building a levee is that one must design for a specific magnitude of sea level rise; by contrast, an island could be raised incrementally.

The Weggel analysis shows that landward migration is more expensive than island raising, primarily because of the increased costs of rebuilding infrastructure. Thus, migration might be less expensive in the case of a very lightly developed island. Levees might be more practical for wide barrier islands where most people do not have a waterfront view.

Nationwide Costs

Table 7-2 shows Weggel's estimates for the index sites and his nationwide estimate. The index sites represent two distinct patterns. Because urban areas such as New York and Miami would be entirely protected by levees, the cost of moving buildings and rebuilding roads and utilities would be relatively small. On the other hand, Weggel concluded that in more rural areas such as Dividing Creek, New Jersey, only the pockets of development would be protected. The roads that connected them would have to be elevated or replaced with bridges, and the small number of isolated buildings would have to be moved.

Weggel estimates that the nationwide cost of protecting developed shorelines would be $25 billion, assuming bulkheads are built, and $80 billion assuming levees are built. Unlike wetlands loss, the cost of protecting developed areas from the sea would be concentrated more in the Northeast than in the Southeast because a much greater portion of the southeastern coast is undeveloped.

Table 7-1. Total Cost of Protecting Long Beach Island from a 2-Meter Rise in Sea Level (millions of 1986 dollars)

Protective measure	Encirclement	Island raising	Island mitigation
Sand Costs			
Beach	290	290	0
Land creation/maintenance	NA	270	321
Moving/elevating houses	NA	74	37
Roads/utilities	0	1072	7352
Levee and drainage	542	0	0
Total	832	1706	7710

NA = Not applicable.
Source: Leatherman (Volume B); Weggel (Volume B)

Table 7-2. Cumulative Cost of Protecting Sheltered Waters for a 2-Meter Rise in Sea Level (millions of 1986 dollars)

	New bulkhead	Raise old bulkhead	Move building	Roads/ utilities	Total
Index sites					
New York	57	205	0.5	9.5	272.3
Long Beach Island	3	4	2.7	3.8	13.7
Dividing Creek	4	6	4.8	18.2	33.0
Miami area	11	111	0.3	8.3	130.7
Corpus Christi	11	29	2.8	40.9	83.4
San Francisco Bay[a]	3	19	2.0	20.0	44.0
Nationwide estimate					
	low		high		
Northeast	6,932		23,607		
Mid-Atlantic	4,354		14,603		
Southeast	9,249		29,883		
West	4,097		12.802		
Nation	24,633		80,176		

[a] Site names refer to the name of the U.S. Geological Survey quadrant, not to the geographical area of the same name.
Source: Weggel et al. (Volume B).

Case Study of the Value of Threatened Coastal Property

Study Design

Yohe's (Volume B) objective was to estimate the loss of property that would result from not holding back the sea. Using estimates of erosion and inundation for Long Beach Island from Leatherman and Park et al., Yohe determined which land would be lost from sea level rise for a sample of strips spanning the island from the ocean to the bay. He then used the Ocean County, New Jersey, tax assessor's estimates of the value of the land and structures that would be lost, assuming that the premium associated with a view of the bay or ocean would be transferred to another property owner and not lost to the community. He estimated the annual stream of rents that would be lost by assuming that the required return on real estate is 10% after tax. Yohe assumed that a property on the bay side was "lost" whenever it was flooded at high tide, and that property on the ocean side was "lost" when the house was within 40 feet of the spring high tide mark. (See Titus and Greene, Volume B, for discussion.)

Limitations

Yohe's results for a sea level rise of less than 18 inches are sensitive to the assumption regarding when a property would be lost. On the bay side, people might learn to tolerate tidal inundation. Unless a major storm occurred, people could probably occupy oceanfront houses until they were flooded at high tide. However, the resulting loss of recreational use of the beach probably would have a greater impact than abandoning the structure. Tax maps do not always provide up-to-date estimates of property values. However, the distinction between the tax assessor's most recent estimate of market value and the current market value is small compared with the possible changes in property values that will occur over the next century; hence, Titus and Greene used tax assessors estimates of market values.

Results

Yohe's results suggest that the cost of gradually raising Long Beach Island would be far less than the value of the resources that would be protected. Figure 7-6 compares Yohe's estimates of the annual loss in rents resulting from not holding back the sea with Weggel's estimates of the annual cost of raising the island for the 2-meter scenario. With the exception of the 2020s, the annual loss in rents resulting from not holding back the sea would be far less than the annual costs of pumping sand and elevating structures. Titus and Greene point out that the cost would be approximately $1,000 per year per house, equivalent to 1 week's rent (peak season).

Nationwide Cost of Pumping Sand Onto Recreational Beaches

Leatherman's goal (Volume B) was to estimate the cost of defending the U.S. ocean coast from a rise in sea level.

Study Design

Owing to time constraints, it was possible to consider only one technology. Based on the Long Beach Island results, Leatherman assumed that the cost of elevating recreational beaches and coastal barrier islands by pumping in offshore sand would provide a more representative cost estimate than assuming that barrier islands would be abandoned, would migrate landward, or would be encircled with dikes and levees.

The first step in Leatherman's analysis was to estimate the area of (1) the beach system, (2) the low bayside, and (3) the slightly elevated oceanside of the island. Given the areas, the volume of sand was estimated by assuming that the beach system would be raised by the amount of sea level rise. The bay and ocean sides of the island would not be raised until after a sea level rise of 1 and 3 feet, respectively. Cost estimates for the sand were derived from inventories conducted by the U.S. Army Corps of Engineers.

Leatherman applied this method to all recreational beaches from Delaware Bay to the mouth of the Rio Grande, as well as California, which accounts for 80% of the nation's beaches. He also examined one representative site in each of the remaining states.

Limitations

Although the samples of sites in the Northeast and Northwest are representative, complete coverage would have been more accurate. Furthermore, Leatherman used conservative assumptions in estimating the unit costs of sand. Generally, a fraction of the sand placed on a beach washes away because the sand's grain is too small. Moreover, as dredges have to move farther offshore to find sand, costs will increase.

For Florida, Leatherman used published estimates of the percentage of fine-grain sand and assumed that the dredging cost would rise $1 per cubic yard for every additional mile offshore the dredge had to move. For the other states, however, he assumed that the deposits mined would have no t-me-grain sand and that dredging costs would not increase. (To test the sensitivity of this assumption, Titus and Greene developed an increasing-cost scenario.) Leatherman assumed no storm worse than the 1-year storm, which underestimates the sand volumes required.

A final limitation of the Leatherman study is that it represents the cost of applying a single technology throughout the ocean coasts of the United States. Undoubtedly, some communities (particularly Galveston and other wide barrier islands in Texas) would find it less expensive to erect levees and seawalls or to accept a natural shoreline retreat.

Results

Table 7-3 illustrates Leatherman's estimates. A total of 1,900 miles of shoreline would be nourished. Of 746 square miles of coastal barrier islands that would be raised for a 4-foot sea level rise, 208 square miles would be for a 2-foot rise. As the table shows, two-thirds of the nationwide costs would be borne by four southeastern states: Texas, Louisiana, Florida, and South Carolina.

Figure 7-11 illustrates the cumulative nationwide costs over time. For the 50- and 200-centimeter scenarios, the cumulative cost would be $2.3 to $4.4 billion through 2020, $11 to $20 billion through 2060, and $14 to $58 billion through 2100. By

Table 7-3. Cost of Placing Sand on U.S. Recreational Beaches and Coastal Barrier Islands and Spits (millions of 1986 dollars).

	Sea level rise by 2100			
State	Baseline	50 cm	100 cm	200 cm
Maine[a]	22.8	119.4	216.8	412.2
New Hampshire[a]	8.1	38.9	73.4	142.0
Massachusetts[a]	168.4	489.5	841.6	1,545.8
Rhode Island[a]	16.3	92.0	160.6	298.2
Connecticut[a]	101.7	516.4	944.1	1,799.5
New York[a]	143.6	769.6	1,373.6	2,581.4
New Jersey[a]	157.6	902.1	1,733.3	3,492.5
Delaware	4.8	33.6	71.1	161.8
Maryland	5.7	34.5	83.3	212.8
Virginia	30.4	200.8	386.5	798.0
North Carolina	137.4	655.7	1,271.2	3,240.4
South Carolina	183.5	1,157.9	2,147.7	4,347.7
Georgia	25.9	153.6	262.6	640.3
Florida (Atlantic coast)	120.1	786.6	1,791.0[b]	7,745.5[b]
Florida (Gulf coast)	149.4	904.3	1,688.4[b]	4,091.6[b]
Alabama	11.0	59.0	105.3	259.6
Mississippi	13.4	71.9	128.3	369.5
Louisiana	1,955.8	2,623.1	3,492.7	5,231.7
Texas	349.6	4,188.3	8,489.7	17,608.3
California	35.7	147.1	324.3	625.7
Oregon[a]	21.9	60.5	152.5	336.3
Washington State[a]	51.6	143.0	360.1	794.4
Hawaii[a]	73.5	337.6	646.9	1,267.5
Nation	3,788.0	14,512.0	26,745.0	58,002.0

[a] Indicates states where estimate was based on extrapolating a representative site to the entire state. All other states have 100% coverage.

[b] Florida estimates account for the percentage of fine-grain sediment, which generally washes away, and for cost escalation as least expensive sand deposits are exhausted. All other estimates conservatively ignore this issue.

Source: Leatherman (Volume B) (baseline derived from Leatherman).

contrast, if current trends continue, the total cost of sea level rise for beach nourishment would be about $35 million per year.

Synthesis of the Three National Studies

Study Design

Although Weggel used Park's topographic data, the analysis in the three nationwide studies proceeded independently. Titus and Greene's primary objectives (Volume B) were to combine various results to estimate the nationwide cost of holding back the sea for various sea level rise scenarios and to derive the ranges for the specific impacts. The objectives were as follows:

1. Use Park's results to weigh weggel's high and low scenarios according to whether levees or bulkheads would be necessary, and interpolate Weggel's cost estimate for the 2-meter rise to rises of 50 and 100 centimeters;
2. Use results from Leatherman and Weggel, along with census data, to estimate the nationwide cost (other than pumping sand) of raising barrier islands;
3. Develop an increasing-cost scenario for the cost of protecting the open ocean coast; and
4. Develop statistical confidence intervals for wetland loss, impacts of the various policy options, and costs of protecting developed shores.

Titus and Greene developed a single estimate for protecting each site with bulkheads and levees by assuming that the portion of developed areas protected with levees would be equal to the portion of the lowlands that Park estimated would be inundated. They interpolated the resulting 2-meter estimate to 50-and 100-centimeter estimates, based on Weggel's assumption that the cost of building bulkheads and levees rises as a function of the structure's height.

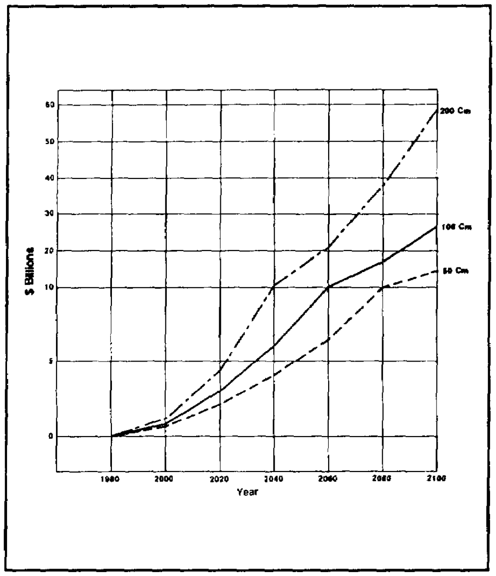

Figure 7-11. Nationwide cost of sand for protecting ocean coast (in 1986 dollars) (Leatherman, Volume B).

Cost of Protecting Sheltered Shores Cost of Raising Barrier Islands Other Than Dredging

Weggel's case study of Long Beach Island provided cost estimates for elevating structures and rebuilding roads, while Leatherman estimated the area that would have to be raised. Many barrier islands have development densities different from those of Long Beach Island because they have large tracts of undeveloped land or larger lot sizes. Therefore, Titus and Greene used census data to estimate a confidence interval for the average building density of barrier islands, and they applied Weggel's cost factors.

Sensitivity of Sand Costs to Increasing Scarcity of Sand

Titus and Greene used Leatherman's escalating cost assumptions for Florida to estimate sand pumping costs for the rest of the nation.

Confidence Intervals

The Park and Weggel studies involved sampling, but the researchers did not calculate statistical confidence intervals. Therefore, Titus and Greene developed 95% confidence intervals for the cost of protecting sheltered coasts, the area of wetlands loss for various scenarios.

Limitations

Besides all of the limitations that apply to the Park, Leatherman, and Weggel studies, a number of others apply to Titus and Greene.

Cost of Protecting Sheltered Shores

Titus and Greene assumed that the portion of the coast requiring levees (instead of bulkheads) would be equal to the portion of lowlands that otherwise would be inundated. This assumption tends to understate the need for levees. For example, a community that is 75% high ground often would still have very low land along all of its shoreline and hence would require a levee along 100% of the shore. But Titus and Greene assume that only 25% would be protected by levees.

Cost of Raising Banier Islands

The data provided by Weggel focused only on elevating roads, buildings, and bulkheads. Thus, Titus and Greene do not consider the cost of replacing sewers, water mains, or buried cables. On the other hand, Weggel's cost factors assume that rebuilt roads would be up to engineering standards; it is possible that communities would tolerate substandard roads. In addition, the census data Titus and Greene used were only available for incorporated communities, many of which are part barrier island and part mainland; thus, the data provide only a rough measure of typical road density.

Sensitivity of Sand Costs to Increased Scarcity of Sand

Finally, Titus and Greene made no attempt to determine how realistic their assumption was that sand costs would increase by the same pattern nationwide as they would in Florida.

Results

Loss of Wetlands and Dryland

Table 7-4 illustrates 95% confidence intervals for the nationwide losses of wetlands and dryland. If all shorelines were protected, a 1-meter rise would result in a loss of 50 to 82% of U.S. coastal wetlands, and a 2-meter rise would result in a loss of 66 to 90%. If only the densely developed areas were protected, the losses would be 29 to 69% and 61 to 80% for the 1- and 2-meter scenarios, respectively. Except for the Northeast, no protection results in only slightly lower wetland loss than protecting only densely developed areas. Although the estimates for the Northeast, midAtlantic, the gulf regions outside Louisiana, and the Florida peninsula are not statistically significant (at the 95% confidence levels), results suggest that wetlands loss would be least in the Northeast and Northwest.

Table 7-4. Nationwide Loss of Wetlands and Dryland[a] (95% confidence intervals)

	Square miles[b]			
	Baseline	50-cm rise	100-cm rise	200-cm rise
Wetlands				
Total protection	N.C.	4944-8077 (38-61)	6503-10843 (50-82)	8653-11843 (66-90)
Standard protection	1168-3341 (9-25)	2591-5934 (20-45)	3813-9068 (29-69)	4350-10995 (33-80)
No protection	N.C.	2216-5592 (17-43)	3388-8703 (26-66)	3758-10025 (29-76)
Dryland				
Total protection	0	0	0	0
Standard protection	1906-3510	2180-6147	4136-9186	6438-13496
Total protection	N.C.	3315-7311	5123-10330	8791-15394

a Wetlands loss refers to vegetative wetlands only. b Numbers in parentheses are percentages N.C.= not calculated.
Source: Titus and Greene (Volume B).

Table 7-5. Cumulative Nationwide Cost of Protecting Barrier Islands and Developed Mainland Through the Year 2100 (billions of 1986 dollars)[a]

	Sea level scenario			
	Baseline	50-cm rise	100-cm rise	200-cm rise
Open coast				
Sand	3.8	15-20	27-41	58-100
Raise houses, roads, utilities	0	9-13	21-57	75-115
Sheltered shores	1.0-2.4	5-13	11-33	30-101
Total[b]	4.8-6.2	32-43	73-111	119-309

[a] Costs due to sea level rise only

[b] Ranges for totals are basd in the square root of the sum of the squared ranges.

Source: Titus and Green (Volume B).

Costs of Holding Back the Sea

Table 7-5 illustrates the Titus and Greene estimates of the costs of holding back the sea. The low range for the sand costs is based on Leatherman's study, and the high range is based on the increasing cost scenario Titus and Greene developed. The uncertainty range for the costs of elevating structures reflects the uncertainty in census data regarding the current density of development. High and low estimates for the cost of protecting sheltered shorelines are based on the sampling errors of the estimates for the 46 sites that both Park et al. and Weggel et al. examined.

Titus and Greene estimated that the cumulative nationwide cost of protecting currently developed areas in the face of a 1-meter rise would be from $73 to 111 billion, with costs for the 50- and 200-centimeter scenarios ranging from $32 to 309 billion. These costs would imply a severalfold increase in annual expenditures for coastal defense. Nevertheless, compared with the value of coastal property, the costs are small.

POLICY IMPLICATIONS

Wetlands Protection

The nationwide analysis showed that a 50- to 200-centimeter rise in sea level could reduce the coastal wetlands acreage (outside Louisiana) by 17 to 76% if no mainland areas were protected, by 20 to 80% if only currently developed areas were protected, and by 38 to 90% if all mainland areas were protected. These estimates of the areal losses understate the differences in impacts for the various land-use options. Although a substantial loss would occur even with no protection, most of today's wetland shorelines would still have wetlands; the strip simply would be narrower. By contrast, protecting all mainland areas would generally replace natural shorelines with bulkheads and levees. This distinction is important because for many species of fish, the length of a wetland shoreline is more critical than the total area.

Options for State and Local Governments

Titus (1986) examined three approaches for maintaining wetland shorelines in the face of a rising sea: (1) no further development in lowlands; (2) no action now but a gradual abandonment of lowlands as sea level rises; and (3) allowing future development only with a binding agreement to allow such development to revert to nature if it is threatened by inundation.

The first option would encounter legal or financial hurdles. The extent to which the "due-process" clause of the Constitution would allow governments to prevent development in anticipation of sea level rise has not been specifically addressed by the courts. Although purchases of land would be feasible for parks and refuges, the cost of buying the majority of lowlands would be prohibitive. Moreover, this approach requires preparation for a rise in sea level of a given magnitude; if and when the sea rises beyond that point, the wetlands would be lost. Finally, preventing future development would not solve the loss of wetlands resulting from areas that have already been developed.

Enacting no policy today and addressing the issue as sea level rises would avoid the costs of planning for the wrong amount of sea level rise but would probably result in less wetlands protection. People are developing coastal property on the assumption that they can use the land indefinitely. It would be difficult for any level of government to tell property owners that they must abandon their land with only a few years' notice, and the cost of purchasing developed areas would be even greater than the cost of buying undeveloped areas.

Economic theory suggests that under the third alternative, people would develop a property only if the temporary use provided benefits greater than the costs of writing it off early. This approach would result in the greatest degree of flexibility, because it would allow real estate markets to incorporate sea level rise and to determine the most efficient use of land as long as it remains dry.

This approach could be implemented by regulations that prohibit construction of bulkheads as sea level rises or by the use of conditional longterm leases that expire when high tide falls above a property's elevation.

The State of Maine (1987) has implemented this third approach through its coastal dune regulations, which state that people building houses along the shore should assume that they will have to move their houses if their presence prevents the natural migration of coastal wetlands, dunes, or other natural shorelines. A number of states also have regulations that discourage bulkheads, although they do not specifically address sea level rise. The option can be implemented through cooperative arrangements between developers, conservancy groups, and local governments. (See Titus and Greene, Volume B, for additional details.)

The Federal Role

Section 404 of the Clean Water Act discourages development of existing wetlands, but it does not address development of areas that might one day be necessary for wetland migration. This program will provide lasting benefits, even if most coastal wetlands are inundated. Although marshes and swamps would be inundated, the shallow waters that formed could provide habitat for fish and submerged aquatic vegetation. No one has assessed the need for a federal program to protect wetlands in the face of rising sea level.

Coastal Protection

State and Local Efforts

State and local governments currently decide which areas would be protected and which would be allowed to erode. Currently, few localities contribute more than 10% of the cost of beach nourishment, with the states taking on an increasing share from the federal government. However, many coastal officials doubt that their states could raise the necessary funds if global warming increased the costs of coastal protection over the next century by $50 to $300 billion. If state funds could not be found, the communities themselves would have to take on the necessary expenditures or adapt to erosion.

Long Beach Island, New Jersey, illustrates the potential difficulties. The annual cost of raising the island would average $200 to $1,000 per house over the next century (Titus and Greene, Volume B). Although this amount is less than one week's rent during the summer, it would more than double property taxes, an action that is difficult for local governments to contemplate. Moreover, the island is divided into six jurisdictions, all of which would have to participate.

More lightly developed communities may decide that the benefits of holding back the sea are not worthwhile. Sand costs would be much less for an island that migrated. Although Weggel estimated that higher costs would be associated with allowing Long Beach Island to migrate landward than with raising the island in place, this conclusion resulted largely from the cost of rebuilding sewers and other utilities that would still be useful if the island were raised.

Regardless of how a barrier island community intends to respond to sea level rise, the eventual costs can be reduced by deciding on a response well in advance. The cost of raising an island can be reduced if roads and utilities are routinely elevated or if they have to be rebuilt for other reasons (e.g., Titus et al., 1987). The cost of a landward migration also can be reduced by discouraging reconstruction of oceanfront houses destroyed by storms (Titus et al., 1984a). The ability to fund the required measures also would be increased by fostering the necessary public debate well before the funds are needed.

Federal Efforts

While state governments generally are responsible for protecting recreational beaches, the U.S. Army Corps of Engineers is responsible for several major federal projects to rebuild beaches and for efforts to curtail land loss in Louisiana. The long-term success of these efforts would be improved if the corps were authorized to develop comprehensive long-term plans to address the impacts of sea level rise.

Beach Erosion

In its erosion-control efforts, the corps has recently shifted its focus from hard structures (e.g., seawalls, bulkheads, and groins) to soft approaches, such as pumping sand onto beaches. This shift is consistent with the implications of sea level rise: groins and seawalls will not prevent loss of beaches due to sea level rise. Although more sand will have to be pumped than current analyses suggest, this approach could ensure the survival of the nation's beaches.

Nevertheless, consideration of accelerated sea level rise would change the cost-benefit ratios of many corps erosion control projects. As with the operations of reservoirs (discussed in Chapter 16: Southeast), the corps is authorized to consider flood protection but not recreation. When they evaluated the benefits of erosion control at Ocean City, Maryland, the corps concluded that less than 10% of the benefits would be for flood control (most were related to recreation). Had they considered accelerated sea level rise, however, the estimated flood protection benefits from having a protective beach would have constituted a considerably higher fraction of the total benefits (Titus, 1985).

Wetlands Loss in Louisiana

By preventing freshwater and sediment from reaching the coastal wetlands, federal management of the Mississippi River is increasing the vulnerability of coastal Louisiana to a sea level rise (e.g., Houck, 1983). For example, current navigation routes require the U.S. Army Corps of Engineers to limit the amount of water flowing through the Atchafalaya River and to close natural breaches in the main channel of the Mississippi; these actions limit the amount of freshwater and sediment reaching the wetlands. Alternative routes have been proposed that would enable water and sediment to reach the wetlands (Louisiana Wetland Protection Panel, 1987). These include dredging additional canals parallel to the existing Mississippi River gulf outlet or constructing a deepwater port east of the city.

Either of these options would cost a few billion dollars. By contrast, annual resources for correcting land loss in Louisiana have been in the tens of millions of dollars. As a result, mitigation activities have focused on freshwater diversion structures and on other strategies that can reduce current wetland loss attributable to high salinities but that would not substantially reduce wetlands loss if sea level rises 50 to 200 centimeters (Louisiana Wetland Protection Panel, 1987).

The prospect of even a 50-centimeter rise in sea level suggests that solving the Louisiana wetlands loss problem is much more urgent than is commonly assumed. Because federal activities are now a major cause of land loss, and would have to be modified to enable wetlands to survive a rising sea, the problem is unlikely to be solved without a congressional mandate. A recent interagency report concluded that "no one has systematically determined what must be done to save 10, 25, or 50 percent of Louisiana's coastal ecosystem" (Louisiana Wetland Protection Panel, 1987). Until someone estimates the costs and likely results of strategies with a chance of protecting a significant fraction of the wetlands in face of rising sea level, it will be difficult for Congress to devise a long-term solution.

Flood Insurance

In 1968, Congress created the National Flood Insurance Program with the objective of reducing federal disaster relief resulting from floods. The Federal Emergency Management Agency (FEMA), which already had responsibility for administering disaster relief, was placed in charge of this program as well.

The National Flood Insurance Program sought to offer localities an incentive to prevent flood-prone construction. In return for requiring that any construction in a floodplain be designed to withstand a 100-year flood, the federal government would provide subsidized insurance to existing homes and a fair-market rate for any new construction (which was itself a benefit, since private insurers generally did not offer flood insurance). Moreover, as long as a community joined the program, it would continue to be eligible for federal disaster relief; if it did not join, it would no longer be eligible. As a result of this program, new coastal houses are generally elevated on pilings.

Although Congress intended to prevent coastal disasters, the National Flood Insurance Act does not require strategic assessments of long-term issues (see Riebsame, Volume J). Thus, FEMA has not conducted strategic assessments of how the program could be managed to minimize flood damage from shoreline retreat caused by both present and future rates of sea level rise.

Congress recently enacted the Upton-Jones Amendment (Public Housing Act of 1988), which commits the federal government to pay for rebuilding or relocating houses that are about to erode into the sea. Although the cost of this provision is modest today, a sea level rise could commit the federal government to purchase the houses on all barrier islands that did not choose to hold back the sea. Furthermore, this commitment could increase the number of communities that decided not to hold back the sea.

The planned implementation of actuarially sound insurance rates would ensure that as sea level rise increased property risk, insurance rates would rise to reflect the risk. This would discourage construction of vulnerable houses, unless their value was great enough to outweigh the likely damages from floods. However, statutes limiting the rate at which flood insurance rates can increase could keep rates from rising as rapidly as the risk of flooding, thereby increasing the federal subsidy.

No assessment of the impacts of sea level rise on the federal flood insurance program has been undertaken.

Sewers and Drains

Sea level rise also would have important impacts on coastal sewage and drainage systems. Wilcoxen (1986) examined the implications of the failure to consider accelerated sea level rise in the design of San Francisco's West Side (sewerage) Transport, which is a large, steel-reinforced concrete box buried under the city's ocean beach. He found that beach erosion will gradually expose the transport to the ocean, leaving the system vulnerable to undermining and eventual collapse. Protection costs for the $100 million project would likely amount to an additional $70 million. Wilcoxen concludes that had sea level rise been considered, the project probably would have been sited elsewhere.

The impacts of sea level rise on the construction grants program probably would be less in most other cases. As sea level rises, larger pumps will be necessary to transport effluents from settling ponds to the adjacent body of water. However, sea level rise would not necessarily require alternative siting. The projects serving barrier islands often are located on the mainland, and projects located on barrier islands are generally elevated well above flood levels. If barrier islands are raised in response to sea level as the nationwide analysis suggests, sewerage treatment plants will be a small part of the infrastructure that has to be modified.

Engineering assessments have concluded that it is already cost-beneficial to consider sea level rise in the construction of coastal drainage systems in urban areas. For example, the extra cost of installing the larger pipes necessary to accommodate a 1-foot rise in sea level would add less than 10% to the cost of rebuilding a drainage system in Charleston, South Carolina; however, failure to consider sea level rise would require premature rebuilding of the $4 million system (Titus et al., 1987).

RESEARCH NEEDS

A much better understanding of erosion processes is needed to (1) understand how much erosion will take place if no action is taken; and (2) help identify the most cost-effective means for protecting sandy shores. An improved understanding of how wetland accretion responds to different temperatures, higher CO_2 concentrations, changing mineral content, and the drowning of adjacent wetlands is needed. This will refine our ability to project future wetlands loss and, perhaps, devise measures for artificially enhancing their vertical growth.

This report did not examine the impacts of increased flooding because flood models have not been applied to the large numbers of coastal sites that would be necessary to conduct a nationwide assessment. Time-dependent estuarine salinity models, such as that of the Delaware River Basin Commission, should be applied to major estuaries to examine impacts on ecosystems and drinking water supplies.

Assessments of the impacts of global warming on coastal environments would be greatly improved by better estimates of future sea level rise. In addition to the improved ocean modeling that will be necessary for better projections of surface air temperatures (see Chapter 2: Climate Change), this will also require a substantial increase in the resources allocated for monitoring and modeling glacial processes. Finally, this report assumed that winds, waves, and storms remained constant; future studies will need estimates of the changes in these climatic variables.

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