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AN OVERVIEW OF THE NATIONWIDE IMPACTS OF SEA LEVEL RISE

by

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FINDINGS[1]

Global warming could cause sea level to rise 0.5 to 2.0 meters by 2100. Such a rise would inundate wetlands, erode beaches, exacerbate coastal flooding, and increase the salinity of estuaries and aquifers.

– A 1-meter rise by the year 2100 could drown approximately 25 to 80% of the U.S. coastal wetlands. Their ability to survive would depend largely on whether they could migrate inland or whether levees and bulkheads block their path of migration.

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

– The long-term survival of coastal wetland ecosystems can be ensured if society takes measures to explicitly declare that developed low lands will be vacated as sea level rises. If implemented today, the purchase of future development rights required to follow such a strategy will be relatively inexpensive; if delayed, those same purchases will become too expensive, and forcing landowners to vacate their coastal property without just compensation would be considered an unconstitutional taking.

[1] Although the information in this report has been funded wholly or partly by the U.S. Environmental Protection Agency, it does not necessarily reflect the Agency's views, and no official endorsement should be inferred from it.

CHAPTER 1

INTRODUCTION

In the last six years, coastal scientists, engineers, and policy makers have gradually begun to consider the prospect of a rise in sea level of one to ten feet over the next century. Because the interest of coastal zone managers in the practical consequences of sea level rise predated a widespread interest at the national level, most case studies on the effects of sea level rise have examined the implications for the specific decisions people make today, rather than estimating nationwide impacts. This paper summarizes the first nationwide assessment of the implications of future sea level rise.

CHAPTER 2

OBJECTIVES AND STRATEGY

Ideally, the goal of our research would be to know the economic and environmental impacts of all of the various scenarios of sea level rise for a possible policy response options and for every coastal community in the nation. Every community would then have sufficient information to rationally consider how they should respond. Moreover, we could estimate. the nationwide impact by picking the best policy response option for each community and adding the costs. Because such a comprehensive analysis is not yet possible, this analysis had a more limited objective: a nationwide assessment that included as many factors as possible.

Our first step was to choose which of the impacts to study; we chose shoreline retreat for several reasons. First,. we excluded saltwater intrusion because only one case study had been conducted; the processes are too complicated to meaningfully represent without detailed models; and the unavoidable economic and environmental impact of increased salinity appeared to be an order of magnitude less than shoreline retreat--and much more sensitive to drought than to sea level rise (Hull and Titus, 1986). We would have liked to have included flooding, which is closely related to shoreline retreat, but the cost of applying flood models to a large number of sites was prohibitive, and models of the resulting property damage are inaccurate without detailed surveys of the elevation and types of structures.

By contrast, examining the costs of (1) natural shoreline retreat and (2) holding back the sea seemed feasible. Estimating inundation of dryland simply requires that one know its elevation; wetland loss requires the elevation and an assumption regarding how rapidly the wetlands might accrete; a first-order estimate of beach erosion can be developed using topographic maps and a simple mathematical formula; and the value of lost property can be estimated using tax maps. The costs of holding back the sea are also fairly straightforward. The additional wetland loss is the area of developed property that could be protected (if these areas were not protected, wetlands would be created); the cost of nourishing beaches can be derived using data collected by the Corps of Engineers, and the cost of elevating land, houses, and infrastructure, and of erecting shore-protection structures, can be calculated by engineers based on experience.

Moreover, the procedures for assessing shoreline retreat tend to implicitly account for flooding caused by storm surges (at least after the first foot of sea level rise). Where development is protected from sea level rise, levees and pumping systems used for preventing inundation would also limit flooding; and raising barrier islands and the structures on them by the amount of sea level rise would leave flood risks constant.[2] Where development is unprotected, the estimates of lost land and structures probably account for the costs of increased flooding; although flood plains would move inland, the value of structures standing in the new flood plain would approximately be balanced by the inundated structures that are lost[3] Nevertheless, for the first foot of sea level rise, examining shoreline retreat probably does not account for flooding: if development is protected, major coastal engineering measures probably would not be taken to counteract the first foot of rise, so the frequency of flooding would incf ease. If development is not protected, the first foot of rise would increase all flood surges but would not threaten many structures.[4]

[2]This assumes that climate change has no impact on storm frequency of magnitude.

[3]This implicitly assumes that the development density of the coastal plain is uniform. Development in coastal areas tends to have the highest density in the first few rows of housing closest to the water (to obtain a waterfront view). The density of development in the rows just out of sight of the sea is slightly less.

[4]One foot is somewhat arbitrary; some areas might require levees with a smaller rise. However, we doubt that many areas will build levees or elevate land and structures until the sea rises at least one foot, but a coastal areas will experience incremental increases in flooding for any rise in sea level.

At the outset, it was clear that it would not be possible to estimate both the cost of shoreline retreat and the cost of holding back the sea in time to meet the report's congressional deadline. From previous studies and conversations with hundreds of state and local officials, it was clear that if we had to choose between the two, the cost of holding back the sea--at least in developed areas--was a more reasonable representation of the nationwide impact of sea level rise. We would learn little, for example, from estimating the value of buildings on Manhattan Island that would be lost if the sea was not held back; because of its value, the area would have to be protected. Furthermore, coastal scientists and engineers had been studying the physical implications of sea level rise, but few economists had investigated the economic implications.

By contrast, the wetlands study could examine the impacts of not holding back the sea as well. Estimating the net loss of wetlands requires one to consider (1) the conversion of existing wetlands to open water and (2) the conversion of dryland to wetlands. The former, which generally does not depend on coastal protection policies, is difficult because it depends on wave erosion and the ability of wetlands to accrete vertically; by contrast, the latter, which does depend on coastal protection, is fairly easy to estimate because over the course of a century virtually any sheltered area with an elevation between mean and spring hightide would convert to wetlands if not protected by levees and other structures.

Given the funding constraints and disciplinary boundaries for assessing sea level rise, we defined four studies:

(1) Park et al. would compile elevation data to estimate the inundation of dryland with and without the protection of developed areas and the loss of coastal wetlands for various shore-protection options.

(2) Leatherman would estimate the cost of dredging sand to nourish recreational beaches and, where necessary, to raise barrier islands in place, and develop data on the areas of developed barrier islands.

(3) Weggel et al. would estimate the cost of protecting developed areas along sheltered coasts, and would develop rough estimates of the cost of elevating houses and rebuilding infrastructure to accommodate a raising of Long Beach Island, New Jersey.

(4) Yohe would estimate the costs of losing land and structures, starting with Long Beach Island, New Jersey.

Besides providing an overview of the four papers, this paper undertakes a number of supplementary analyses. We examine statistical uncertainty due to sampling for the Park et al. and Weggel et al. studies. For the cost of protecting sheltered shorelines, we also combine the Park et al. estimates of inundated lowlands with the Weggel et al. cost assumptions for bulkheads and levees to develop cost estimates (1) for sea level rise scenarios that Weggel et al. did not consider and (2) that explicitly calculate the mix of levees and bulkheads necessary to protect each site. For the cost of protecting the open coast, we combine the cost factors of Weggel et al. and Leatherman's estimates of the area of U.S. barrier islands with Census data on housing densities to estimate the (non-sand) cost of raising barrier islands in place in response to a rise in sea level. We also use Leatherman’s results to estimate national and state sand costs if unit sand costs increase as nearshore deposits are exhausted.

Figure 1 illustrates the relationships between the studies. The assessment of the nationwide costs of holding back the sea began with a case study of Long Beach Island, New Jersey. In the study of Long Beach Island, Leatherman and Park et al. followed the same procedures they would subsequently apply nationwide. Weggel et al. examined additional shore protection options as a check to ensure that the option used by Leatherman was reasonable.

The choice of shore protection options used in this study results from the need to develop a nationwide estimate of the costs associated with sea level rise, they are not necessarily presumed to be the most appropriate responses. The assumption of a uniform nationwide approach to shore protection was a computational necessity and not a reflection of how we expect society to respond The justifications we provide show why these are reasonable options, but they should not be construed as an endorsement.

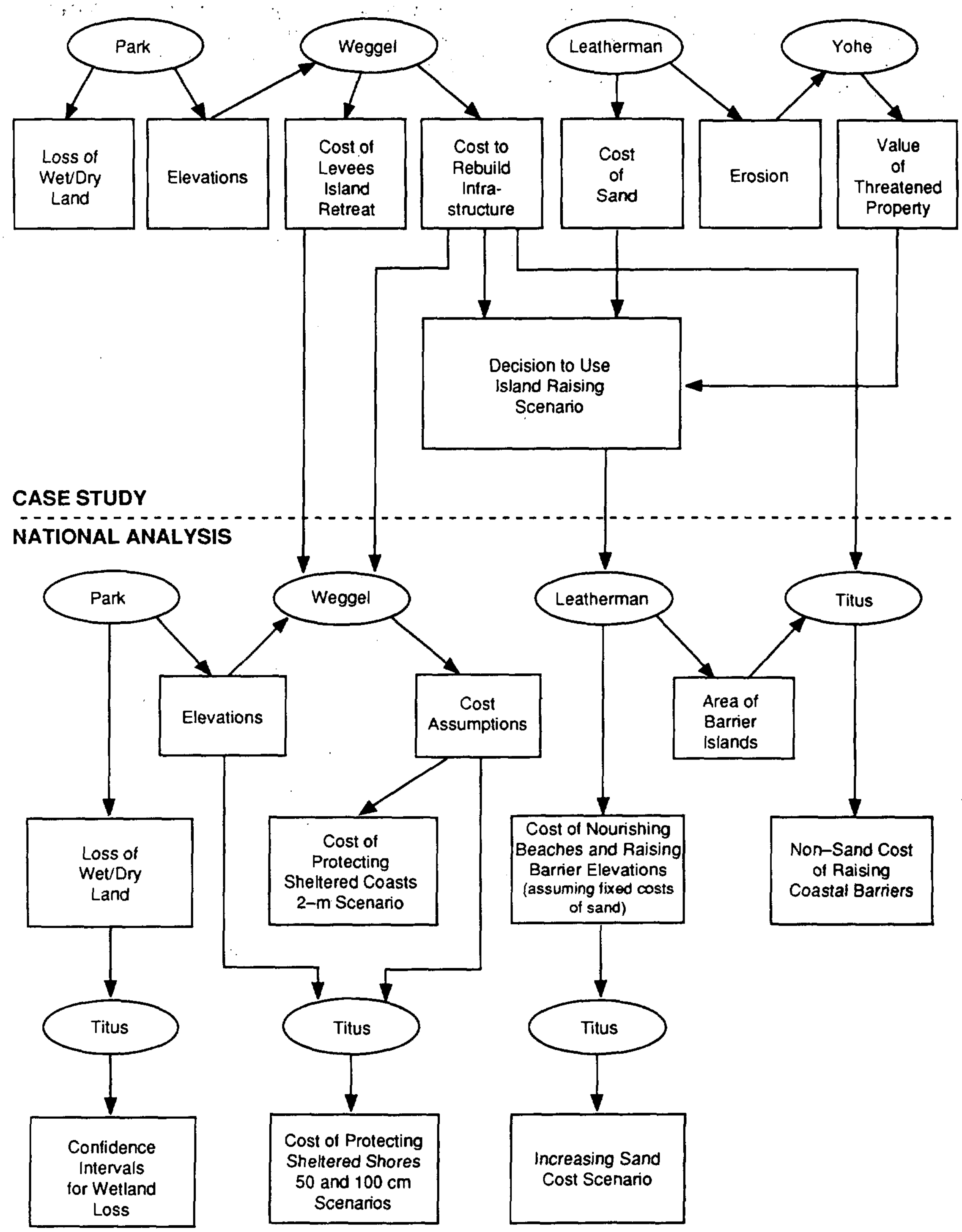

Figure 1. Overview of sea level rise studies -- authors and impacts.

CHAPTER 3

SCENARIOS

We chose three scenarios of sea level rise for this study: 50, 100, and 200 centimeters (cm) by the year 2100. Following the convention of a recent National Research Council report (Dean et A, 1987), the rise was interpolated throughout the 21st century using a parabola, as shown in Figure 2. For each site, local subsidence was added to determine relative sea level rise. In addition to the three accelerated sea level rise scenarios, we also included a baseline scenario, which assumes that sea level will continue to rise at the historical rate of 12 cm per century or 14 cm by the year 2100.

We also devised three alternative scenarios of shoreline protection: no protection, standard protection, and total protection. In the no protection case, we assumed that no shoreline would be defended from a rising sea. For standard protection, we assumed that densely developed, sheltered coasts would be defended by either seawalls or levees (the cost of which was calculated without drainage systems for all but the Long Beach Island case study).[5] For the total protection case, every mile of sheltered coastal lowlands would be protected with either bulkheads or levees.

[5]The exclusion of drainage system costs for the national assessment of protecting developed sheltered shorelines gives us a conservative (e.g., low) estimate of the costs that the country may face.

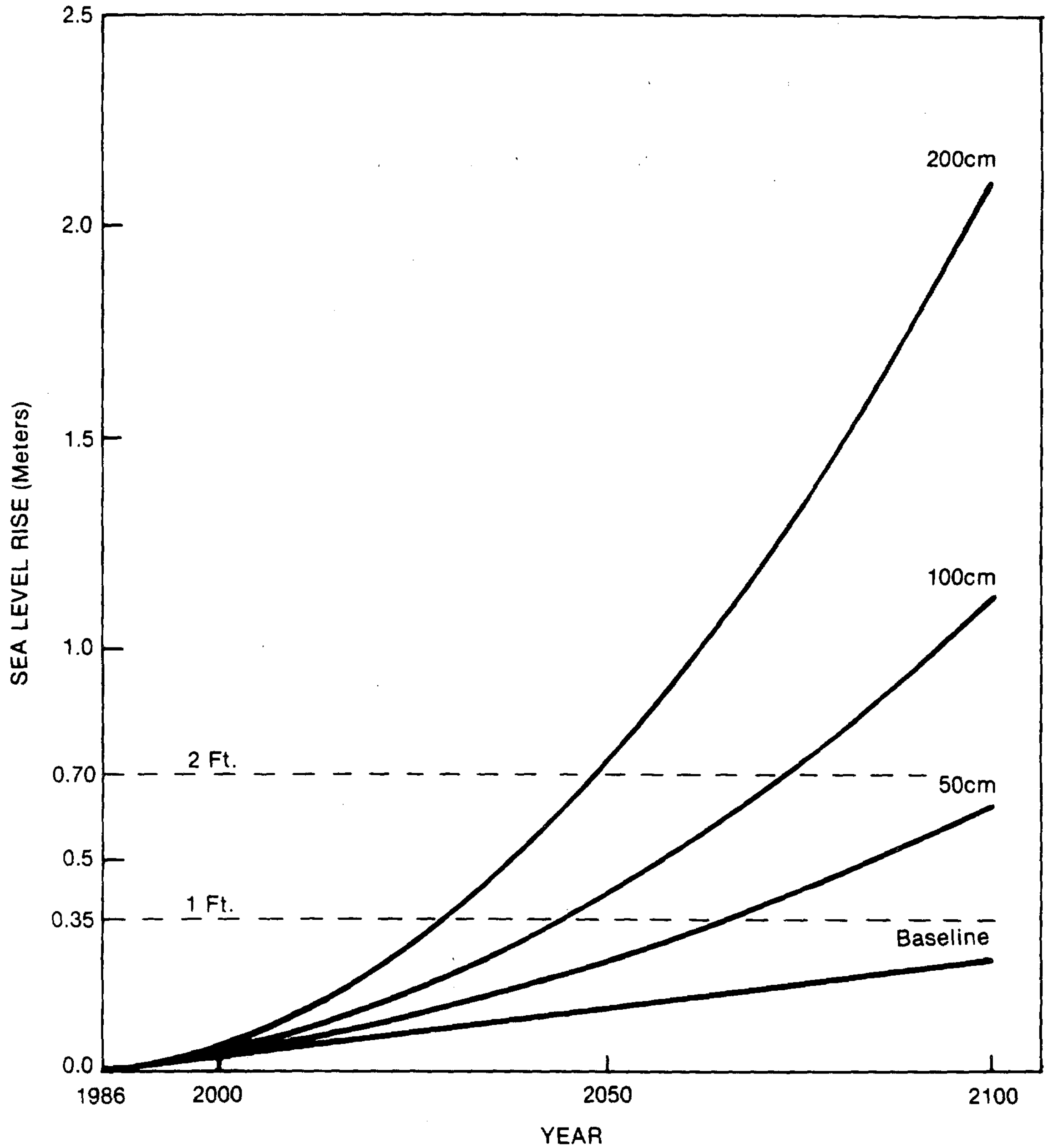

Figure 2. Sea level rise scenarios for Miami Beach (including local subsidence).

CHAPTER 4

CASE STUDY OF LONG BEACH ISLAND.

We picked Long Beach Island (LBI), N.J., for the case study because we had experience there and because it provided most of the features that had to be considered: a narrow well-developed barrier island and a low-lying, partially developed mainland with extensive marshes.

Although the Park et al. and Leatherman studies of Long Beach Island were to be similar to their respective approaches in the nationwide assessment, we needed a more detailed engineering assessment from Weggel et al.: Leatherman was going to estimate only the cost of pumping sand onto beaches and coastal barriers; he was not going to estimate the cost of elevating buildings and roads. By examining Long Beach Island, Weggel et al. would provide us with engineer ing cost factors that we could apply to other communities. Moreover, we wanted to confirm the reasonableness of the hypothesis on which Leatherman's study would be based: that raising barrier islands was a reasonable assumption for estimating the cost of defending the open coast. Therefore, Weggel et al. also examined two alternative options: (1) a landward migration of the barrier island and (2) building a levee and drainage system. Finally, it would not have been feasible for Weggel et al. to visit every site the study would assess. Therefore, the investigators used Long Beach Island and five other sites to develop engineering rules-of-thumb that could be applied to a broader selection of sites.

METHODS USED IN THE LBI CASE STUDY

Loss of Coastal Wetlands

Park et al. sought to (1) compare the results of their model of wetland loss around Long Beach Island with the survey-based estimates from Kana et al. (1988), and (2) determine the impact of shore-protection efforts on wetland loss. First, the elevations of both wetlands and dryland had to be characterized. For wetlands, satellite imagery was used to determine plant species for 60- by 80-meter parcels. Using estimates from the literature on the frequency of flooding that various wetland plants can tolerate, it was then possible to estimate the percentage of time a particular parcel is underwater. Park et al. then used estimates of local tidal ranges to calculate the corresponding wetland elevation. For dryland, spot elevation measurements were used to interpolate between contours on USGS topographic maps and the elevations defined by the upper boundary of tidal wetland vegetation. To keep computations manageable, Park et al. aggregated the results into 500-meter cells; however, they also kept track of the percentages of the cell that corresponded to various elevations and wetland types.

Park et al. estimated the loss of wet and dryland for no protection and protection of developed areas. For the no-protection scenario, estimating the loss of dryland is straightforward. However, for calculating wetland loss, Park et al. had to consider the wetlands' vertical growth. For the baseline scenario, published rates of vertical accretion were used. For accelerated sea level rise, allowance was made for some acceleration of vertical accretion in areas with ample supplies of sediment, such as the tidal deltas.[6]

Sand Costs to Raise LBI and Maintain the Shoreline

Leatherman sought to estimate the cost of pumping enough sand to maintain the shoreline and gradually raise Long Beach Island. This required estimating the area of (1) the beach system, (2) the low bayside, and (3) the slightly

[6]1n some areas, vertical accretion is limited by -sea level rise, not available sediment. If sea level rise accelerates some sediment flow that would otherwise wash onto beaches, sandbars, or into deep water, the sediment will instead wash into the wetlands.

elevated oceanside of the island. Leatherman used the "raising the profile" method, which we explain in a following section ("National Studies: Additional Methodological Considerations"). The area of the each system was found by multiplying the length of the island times the length of the beach profile, which Leatherman calculated based on a 1-year storm, which in this case implied the 23-foot contour.[7] Topographic maps were used to estimate the area of land above and below 5 feet NGVD (1929)[8], which is about 4.5 feet above current sea level.

Given the beach areas, the volume of sand was estimated by assuming that the beach system would be raised by the amount of sea level rise, and that the bay and ocean sides of the island would be raised after a rise in sea level of one and three feet, respectively. Leatherman assumed that sand would cost $7.85 per cubic yard, based on published sand inventories conducted by the Corps of Engineers.

Alter natives to Raising Barrier Islands

Examining the practicality of raising barrier islands required an assessment of two alternatives that had received more attention in previous studies: (1) protecting the, island with seawalls and levees or (2) allowing it to migrate landward (imitating the natural barrier island overwash process by allowing the oceanside of the island to erode and pumping sand into the bayside to build land). After visiting Long Beach Island and the adjacent mainland, Weggel et al. designed and estimated the cost of an encirclement scheme consisting of dikes, levees, and a drainage system involving pumping and underground retention of stormwater. For island migration, the Bruun Rule (see Leatherman, this volume, for a description of this rule) was used to estimate oceanside erosion, and navigation charts were used to calculate the sand necessary to rill the bay landward by an amount equivalent to the oceanside erosion. For island raising and island migration, Weggel et al. used the literature to estimate the cost of elevating and moving houses and of rebuilding roads and utilities.[9]

In preparation for the national study, Weggel et al. estimated the cost of protecting the mainland shore in the vicinity of Long Beach Island and compared the detailed shoreline information with the rougher data provided by the 500-meter cells of Park et al.

Value of Threatened Structures

Yohe's case study is the only part of his report that was contracted to be available by publication of this report; the national estimate of the value of threatened structures and property is expected in the latter half of 1989. His objective was to provide economic information necessary to place the estimates of shore protection into their proper context (by estimating the value of land and structures that would be lost if the sea were not held back) after the other studies had been completed.

On the bay side of the island, the approach was relatively straightforward: any structures or land flooded at high

[7]Large storms have an impact on sediment transport farther out to sea than do small storms. With larger storms come larger waves and excessively high and low tides. Thus, the larger the storm considered, the farther out to sea the beach profile extends.

[8]Because sea level has been rising, a contour that was rive feet above sea level fifty years ago may only be 4.5 feet above sea level today. To avoid potential confusion, most maps today express elevations with respect to the "National Geodetic Vertical Datum" (NGVD) reference plane, which is a fixed reference unaffected by changes in sea level.

[9]Only the direct costs associated with raising the barrier island are included in the analysis. Indirect and less tangible costs that may be felt (i.e., the inconvenience suffered by the community when roads and utilities are dug up and raised, or when houses must be raised or moved as sand is pumped onto the island) are not included. These costs may be substantial and may change the outcome of our analysis. We are, however, unequipped to estimate them.

tide would be considered lost. However, on the more elevated oceanside, Yohe had to specify the timing of the removal of the structures. Would they be removed only after the beach was lost and the structures were flooded at high tide or when the beach narrowed to a critical width? The latter approach was chosen for three reasons. First, the former approach would require Yohe to estimate the demand for beach area, something that was beyond the study's resources. Second, houses in front of the dunes would be vulnerable to storm damage and probably would not be able to stand in front of the dunes for more than a few years. Finally, in most cases, the value of the beach is greater than the value of the oceanfront structure, since the beach is one of the main reasons people buy property on or travel to barrier islands. Therefore, it seemed reasonable to assume that if a community decided to allow its shores to retreat, it would also require that structures be removed before they disrupted use of the beach. (The Texas Open Beaches Act already requires houses to be removed if they are within the dune vegetation area, and many other areas administratively follow this policy where possible.)

Nevertheless, some narrowing of the beach would probably be tolerated. Particularly along the northern part of the island, houses are generally set back over one hundred feet from spring high tide. To be conservative, Yohe settled on a minimum distance of forty feet from a structure to spring high tide, which is about equal to the distance from the crest of the dunes to the wet part of the beach. Because Yohe did not estimate the demand for beach area, he could not estimate the recreational benefits that would be lost if the beach narrowed. Nor did he consider the diminished flood protection value.

Given these behavioral assumptions, and estimates of erosion and inundation from Leatherman, Yohe determined which property would be lost from sea level rise for a sample of 25 strips spanning the island from ocean to bay. He then consulted tax maps to estimate the value of the land and structures that would be lost. Because a 50- by 100-foot oceanfront lot is typically worth about $100,000 more than an interior lot of similar size, Yohe had to consider the fact that this oceanfront premium would be transferred to another owner, not lost to the community. Thus, the value of land lost is the value of an interior lot.[10]

RESULTS AND IMPLICATIONS FOR THE NATIONAL STUDY

Table 1 summarizes the case study results for Long Beach Island for two policy options: (1) raising the island and bulkheading mainland sheltered shorelines and (2) natural shoreline retreat.

Wetlands Losses

The estimates by Park et aL largely confirmed previous estimates by Kana et al. (1988) that a 2-meter rise in sea level would drown 80% of the wetlands around Long Beach Island if shores were not protected. However, the results were not consistent with the hypothesis that wetlands loss would be substantially greater if the shores were protected; bulkheading the shores decreased the area of surviving wetlands by less than 10% in all scenarios. Two possible explanations are:

(1) A large portion of the wetlands are on marsh islands that would not be bulkheaded under any circumstances.

(2) At the coarse (500-meter) scale Park et al. used, the assumption of only protecting developed areas amounted to not protecting a number of mainland areas where the shoreline is developed but areas behind the shoreline are not.

As a result of the latter reason, it seemed reasonable to investigate the implications for coastal wetlands of protecting all coastal lowlands (total protection).

[10]Adjustments were made to these data to ensure that the information was up-to-date. See Yohe's paper in this volume.

Table 1. Results for Long Beach Island Case Study

Wetland Losses* (Percent of Original Area)			
Response	50 cm	100 cm	200 cm
Raise Island/Bulkhead Mainland	45%	70%	78%
Natural Shoreline Retreat	50%	73%	80%

Response Costs** (Millions of 1986 Dollars)			
Response	50 cm	100 cm	200 cm
Raise Island/Bulkhead Mainland:			
Sand Cost	158	303	611
Elevating Houses/Roads	457	856	1,109
Total	615	1,156	1,720
Natural Shoreline Retreat:			
Loss of Rents	2,663	6,096	9,696

Sources:
- Wetland Loss – Park et al.
- Sand Costs – Leatherman
- Other Engineering Costs for 2-meter Scenario – Weggel et al.
- Lost Rents – Yohe

NOTE: All researchers have added approximately 20 cm of local subsidence to the global sea level rise scenarios. Therefore, our deviations of other engineering costs for 50- and 100-cm scenarios based on Weggel et al. estimate of the cumulative cost in the 2-meter scenario when local sea level had risen 70 and 120 cm, respectively.

* Wetland loss estimates reflect Park's original run. His current paper reports on a subsequent run and results are substantially different.

** Dollar figures are cumulative, not discounted.

Is Raising Barrier Islands In Place a Reasonable Scenario?

The results by Weggel et al. clearly indicate that it would be much less expensive to raise Long Beach Island than to allow it to migrate landward, as shown in Table 2. A casual glance at the table also suggests that the option of building a levee around the island would be even less expensive. However, other considerations suggest that island raising would be more reasonable. First, a levee would eliminate the bayfront view. Second, because most of the levee costs would have to be borne all at once, financing it would be difficult. Third, Weggel et al. concluded that the levee would have to be built in the 2020's, and island raising could take place gradually between 2020 and 2100. This implies that the (discounted) present value of the levee cost would be greater.[11] For example, by the middle of the 2020's, the present value of the cost for island raising through. the end of the century would be $400 million at a 3% discount rate and $200 million at a 10% discount rate, which would be far less than the $8W million for the levee system.[12] Fourth, a levee would alter the ecology of the undeveloped tracts of land. Finally, some people would feel unsafe residing on a barrier island below sea level.

Therefore, we concluded that it would be reasonable for Leatherman to assume that entire developed coastal barriers like Long Beach Island are raised in place, given that he could examine only one option for his national study. However, we caution that this assumption would probably not be reasonable for islands whose characteristics are vastly different. A very lightly developed island might rind migration cheaper. For example, the analysis of Weggel et al. shows that landward migration is more expensive than island raising primarily because of the increased costs of rebuilding water and sewer lines and other utilities. But considerably less sand is required. (See Titus 1987b for a discussion of the institutional challenges this option would face.)

On the other hand, levees might be more practical for wide barrier islands where most people do not have a waterfront view. The most noteworthy example in the United States is Galveston, Texas, which is already protected by a seawall. Recently, people there have discussed totally encircling Galveston Island with a levee. The cost of raising an island with a given development density depends on the area of the island, while the cost of a levee depends on the island's perimeter. Thus, levees are least practical for narrow barrier islands. But for an island as long as Long Beach Island but five times as wide, the cost of a levee would be about the same, and the cost of raising the island would be five times as great.

A final question concerning the reasonableness of raising islands is whether. the costs would be so great that it would be better to simply abandon the island. This is not likely to be a serious option for Long Beach Island in the next century, even for the 2-meter sea level rise scenario. Figure 3 compares the annual cost for elevating the island under the 2-meter scenario with Yohe's estimate of the value of the economic returns (rental income) lost in a particular year due to the cumulative loss of land and structures. The annual cost for elevating the island would gradually rise to $22 million/year by 2100. By contrast, the annual loss of rents (and property as well) would reach this level by the 2030's; by 2100, the annual loss of rents would be about $200 million, ten times the cost of shore protection. Right from the start, shore protection at Long Beach Island would be cost-effective and it would continue to be so. (The fact that shore protection is cost-effective means that the island has the resources to protect itself, but it does not address whether the residents, taxpayers, or contributors of greenhouse gases should bear the costs.)

[11]In principle, some of the costs of a levee and drainage system could be deferred by raising the levee in stages, but the initial cost would be more than half of the total cost due to the need for land purchases, pumping systems, and design.

[12]The term "discounting" refers to a procedure by which economists equate dollars in one year with dollars in another year, generally by using a rate of return (interest rate). The present (discounted) value of one dollar Y years hence at a discount rate of R is:

$$1/(1 + R/100)^{Y}.$$

Table 2. Results for Long Beach Island Case Study

Protection Costs for 2-Meter Sea Level Rise Scenario (Millions of 1986 Dollars)			
	Encirclement	Island Raising	Island Migration
Sand Costs			
Beach	290	290	0
Land Creation/Maintenance	0	270	321
Moving/Elevating Houses	0	37	74
Roads/Utilities	0	1,072	7,352
Levee and Drainage**	542	0	0
Total	832	1,669	7,747

Sources: Leatherman, Weggel et al.

NOTE: Weggel et al. estimated sand cost of $560 mil. ("Island Raising" above) differs from Leatherman's estimate of $611 mil. (Table 1 for 200 cm scenario) because each investigator made different assumptions regarding the closure depth of the beach profile (i.e. they assume different widths for the beach profile).

* Sand costs include the incremental periodic beach nourishment costs to raise the entire beach profile.

** Designed to withstand 100-year storm.

CHAPTER 5

THE NATIONAL STUDIES: ADDITIONAL METHODOLOGICAL CONSIDERATIONS

SITE SELECTION

Ideally, we would have studied the entire coastal zone of the United States. Unfortunately, the cost of satellite data collection and interpretation made it impossible for Park et al. to encode more than 20% of the U.S. coast; because Weggel et al. used the same sites, they were similarly limited.

Site selection was motivated by two concerns: First, we wanted the sample to be unbiased and to yield statistically efficient estimates. Second, state and local coastal zone agencies expressed a need for information to be as site-specific as possible, and certainly aggregated at no more than the state level. Leatherman sought to satisfy both needs by examining every recreational beach in the country. To date, he has examined all of the beaches in all of the coastal states except Hawaii,* Washington, Oregon, and Maine through New Jersey. In these states, wl-&h account for 20% of the nation's recreational open-coast beaches, he examined one beach per state.

For the other studies, however, we knew that sampling would be necessary. Thus we had to choose between a random sample and sampling at regular intervals. We decided to adopt the latter approach. because it guarantees that particular regions will be represented in proportion to their total area in the coastal zone, while a random sample would have left open the possibility that Louisiana of another atypical region would have a disproportionate fraction of the sites. Such a condition would be more likely to significantly bias the nationwide estimates and 'might have left an important region uncovered. Accordingly, 92 sites were picked at regular intervals along the coast, accounting for 20% of the U.S. coastal zone. (This paper discusses only the results from a subsample of 46 sites for the Park et al. study, while the study of Weggel et al, includes the entire sample.) These studies did not consider Hawaii or Alaska.

In presenting results from the studies of Park et al. and Weggel et al., we group the sites 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 Pacific Coast. Figure 4 illustrates these regions.

LOSS OF COASTAL WETLANDS AND DRYLANDS

Park et al. sought to test a number of hypotheses that previous'publications had put forth:

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

(2) The loss of wetlands would be greatest if all developed areas are protected (total protection), less if only densely developed areas are protected (standard protection), and least if shorelines retreat naturally (no protection).

(3) The loss of coastal wetlands would be greatest in the southeast, particularly Louisiana.

Park et al. applied the same procedures to the nationwide study that had been used in the case study. The only major difference was that for sites in the Southeast, where they considered the gradual replacement of salt marshes by mangrove swamps as areas became warmer.

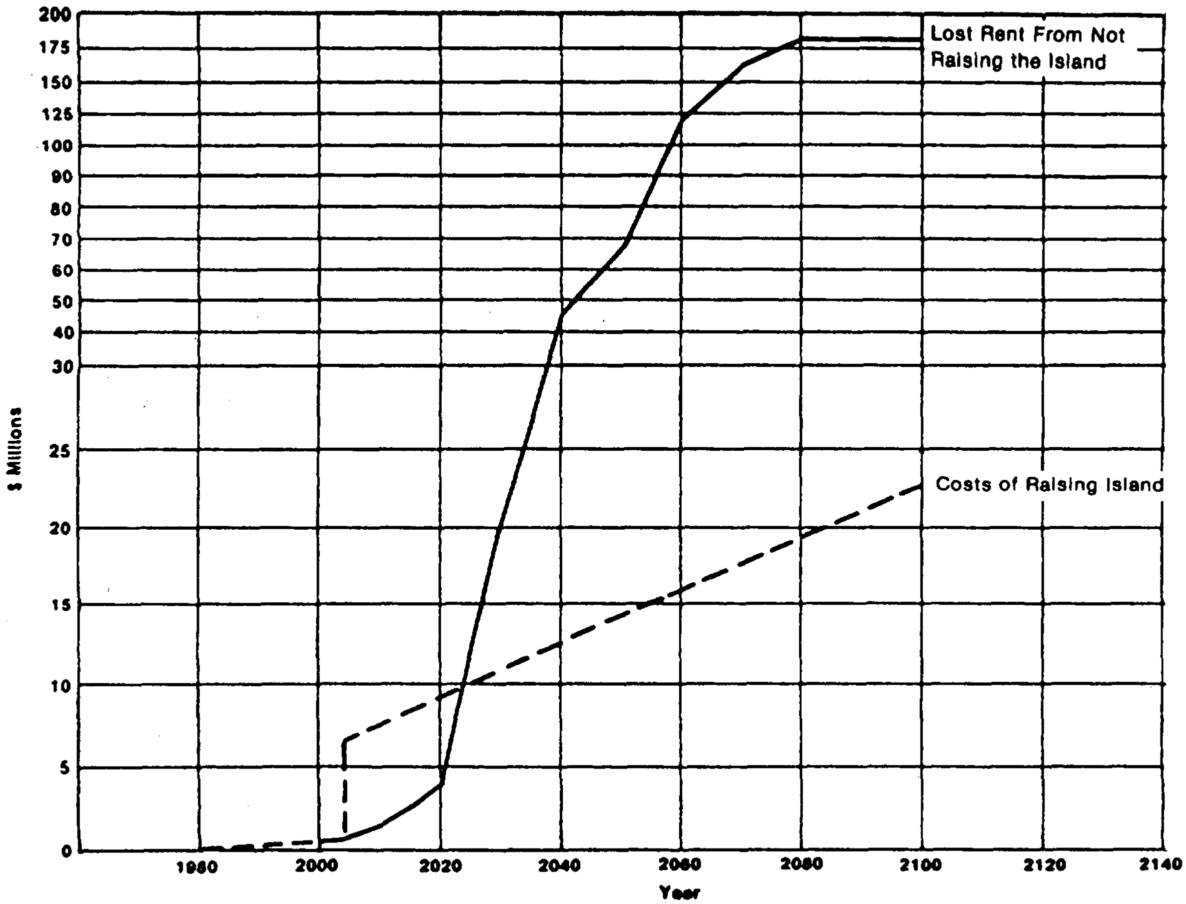

Figure 3. Annual cost of elevating Long Beach Island versus lost economic rent from not raising island.

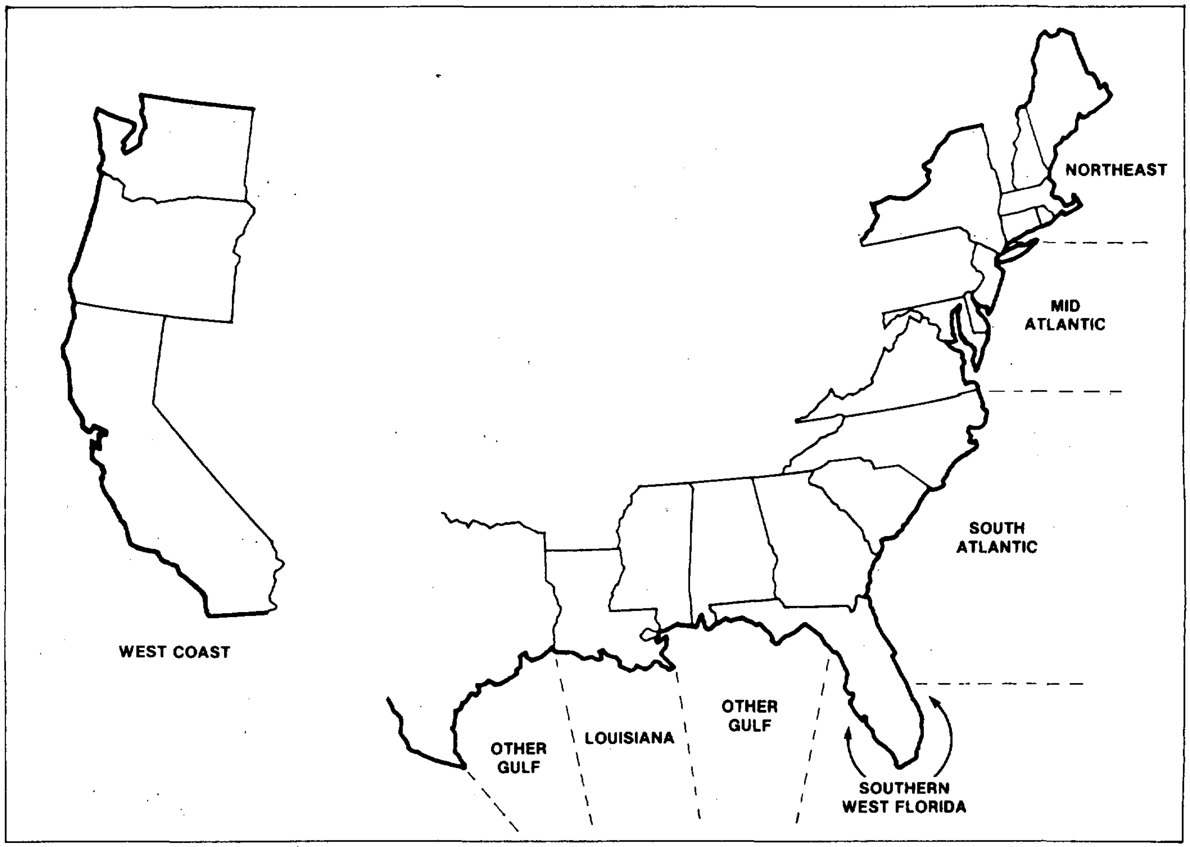

Figure 4. Coastal regions used in this study.

The greatest uncertainty in the analysis of this study comes from the poor understanding of vertical accretion rates. This uncertainty could substantially affect the results for the baseline and 0.5-meter sea level rise scenarios. However, for a rise of one meter by 2100, there is no evidence that wetland accretion could keep pace with the 1- to 2-cm/yr accelerated rise that the scenario implies for the second half of the 21st century. For a 2-meter rise, the uncertainty regarding accretion rates has little, if any, practical significance; no natural amount of accretion would be able to keep up with sea level.

Another limitation is that Park et al. do not consider the potential implications of alternative ways of managing river flow. This is a particularly serious limitation for application to Louisiana, where a wide variety of measures have been proposed for increasing 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. If currently undeveloped areas are developed and protected, wetland losses will be higher.

DEFENDING SHELTERED SHORES

Weggel et al. sought to estimate the cost of protecting developed areas along sheltered waters. Their approach was to examine a number of index sites in depth to develop generalized cost estimates for protecting different types of shorelines; to use the topographic information collected by Park et al. for the sample sites to determine the area and shoreline length that had to be protected; to apply the cost estimation factors to each site; and to extrapolate the sample to the entire coast.

After assessing Long Beach Island, less detailed studies of protecting developed areas from a 2-meter rise were conducted at five other index sites: metropolitan New York; Dividing Creek, N.J.; Miami and Miami Beach; the area around Corpus Christi, Texas; and parts of San Francisco Bay. Weggel et al. then developed high- and low-cost estimates for the entire sample of sites, based primarily on shoreline lengths for the other sites provided by Park et al. The high estimates assumed that levees would have to be built; the low estimates assumed that only bulkheads would be necessary. The estimates netted out costs that would normally occur without sea level rise, such as rebuilding existing bulkheads as they reached the end of their useful lives.

The most serious limitation of this study is that cruder methods are used for the extrapolation than for the index sites. Even for the index sites, the cost estimates are based on the literature, not site-specific designs that take into consideration wave data for bulkheads or the potential savings from tolerating substandard roads. The exclusion of drainage systems in the nationwide costs understates the cost of protection since drainage systems will be necessary for areas protected by levees. The engineering assessment of Weggel et al. does not assess the environmental impacts of artificial drainage on water quality. Finally, the investigators were able to examine only one scenario: a 2-meter rise by 2100. Although the 1-meter rise is more likely, we chose to interpolate the impacts of a 1-meter rise from the 2-meter estimates of Weggel et al.; we felt this would yield more accurate estimates than if we chose to extrapolate from a 1-meter rise to a 2-meter rise.

Compared with the Leatherman and Park et al. studies, the methods of Weggel et al. are crude. This relative inaccuracy results more from the relative difficulty of achieving the Weggel et al. objective than from failure on the investigators' part to employ better methods. While literature, maps, and remote sensing provided Leatherman and Park et al. with sufficient data for all sites, a similarly valid sample for Weggel et al. would have required a few dozen prohibitively costly engineering assessments.

Nevertheless, the approach of Weggel et al. seems sufficient to provide a useful, conservative (that is, likely to understate the cost) first approximation. It is useful because it considers the length of shorelines that would have to be protected and uses typical cost-estimation factors for bulkheads and levees that should be accurate within a factor of two for a large sample. It is conservative because it does not include the cost of the extensive drainage systems that would accompany levees. In the Long Beach Island case, Weggel et al. estimate that the drainage system would be almost as expensive as the levees. Barrier islands have a large amount of shoreline for a small area; because drainage costs primarily depend on the area being drained rather than upon shoreline length, the costs for mainland areas could, be several times the cost of building levees. Thus it is possible that the nationwide cost estimates of Weggel et al. are several fold too low.

RAISING THE PROFILE: A SIMPLE PROCEDURE FOR ESTIMATING SAND REQUIREMENTS DUE TO SEA LEVEL RISE

Several studies on the impacts of sea level rise have estimated shoreline retreat, but only two studies of Ocean City, Maryland (Everts, 1985; Kriebel and Dean, 198S) have estimated the quantity of sand necessary to maintain the current shoreline, and the methods employed by those researchers require substantial amounts of data. However, a rough estimate can be developed simply by assuming that the entire beach profile is raised as much as the sea rises. For the this analysis, we define the variables as follows:

D	=	duration.
E	=	erosion.
H	=	vertical height of the beach profile from dune crest to closure depth (outer point of sediment transport).
L	=	horizontal length of the beach profile from dunes to point of closure.
P	=	average slope of the beach profile.
S	=	sand volume required to raise beach profile by amount of sea level rise.
SLR	=	sea level rise for a particular scenario by the year 2100 in feet.

The assumption of raising the beach profile by the amount of sea level rise is a corollary of the Bruun rule (1962),

(1) E = SLR * L/ H.

Erosion can be counteracted if S=E*H. Substituting E=S/H into equation 1 and multiplying by H, we have,

(2) E = SLR * L,

which is the same as raising the entire beach profile.

In the Ocean City report, Titus (1985) called this approach "Bruun" because the study was designed to compare estimates of shoreline retreat and sand requirements for different methods, and there was no point in changing names. However, in this report, we use the term "raising the profile method" because it more accurately conveys the procedure. Moreover, the fact that it is a corollary of the Bruun rule does not mean that all of the requirements for the Bruun rule must be satisfied for it to apply. Critics of the Bruun rule such as Devoy (1987) are concerned with the two-dimensional formulation s inability to predict the alongshore transport (e.g., from headland to embayment) that might be induced by sea level, rise, as well as the fact that it ignores present day alongshore sand transport. However, when the objective is to estimate the sand requirements for an entire coast, the net alongshore transport is negligible.

Both methods share the requirement of defining the profile. Strictly speaking, we should not view the profile as f(x), but as f(x, D, epsilon), with D equal to the period of time the profile has had to adjust to sea level rise, with epsilon equal to the rate of sand transport viewed as sufficient for a location to be considered as being within the profile, and with x and f(x) equal to the horizontal and vertical dimensions, respectively. The domain of this function would extend farther inland and out to sea as D increases and as epsilon decreases (and hence the profile would be longer). -

If epsilon is equal to the amount of transport necessary to bury one's feet in 60 seconds and D equals 10 minutes, the profile would be confined to the relatively small breakers and swash zone. If D is 12 hours with the same epsilon, the profile may extend over an extra 100 feet or so as tide goes in and out.

For a smaller epsilon, with D equal to a year, the profile might extend out to around the -20' contour along much of the Atlantic. coast, and with a SO-year D, out to the -3(Y contour. Hallermeier (1981) outlines procedures for estimating the profile length for a particular D; topographic maps and navigation charts enable one to estimate height given the length. Thus, a time-dependent application of the Bruun rule would be,

(3) $$E(t) = \int_{-\infty}^{0} SLR'(t - D) * P' \delta D,$$

where SLR' equals the rate of sea level rise and P' is the derivative of the ratio L(D)/H(D). Similarly, a time-dependent means of raising the profile would be,

(4) $$S(t) = \int_{-\infty}^{0} SLR'(t - D) * L'(D) \delta D.$$

As a practical matter, the profile does not get much longer as D increases beyond 5O years, and most people are content to pick a single value for D and use Hallermeier's estimates; Leatherman's study also follows this convention. However, we hope that future studies will use more general formulations such as:

(5) $$E(t) = \sum_{D=0}^{T} [SLR'(t - D) * \{L(D) / H(D) - L(D - 1) / H(D - 1)\}]$$

where T ranges from SO to 100 years, and

(6) $$S(t) = \sum_{D=0}^{T} [SLR'(t - D) * \{L(D) - L(D - 1)\}] .$$

The function L(D) could be approximated by fitting a polynomial through published estimates for specific values f D; H(D) could be approximated with whatever functional specification one uses to describe the shape of the beach profile.

We note that our formulation assumes that over a period of D years the profile adjusts to a D-year storm. This represents a maximum likelihood estimate, but not necessarily an unbiased or median estimate. For example, while we assume that the worst storm in a 100-year period will be the.100-year storm, the probability that the worst storm will be milder is $.99^{10}0$= 37%, while there is a 63% chance that it will be worse.

Given that Leatherman did not have time to employ the more general formula, he had to pick a value for D.

Because the general approach was to underestimate the cost of sea level rise, Leatherman picked a 1-year storm.

COST OF PROTECTING THE OPEN COAST

Leatherman applied the "raising the profile" methods for all recreational beaches from Delaware Bay to the mouth of the Rio Grande plus California, which account for 80% of the nation's beaches. He also examined one representative site in each of the remaining states.

Leatherman's analysis provides a state-of-the-art assessment of the beach nourishment costs for the nation, with two caveats: (1) Although the sample of sites in the Northeast and Northwest are representative, complete coverage would have been more accurate; and (2) Leatherman used very conservative assumptions in estimating unit costs of sand. Generally, a fraction of the sand that is placed on a beach washes away because of insufficient grain size; and as the least expensive sand is used and dredges have to go farther offshore, 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/cubic yard for every additional mile offshore the dredge had to go. For the other states, however, he assumed,that the deposits mined would have no fine-grain sand and that dredging costs would not increase. Leatherman is also underestimating sand costs by assuming that the beach profile extends out only to the point where the annual severe storm would deposit sand.

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, there are areas where communities would choose to erect levees and seawalls–particularly Galveston and other wide barrier islands in Texas--or to accept a natural shoreline retreat.

CHAPTER 6

RESULTS

RESULTS: NATIONWIDE LOSS OF WETLANDS AND DRYLANDS

Estimates of Park et al.

Table 3 compares the current area of wetlands estimated by Park et al. with the estimates from a recent NOAA inventory of coastal wetlands (Alexander et al., 1986). For the nation and for five of the seven regions, the differences between the estimates are within the sampling margin of error. However, the sample of Park et al. substantially underestimates the coastal wetlands of the middle Atlantic and the Pacific Coast, which together account for about IS% of U.S. coastal wetlands.

The Park et al. results generally supported the hypotheses suggested by previous studies (see Table 4). For a 1-meter rise in sea level, 66% of all coastal wetlands would be lost if all shorelines were protected, 49% would be lost if only currently developed areas were protected, and 46% would be lost if shorelines retreated naturally.[13]

As expected, the greatest losses would be in the Southeast. Figure 5 illustrates the loss of coastal wetlands for this region for three scenarios of shore protection. Even under the baseline scenario, a substantial fraction of Louisiana7s wetlands -would be lost. (See Chapter 6 of the main report to Congress.) Most other areas would experience slight gains in wetland areas. Of the 6046-8673 square miles of U.S. wetlands that would be lost from a 1-meter rise, 90-95% would be in the Southeast.

Analysis: Sampling Error

Table 4 illustrates wetland loss (in square miles and percentage terms) by region for each of the scenarios, along with sampling error (i.e., the standard deviation times the square root of the sample size). For the total protection scenario, the estimated loss of wetlands was greater than the sampling error for all regions, and hence could be viewed as statistically significant at the 60-70% level of confidence. However, to be significant at the 95% level, Student's-t distribution would require the losses to be 2.1-3.1 times as great as error (depending on sample size).[14] At this level of confidence, only the South Atlantic, Louisiana, and (barely) Mid-Atlantic show statistically significant losses for the total protection scenario; for other shore protection scenarios, only the South Atlantic and Louisiana are significant.

Given the small regional samples, the lack of statistical significance at the 95% level for area of wetlands lost could have been expected. However, we note that the uncertainty results largely from the fact that different sites had varying amounts of initial wetland coverage. We had hoped that this problem could be circumvented by considering percentage losses of coastal wetlands. Unfortunately, we found large standard deviations for percent losses as well, largely because most of the regions had at least one outlier (e.g., most of the sites in a region show 40-60% losses but one site shows a 1000% gain). We did not have time to undertake more sophisticated approaches such as discarding outliers; hence we simply accepted the lack of significance at the regional level.

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[13] When all shorelines are protected, as sea level rises, the protective structures limit wetlands forming upland everywhere. On the other hand, with protection limited to developed shorelines, wetlands can form upland in undeveloped areas. Thus, the net area of wetlands is less after sea level rise under the total shore protection scenario than under the standard shoreline protection scenario.

[14] In the following analysis of wetlands and dryland losses, we have presented our results using 95% confidence intervals. We chose this level because we believe that even the losses at the low end of the interval are high enough to induce decision makers to plan ahead for sea level rise.

Table 3. Comparison of Park Baseline Data for Vegetated Wetlands (1985) and NOAA Wetlands Inventory

Region (Sample Sites)	Percent of Coast in Sample	Park Estimate	Sampling Error	NOAA Estimate*
Northeast (4)	3.4	600	389	382
Mid-Atlantic (7)	8.6	746	245	2080
South Atlantic (8)	10.1	3813	848	3967**
Louisiana (7)	13.7	4835	876	4491
Gulf Except LA (14)	12.2	3087	1169	3608
W/SW Florida (6)	10.7	1869	957	na
Other Gulf (8)	13.1	1218	673	na
West (6)	4.9	64	45	195
USA	9.7	13145	2105***	14723

na = not available.

* Alexander et al. (1986) also estimate the area of tidal flats for several states; we present only the sum of their estimates for vegetated wetlands.

** We have modified data from Alexander et al. to account for differences in the definition of coastal wetlands for North Carolina. Alexander et al. include all wetlands in coastal counties regardless of elevation, while Park et al. excluded wetlands above 12 ft NGVD. Because of extensive swamps above 12 ft in North Carolina's coastal counties Alexander et al. found the area of coastal swamps to be 8.4 times the area of marsh, while the boundaries of the sample of Park et al. found only 1.6 times as much.

*** Standard deviation of the estimate of the sum (i.e., sample standard deviation times the square root of the sample size).

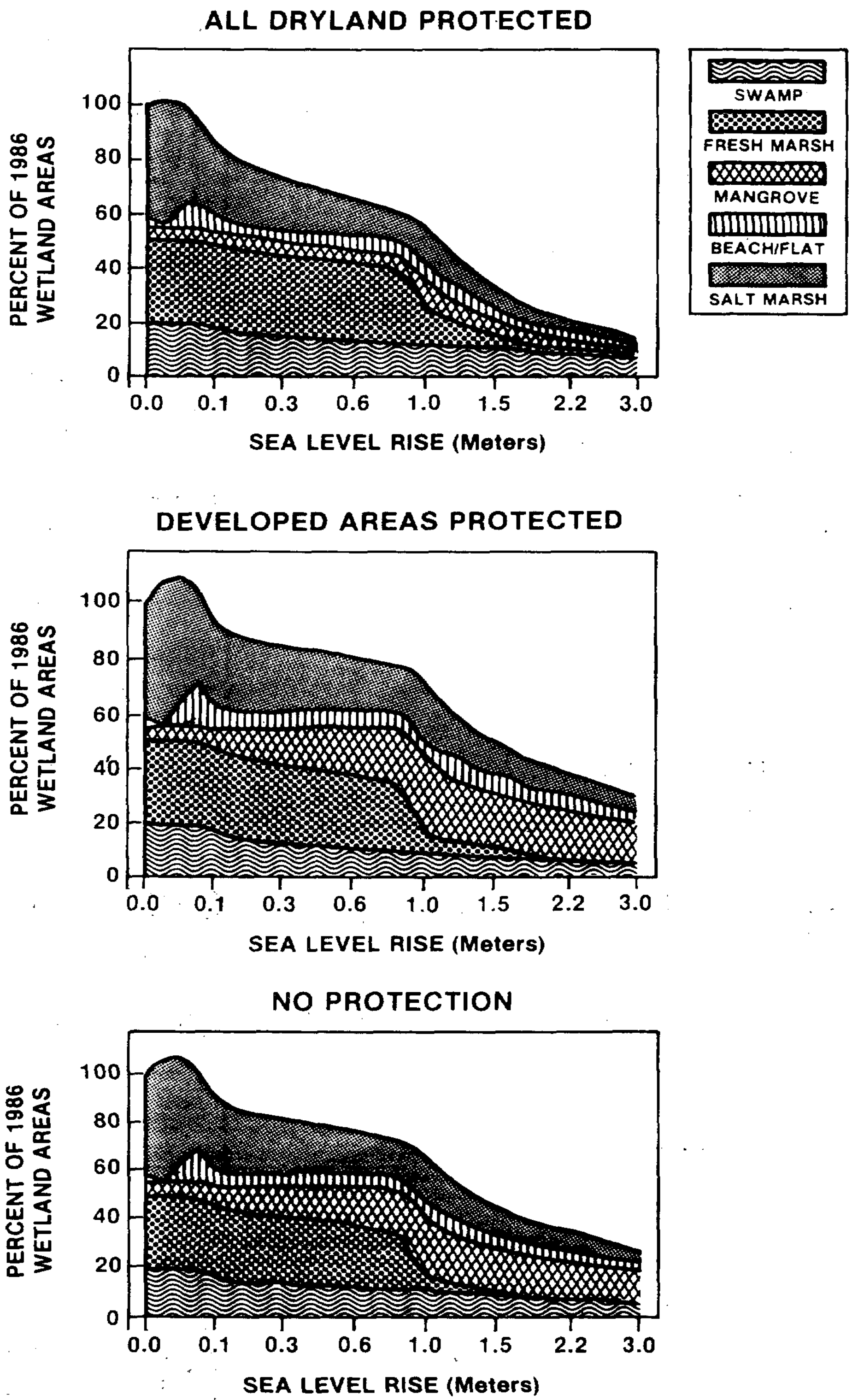

Figure 5. Southeastern wetland losses for three shoreline protection options.

Region	Standard Protection	Total Protection			Standard Protection			No Protection		
	Baseline	50 cm	100 cm	200 cm	50 cm	100 cm	200 cm	50 cm	100 cm	200 cm
Northeast										
Best Estimate (sq mi)	39	88	93	100	55	58	33	27	8	-67
Best estimate (%)	7	15	16	17	9	10	6	5	1	-11
Sampling Error (sq mi)	20	56	60	64	29	34	25	43	69	112
Mid-Atlantic										
Best Estimate (sq mi)	-39	485	520	625	201	341	429	120	280	361
Best estimate (%)	-5	65	70	84	27	46	58	16	38	48
Sampling Error (sq mi)	87	197	200	208	273	238	247	270	232	241
South Atlantic										
Best Estimate (sq mi)	59	2295	2422	2542	1438	1669	1812	1313	1516	1606
Best estimate (%)	-2	60	64	67	38	44	48	24	40	42
Sampling Error (sq mi)	201	526	506	510	516	558	621	517	473	656
South/Gulf Coast of Florida Peninsula										
Best Estimate (sq mi)	-157	623	829	1020	92	157	165	63	122	120
Best estimate (%)	-8	33	44	55	5	8	9	3	7	6
Sampling Error (sq mi)	110	274	380	477	230	313	474	235	320	481
Louisiana										
Best Estimate (sq mi)	2271	2450	3742	4758	2368	3732	4686	2354	3732	4685
Best estimate (%)	52	56	85	99	54	85	99	54	85	99
Sampling Error (sq mi)	421	338	735	882	385	735	902	385	735	902
Florida Panhandle, Alabama, Mississippi, Texas										
Best Estimate (sq mi)	270	530	1031	1121	396	932	994	360	918	982
Best estimate (%)	22	44	85	92	33	77	82	30	75	81
Sampling Error (sq mi)	209	279	761	812	306	779	821	319	779	823

Region	Standard Protection	Total Protection			Standard Protection			No Protection		
	Baseline	50 cm	100 cm	200 cm	50 cm	100 cm	200 cm	50 cm	100 cm	200 cm
West Coast										
Best Estimate (sq mi)	-71	37	36	39	-286	-440	-651	-332	-518	-791
Best estimate (%)	-111	58	56	61	-447	-688	-1017	-519	-809	-1236
Sampling Error (sq mi)	44	22	21	23	202	282	336	209	280	371
Southeast (original 11,735)										
Wetlands Lost:										
Best Estimate (sq mi)	2,325	5899	8024	9443	425596	6491	7647	4090	6289	7342
Best estimate (%)	+20	50	68	80	37	55	65	35	54	63
95% low (sq mi)	a	4408(37)	5535(47)	a	2783(24)	3976(34)	4722(40)	2563(22)	3572(30)	4379(37)
95% high (sq mi)	a	7390(63)	10513(90)	a	5809(50)	9006(77)	10572(90)	5617(48)	8826(75)	10305(88)
Wetlands Left:[b]										
Best Estimate (sq mi)	NC	NC	2843	2294	NC	NC	NC	NC	NC	NC
Best estimate (%)	NC	NC	24	20	NC	NC	NC	NC	NC	NC
95% low (sq mi)	NC	NC	779	848	NC	NC	NC	NC	NC	NC
95% high (sq mi)	NC	NC	4907	3740	NC	NC	NC	NC	NC	NC
United States (original 13,145)										
Wetlands Lost:										
Best Estimate (sq mi)	2255	6511	8673	10206	4263	6441	7423	3904	6046	6892
Best estimate (%)	17	50	66	78	32	49	56	30	50	52
95% low (sq mi)	1168(9)	4944(38)	a	a	2591(20)	3813(29)	4350(33)	2216(17)	3388(26)	3758(29)
95% high (sq mi)	3341(25)	8077(61)	a	a	5934(45)	9068(69)	10495(80)	5592(43)	8703(66)	10025(76)
Wetlands Left:[b]										
Best Estimate (sq mi)	NC	NC	4472	2897	NC	NC	NC	NC	NC	NC
Best estimate (%)	NC	NC	34	22	NC	NC	NC	NC	NC	NC
95% low (sq mi)	NC	NC	2302(18)	1302(10)	NC	NC	NC	NC	NC	NC
95% high (sq mi)	NC	NC	6642(51)	4492(34)	NC	NC	NC	NC	NC	NC

NC = Not calculated.
a = Confidence intervals not calculated for cases where sampling error exceeds best estimate.
b = Wetlands left only calculated for cases when sampling error exceeded best estimate for wetlands lost.

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Table 5. Loss of Dryland (square miles)

	Baseline	50 cm	100 cm	200 cm
Northeast				
No Protection	nc	139	235	472
Standard Protection	32	71	126	262
Mid Atlantic				
No Protection	nc	904	1205	1771
Standard Protection	448	705	928	1385
South Atlantic				
No Protection	nc	1094	1600	2561
Standard Protection	493	886	1272	2023
South Florida and Gulf Coast of Florida Peninsula				
No Protection	nc	768	1278	2035
Standard Protection	272	717	1196	1907
Louisiana				
No Protection	nc	1364	1417	1638
Standard Protection	1178	1249	1295	1449
Florida Panhandle, Alabama, Mississippi, and Texas				
No Protection	nc	905	1091	1548
Standard Protection	563	809	976	1405
Pacific Coast				
No Protection	nc	511	903	1771
Standard Protection	92	444	867	1537
United States				
No Protection				
Best Estimate	nc	5313	7727	11793
Error	nc	989	1289	1783
95% High	nc	7311	10330	15394
95% Low	nc	3315	5123	8191
Standard Protection				
Best Estimate	3078	4164	6661	9967
Error	804	982	1250	1747
95% High	4686	6147	9186	13496
95% Low	1470	2180	4136	6493
Southeast				
No Protection				
Best Estimate	nc	4131	5386	7782
Error	nc	890	1084	1478
95% High	nc	5929	3196	4796
95% Low	nc	2333	7576	10767
Standard Protection				
Best Estimate	nc	3661	4739	7116
Error	nc	888	1075	1460
95% High	nc	5455	6910	10065
95% Low	nc	1867	2567	4166

The one instance where we were able to reduce estimated sampling error concerns the "total protection" scenario. In a number of cases, we found that the standard deviation of remaining wetlands was much less than that for wetlands lost, as the table illustrates.

Despite the lack of significance for most regions, at the nationwide and southeast-wide levels of aggregation, the results are highly significant. The 95% confidence intervals for the nationwide percentage wetland loss are 38-61, 50-66, and 66-90% for the 50-, 100-, and 200-cm sea level rise scenarios and the total protection case and 17-43, 26-66, and 29-76% for the no-protection scenario. Statistical significance for the loss of dryland followed the same pattern. The best estimates indicate that if shorelines retreat naturally (no protection), a 1-meter rise would inundate 7727 square miles of. dryland, an area the size of Massachusetts; with a 2-meter rise, 11,793 square miles could be lost. Again, most of the land loss would occur in the Southeast, particularly Florida, Louisiana, and North Carolina. The corresponding 95% confidence intervals are 3,000-8,000, 5,000-10,000, and 8,000-15,000 square miles lost for the 50-, 100-, and 200-cm sea level rise scenarios, respectively. Of course, with total protection of coastal lowlands, there would be no losses for any of the sea level rise scenarios.

RESULTS: THE NATIONWIDE COST OF PROTECTING SHELTERED SHORES

Estimates of Weggel et al.

Table 6 shows estimates from Weggel et al. for the index sites and the nationwide estimate. The index sites represent two distinct patterns. Because urban areas like New York would be entirely protected by levees, the cost of moving buildings and rebuilding roads and utilities would be relatively small.[15] On the other hand, Weggel et al. concluded that in more rural areas like Dividing Creek, NJ., 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 et al. estimate that the nationwide cost of protecting developed shorelines from a 2-meter rise in sea level would be $25 billion if only bulkheads are necessary and $80 billion if levees are required. Unlike wetland loss, the cost of protecting developed areas from the sea would be concentrated more in the Northeast than the Southeast, because a much greater portion of the coast is developed in the Northeast. (The Southeast still accounts for a large percentage of total costs owing to its majority share of the U.S. sheltered shorelines.)

Analysis: Interpolating Results of Weggel et al. for 0.5- and 1-Meter Sea Level Rise Scenarios

Our objectives were to (1) interpolate the 2-meter sea level rise cost estimates developed by Weggel et al. to the 50 and 100-cm scenarios, (2) develop statistical confidence intervals of the costs of protection, and (3) explicitly consider whether particular sites would be protected with levees or bulkheads.

Weggel et al. assumed that even in the baseline scenario, bulkheads must be rebuilt every ten years. Their estimate for the cost of sea level rise is the cost of the additional height required by sea level rise. He assumes that in the baseline scenario, a rive-foot bulkhead is necessary, at $130 or $500 per foot, and that costs rise with height to the 1.5 power. Thus, if SLR(t) represents the sea level rise in feet by the year t, the cost of bulkheads for the $130/foot estimate is simply,

(7) $\text{Bulkhead Cost} = ((5 + SLR)/5)^{1.5} * 130,$

and the incremental cost due to sea level rise is,

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[15]One reviewer noted that the cost of protecting Miami, Florida, may be too low. The city is located on a porous limestone base, a factor that may cause severe seepage and drainage problems.

Table 6. Cost of Protecting Sheltered Waters Against a 2-Meter Sea Level Rise
(Millions of 1986 Dollars)

Index Sites*	New Bulkhead	Raise Old Bulkhead	Move Building	Raise Roads and Utilities	Total
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	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		
USA		24,633	80,176		

Source: Weggel et al.

* This is the cost for the low estimate only.
** Assumes no extraordinary seepage problems.

(8) $$Cost = ((5 + SLR) / 5)^{1.5} * 130 - 130$$

We now present our procedure for the 1-meter scenario; the 50-cm scenario is analogous. The ratio of costs due to sea level rise incurred for a particular year between the 2-meter and 1-meter scenarios is,

(9) $$Ratio(t) = COST\_1m(t)/COST\_2m(t) = \frac{(5 + SLR\_1m(t)/5)^{1.5} - 1}{5 + SLR\_2m(t)/5)^{1.5} - 1}$$

(Although the elasticity of total cost with respect to sea level rise is 1.5, the elasticity of costs due to sea level rise is only 1.08 over the 50- to 200-cm range.)

We are interested in estimating the cumulative cost for the SO- and 100-cm scenarios, which requires considering,

(10) $$\sum_{t=1986}^{2100} COST\_1m(t) \Big/ \sum_{1986}^{2100} COST\_2m(t)$$

Because Weggel et al. reported the denominator (i.e., the sum) and not the cost for specific years, we could not calculate this ratio precisely. Instead, we use a conservative approximation, COST_ lm(2100)/COST_2m(2100). (See Appendix 1 for proof that this ratio provides a conservative approximation.)

We wanted our analysis to explicitly consider the suggestion of Weggel et al. that $130/foot applies to areas above sea level that simply need bulkheads, while $500/foot applies to areas that would be inundated and hence need levees and pumping systems. Unfortunately, Weggel et al. were not able to determine the portion of developed shores that would require levees. However, Park et al. provide estimates of lost lowland. We assumed that the percentage of the developed shoreline requiring a levee would be equal to the percentage of coastal lowlands (below 12 feet NGVD) flooded by spring high tide under the no-protection scenario.[16]

Thus, we define the cost for protecting developed sheltered shorelines as,

(11) Cost = [500/130 * (Lowland Lost/Lowlands 1986) + (1-Lowland Lost/Lowlands 1986)]

* WeggeLCost-130 * Ratio(SLR)

---

[16]This assumption is conservative in that it underestimates the area of land that would need levees. Even today, cities like New Orleans that are completely protected by levees often have substantial areas above sea level, for two reasons: (1) even if only a small portion of the total land is low enough to need a levee, the entire shoreline can consist of lowland that needs protection, and (2) levees may be needed to protect areas from flooding during storms. The fraction of the shore requiring a levee would be less than the fraction of area below sea level only in unusual cases, such as a site with a straight lowland shore accompanied by uplands that jut into the sea like fingers.

where:

Weggel_Cost_130 = Weggel's estimate of the cost of protecting a site in the 2-meter scenario assuming $130/foot.

Lowlands_Lost = Area of lowlands lost at time t.

Lowlands_1986 = Area of lowlands in 1986.

Ratio(SLR) = ((5 + SLR)/(5+6.56))1-5

SLR = Sea level rise for a particular scenario by,year 2100 in feet.

6.56 = The rise in sea level by 2100 in feet for the 2-meter scenario.

Using this equation, we calculated the cost of protecting developed shores for each of the 46 sites in the Park et al. subsample.

As a final step, we sought to incorporate the additional information from the other 49 sites Weggel et al. examined. As Table '7 shows, the estimates from the full sample were within the sampling error for the Northeast, mid-Atlantic, and Southeast. However, by chance, the Park et al. subsample of the west coast had excluded all of the sites that would require significant amounts of bulkheads and levees; the full sample results in an estimate over six times as great. We followed the simple procedure of adjusting the estimates from equation 11 by the ratio of the Weggel et al. cost estimates for each of the four major areas of the nation; we adjusted statistical error by the ratio of errors for the two samples.

Table 7. Comparison of Weggel Low Cost Estimates for Park's Subsample and Full Sample
Billions of 1986 Dollars

	Subsample		Full Sample		Ratio*	
	estimate	error	estimate	error	estimate	error
Northeast	4.91	3.28	6.93	3.65	1.41	1.11
Mid-Atlantic	2.85	1.23	4.35	2.45	1.53	1.99
Southeast	11.22	3.43	9.25	2.12	0.82	0.62
West	0.65	0.02	4.10	0.37	6.31	23.40

* Ratio of Full Sample to Subsample.

Table 8 illustrates estimated costs of protecting sheltered shores for both the sample and subsample for each of the four major regions, and confidence intervals for the nation. For the three sea level rise scenarios, our estimated confidence intervals are 5-13, 11-33, and 29-100 billion dollars. Thus, for the nation at large, the elasticity of total cost with respect to sea level rise is 1.4; that is, a quadrupling of sea level rise from 50 to 200 cm increases costs sevenfold.[17] The elasticity would have been greater if the levee estimates had included the cost of drainage systems.

RESULTS: NATIONWIDE COST OF PROTECTING THE OPEN COAST

Leatherman Estimate of Sand Costs

Table 9 illustrates Leatherman's estimates. A total of 1920 miles of shorelines would be nourished. An area of 931 square miles would be raised, 235 of this after a 1-foot rise in sea level. As the table shows, two-thirds of the nationwide costs would be borne by four southeastern states: Texas, Louisiana, Florida, and South Carolina. Figure 6 illustrates the cumulative nationwide costs over time. For the 50 and 200 cm scenarios, the cumulative cost would be $2.3-4.4 billion through 2020, $11-20 billion through 2060, and $14-58 billion through 2100.

Analysis: An Increasing Cost Scenario for Sand

In the past, we have shown that if unit sand costs increase substantially over time, a community that chooses to hold back the sea at first may eventually decide to migrate landward (Titus, 1987). However, that analysis was based on hypothetical increases in dredging costs. We wanted this study to provide at least a first-order estimate of how costs might escalate. In this section, we use the sand cost function Leatherman developed for Florida to develop an increasing-cost scenario. We emphasize that unlike our other estimates, no statistical interpretation can be attached to this estimate. We hope that this crude estimate encourages other researchers to consider cost-escalation in the future.

Leatherman's cost function for total available sand off Florida's Atlantic coast was based on the following:

Distance Offshore (miles)	Available Sand (millions cu yd)	Unit Cost (dollars)
0-1	66	4
1-2	87	5
2-3	122	6
3-4	48	7
4-5	0	8
5+	Plenty	10

[17] Elasticities are used to measure the effect a change in one variable has upon another. In this case, the elasticity is calculated with the equation 1n(Cl/C2)/ln(SLR,/SLR2), where T" is cost and "SLR" is sea level rise.

Table 8. Cost of Protecting Developed Sheltered Shorelines Through 2100.
(Billions of 1986 Dollars)

Region	Baseline	Park Subsample			Weggel Full Sample		
		50 cm	100 cm	200 cm	50 cm	100 cm	200 cm
Northeast (4/8)							
total	0.41	1.89	4.41	16.06	2.66	6.22	22.64
error	0.29	1.34	3.84	12.00	1.49	4.26	13.32
Mid-Atlantic (7/15)							
total	0.31	1.33	3.35	9.13	2.03	5.12	13.97
error	0.11	0.54	1.45	4.31	1.07	2.88	8.58
South Atlantic (8)							
total	0.58	2.86	7.75	21.64	nc	nc	nc
error	0.23	1.09	3.13	8.91	nc	nc	nc
Southwest Florida (6)							
total	0.15	0.65	1.64	4.44	nc	nc	nc
error	0.13	0.56	1.39	8.87	nc	nc	nc
Louisiana (7)							
total	0.11	0.37	0.65	2.12	nc	nc	nc
error	0.06	0.18	0.42	1.21	nc	nc	nc
Other Gulf (8)							
total	0.07	0.28	0.81	1.64	nc	nc	nc
error	0.03	0.11	0.24	0.65	nc	nc	nc
Southeast (29/54)							
total	0.91	4.16	10.82	29.84	3.43	8.91	24.59
error	0.27	1.24	3.46	12.65	0.77	2.14	7.82
95% low	nc	nc	nc	nc	1.87	4.59	8.79
95% high	nc	nc	nc	nc	4.99	13.23	40.39
Pacific (6/17)							
total	0.04	0.14	0.29	0.65	0.88	1.82	4.10
error	0.00	0.00	0.01	0.02	0.08	0.16	0.37
United States							
total	2.00	7.52	19.86	55.68	9.00	22.07	65.30
error	0.41	1.90	5.37	17.94	1.99	5.57	17.67
95% low	2.80	nc	nc	nc	4.98	10.82	29.60
95% high	1.20	nc	nc	nc	13.02	33.32	100.99

* Full sample estimates are based on the ratios calculated in Table 7. Baseline was not calculated for the full sample.

** Numbers in parenthesis after each region are the number of sites in the subsample and full sample, respectively.

Table 9. Cumulative Cost of Placing Sand on U.S. Recreational Beaches, Coastal Barrier Islands, and Spits. (Millions of 1986 Dollars)*

	Baseline	50 cm	100 cm	200 cm
Maine**	23	119	217	412
NH**	8	39	73	142
Mass**	168	490	842	1546
RI**	16	92	161	298
CT**	102	516	944	1800
NY**				
	144	770	1374	2581
NJ**	158	902	1733	3493
Del	5	34	71	162
MD	6	35	83	213
VA	30	201	387	798
NC	137	656	1271	3240
SC	184	1158	2148	4348
GA	26	154	263	640
FL (AT)#	120	787	1938	8565
FL (G)	149	904	1688	4092
AL	11	59	105	260
MS	13	72	128	370
LA	1956	2623	3493	5232
TX	350	4188	8490	17608
CA	36	174	324	626
OR**	22	61	153	336
WA**	52	143	360	794
HA**	74	338	647	1268
Nation	3,790	14,515	26,893	58,824
SE	2,946	10,601	19,524	44,355

* Incremental cost due to relative sea level rise only.

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

\# Florida Atlantic estimates account for the percentage of fine grain sediment, which generally washes away, and for the cost escalation at least expensive sand deposits are exhausted. All other estimates conservatively ignore this issue.

Source: Baseline Costs derived from Leatherman.

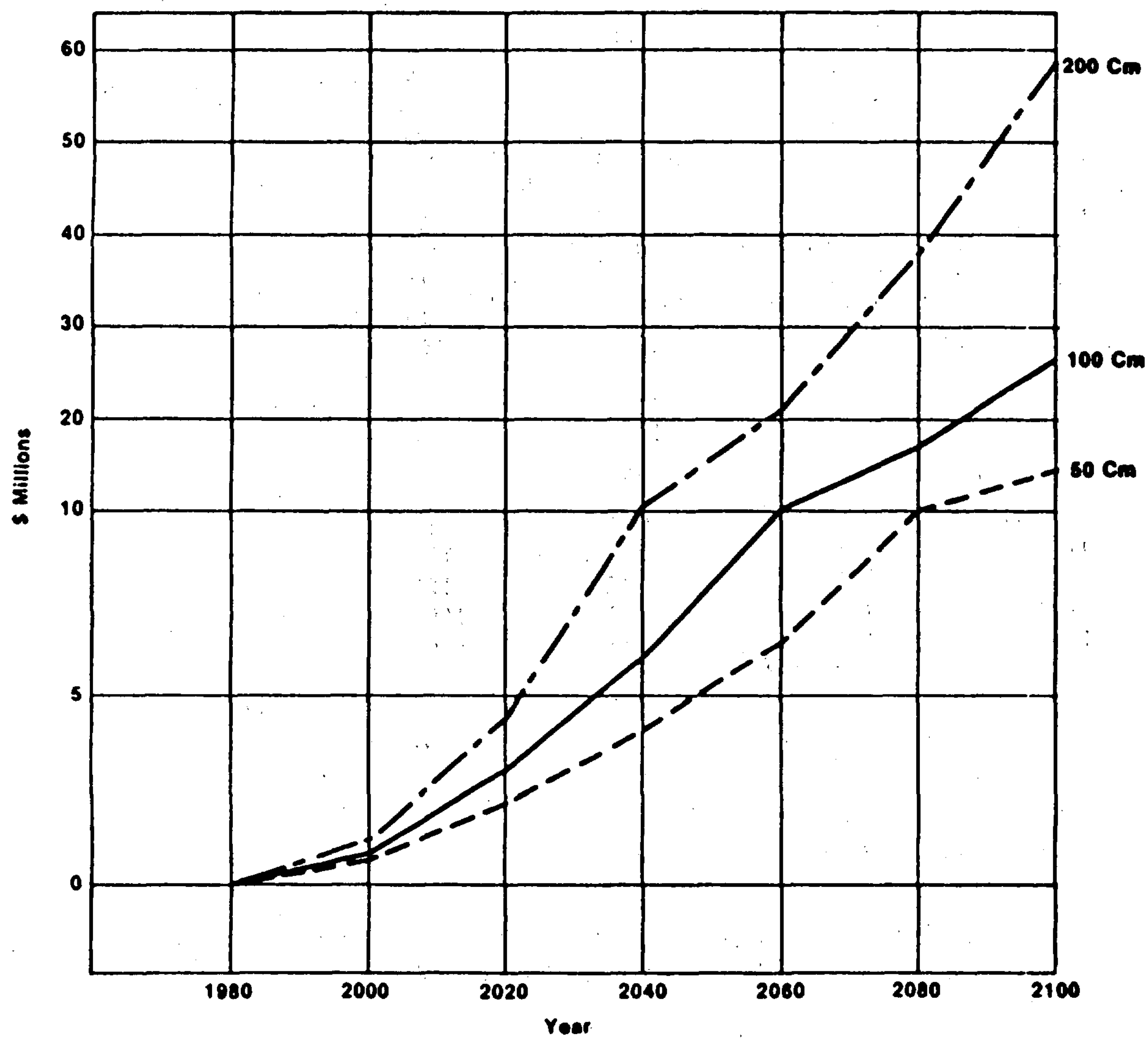

Figure 6. Nationwide cost of sand for protecting ocean cost.

The sand quantities are based on surveys by the Corps of Engineers. Unit cost estimates up to five miles assume that dredges pump the sand onto the shore, and use the generally accepted rule-of-thumb that each additional mile offshore adds $1/cubic yard for the booster pumps that would be necessary. Leatherman assumed that for distances greater than five miles, pipelines would be infeasible, and barges and dump trucks would be employed at a cost of $10/cubic yard, regardless of how far offshore one travels. Leatherman did not consider the possibility that improved technologies would reduce costs, nor the possibility that higher energy prices would increase costs.

Let CFL(SAND) represent this cost function for Florida, and C,(SAND) represent the function for a state S.

Ideally, we would like dC/dSAND to recognize the differences in sand availability, state-specific economic and environmental factors that influence the cost of dredging, and the fact that, all else equal, the amount of sand a particular distance from the shore is proportional to the amount of coastline. By scaling the Florida equation using state-specific data provided by Leatherman, we can accurately account for the latter factor and crudely attempt to account for the first two.

First, we scale the cost function C_{FL} by 293 miles, Leatherman's estimate of the length of the recreational beaches of Florida's Atlantic coast. This new function, which we call C*, refers to the cost of nourishing one mile of beach. The unit cost of nourishing one mile of beach is C*'. Then,

(12) $C^*(SAND) = C_{FL}(SAND/293)$,

and

(13) $C^{*\prime}(SAND) = C_{FL}'(SAND/293)$.

If we define C_S(SAND) as total sand cost and C'_S(SAND) as the unit cost for a particular state and a given amount of sand (e.g., C'(0) is the current unit cost), we can scale for differences in current sand costs and shoreline lengths:

(14) $C_S'(SAND) = C^{*\prime}(SAND / SHORELINE\ LENGTH(STATE)) + C_S'(0) - \$4.00$.

This equation simply says that the unit cost of sand for a state increases by the same pattern as the cost in Florida, but (1) the base cost is whatever Leatherman found it to be for that particular state, and if a state's shoreline is L times that of Florida, it can dredge L times as much sand as Florida can before it must go another mile out to sea. Our additive incorporation of the current cost into this equation is probably conservative for states where the current cost is greater than in Florida, and too liberal in the minor case of Mississippi where the cost is less". Greater costs for sand often imply that one must already go farther out to sea than Florida, which may indicate that there is less sand at any distance from shore for such a state than there is for Florida. Although this situation would suggest a multiplicative relation, we decided to keep the additive formulation because cost differences due to other factors such as wage rates, average deposit size, and using barges would not increase with the distance from shore.

Table 10 illustrates the shoreline lengths, base costs, and sand required for the three sea level rise scenarios for each state. Table 11 shows the implied sand requirements and cost per mile assuming constant costs. Table 12 shows the cumulative costs by state for the increasing cost scenario. Excluding Louisiana, the cost elasticity is 1.25 (i.e., costs rise with the 1.25 power of sea level rise).[18]

<u>Analysis: The Cost of Elevating Buildings and Roadways</u>

If all the nation's developed barrier islands were developed like Long Beach Island, we could simply multiply

[18]Louisiana was excluded from this calculation because even without sea level rise, the Louisiana coast win require large amounts of nourishment.

Table 10. Increasing Marginal Sand Cost Scenario For Dredging Sand

State	Developed Sand Ocean Shoreline* (miles)	Unit cost of sand ($/yd3)	Sand Required for Sea Level Rise Scenario (millions of cubic yards)		
			50 cm	100 cm	200 cm
Maine	31	4.00	30	54	103
NH	9	4.00	10	18	35
MASS	100	7.87	62	107	197
RI	27	6.00	15	27	50
CT	64	6.00	86	157	300
NY	120	7.85	98	175	329
NJ	125	7.85	115	221	445
DE	10	8.00	4	9	20
MD	9	6.00	6	14	35
VA	17	8.00	25	48	100
NC	143	7.00	94	182	463
SC	93	4.50	257	477	966
GA	16	4.00	38	74	160
FL (Atl)	293	4.00	177	340	1003
FL (Gulf)	251	4.00	226	422	1023
AL	36	4.00	15	26	65
MS**	43	2.75	26	47	134
LA**	85	5.00	525	698	1046
TX	230	9.25	543	917	1903
CA	78	4.00	44	81	156
OR	28	4.00	15	38	84
WA	48	4.00	36	90	199
HA	64	5.00	68	129	253

Source: Leatherman

* The calculations in this table are based on the assumption that the National Parks and Wildlife Refuges would not be protected. Areas included under the Coastal Barrier Resources Act (COBRA) are not included unless connected to mainland by bridge.

** None of the barrier islands in the Mississippi and only some barrier island in Louisiana are developed. These calculations assume that all Louisiana barriers are raised for storm protection and that the beaches and low resort communities behind Mississippi's barriers are raised.

Table 11. Average Quantity and Cost of Sand Per Mile of Shoreline*

State	Sand per mile (millions of cubic yards)			Cost (millions of 1986 dollars)		
	20 cm	100 cm	200 cm	50 cm	100 cm	200 cm
Maine	0.97	1.74	3.32	5.0	12.4	28.2
NH	1.11	2.00	3.89	6.1	15.0	33.9
MASS	0.62	1.07	1.97	5.4	9.9	22.3
RI	0.56	1.00	1.85	3.7	7.3	17.2
CT	1.34	2.45	4.69	11.1	24.4	51.3
NY	0.82	1.46	2.74	7.3	15.2	33.0
NJ	0.92	1.77	3.56	8.3	19.5	44.3
DE	0.40	0.90	2.00	3.4	8.3	23.0
MD	0.67	1.56	3.89	4.6	13.7	41.7
VA	1.47	2.82	5.88	16.0	34.5	77.3
NC	0.66	1.27	3.24	5.2	11.5	37.1
SC	2.76	5.13	10.39	24.0	48.9	104.1
GA	2.38	4.63	10.00	18.8	41.3	95.0
FL (Atl)	0.60	1.16	3.42	2.9	6.6	29.2
FL (Gulf)	0.90	1.68	4.08	4.7	11.8	35.8
AL	0.42	0.72	1.81	1.9	3.6	13.1
MS**	0.60	1.09	3.12	2.1	4.6	22.3
LA**	6.18	8.21	12.31	63.0	85.3	130.4
TX	1.97	3.99	8.27	25.1	55.9	121.1
CA	0.56	1.04	2.00	2.6	52.6	15.0
OR	0.54	1.36	3.00	2.5	8.6	25.0
WA	0.75	1.88	4.15	3.8	13.8	36.5
HA	1.06	2.02	3.95	6.8	17.2	38.5

* Scenario assumes that distribution of sand off Florida's Atlantic Cost is typical of sand distribution off all states' coasts.

Note: Cost escalation is based on the equation,
C*' (SAND) = A = $4.00 for SAND = 0 to 225,000 cubic yards/mile A + $5.00
for SAND = 225,000 to 522,000 cu yd/mi
A + $6.00 for SAND = 522,000 to 938,000 cu yd/mi
A + $7.00 for SAND = 938,000 to 1,100,000 cu yd/mi
A + $10.00 for SAND > 1,100,000 cu yd/mi

for 0-1 miles off shore, 1-2, 2-3, and 5+ miles of shore, respectively (Leatherman's cost function shows no sand in the 4-5 mile range off Florida's coast, our calculations for the other states follow this assumption, also). C*' is the unit cost of sand and A is the difference between the initial unit cost for a state and the of Florida ($4.00).

Table 12. Cost by State of Protecting Open Coast Under Increasing Sand Cost Scenario*

State	(Millions of 1986 Dollars)		
	20 cm	100 cm	200 cm
Maine	155	384	874
NH	55	135	305
MASS	540	990	2,230
RI	100	197	464
CT	710	1,562	3,283
NY	876	1,824	3,960
NJ	1,038	2,438	5,538
DE	34	83	230
MD	41	123	375
VA	272	587	1,314
NC	744	1,645	5,305
SC	2,232	4,548	9,681
GA	301	661	1,520
FL (Atl)	850	1,934	8,556
FL (Gulf)	1,180	2,962	8,986
AL	68	130	472
MS**	90	198	959
LA**	5,355	7,251	11,084
TX	5,773	12,857	27,853
CA	203	437	1,170
OR	70	241	700
WA	182	662	1,752
HA	435	1,101	2,464
USA (Increasing Cost)	21,304	42,950	99,075
USA (Fixed Cost) **	14,515	26,893	58,824
Southeast (IC)	16,593	32,186	74,416
USA (IC - Excluding LA)	15,949	35,699	87,991

* The calculations in this table are based on the assumption that National Parks and Wildlife Refuges would not be protected. Areas included under the Coastal Barrier Resources Act (COBRA) are not included unless connected to the mainland be a bridge.

** Leatherman national estimate minus the difference between Leatherman estimate for Florida (increasing cost) and the estimate implied by a constant cost of $4.00/cu yd.

the unit cost estimates described in the case study by the area of barrier islands that had to be raised. However, most islands are developed less densely. However, for barrier 'communities which are more densely developed, like Ocean City, Maryland, the infrastructure cost would not be proportionately greater. For the most part, a greater density reflects the presence of high-rises instead of single-family homes; the density of roads and utilities is not necessarily much greater. Thus, we use the following procedure:

(1) Collect census data for a random sample of coastal barrier communities on the number of buildings and divide by area to get density.

(2) Calculate the mean values and confidence intervals for densities in three coastal regions: the Gulf Coast, the Southeast Atlantic (Florida to North Carolina), and the mid and Northeast Atlantic States.

(3) Develop equations relating cost to shoreline length, area, and density, and apply the equation to the confidence interval for densities, for each of the three scenarios.

(4) Adjust the estimates (usually downward) for the SO- and 100-cm scenarios to account for the fact that the relative elevated ocean sides may not have to be raised for these scenarios.

Census Data

Table 13 illustrates census data on densities for the sites in our random sample. We note that there may be an upward bias, in that the Bureau of Census does not provide data if there are not at least 1000 year-round residents. On the other hand, there is a downward bias in that some of the barriers are lumped in with a township that extends to the mainland, which is generally less dense than the barrier. If census data were not available for a particular site, data from a nearby locale were used. In some instances, data from a nearby coastal (instead of a barrier) town had to be used. Another problem with census data is that it provides the number of housing units and the number of single-family homes, but not the total number of buildings, which we need to estimate road density. Thus, we were forced to use the number of single family homes as a proxy for building density. This last assumption effectively treats multi-unit structures as vacant lots; it is still more accurate than treating a condominium with 100 units as 100 houses.

Extrapolation Procedure

With means and confidence intervals for the densities calculated, we can now use the estimates of Weggel et al. to calculate the cost of elevating infrastructure for the nation's developed barrier islands. Because these costs are mostly related to roads, we begin with an equation relating Long Beach Island's development density (and, hence, infrastructure) to other barrier islands' level of development and size:

Table 13. Building Densities For a Sample of Coastal Barriers

Site	Area ($mile^2$)	Housing Units	Single Units	Units/$mile^2$	
				Housing Density	Single Density
Gulf					
Galveston, TX	35.5	27,850	17,908	785	504
Freeport, TX	7.2	4,978	3,629	691	504
Grand I., LA	4.8	1,719	1,294	358	270
Gulf Shores, AL	8.8	1,567	1,327	178	151
Panama, FL	15.8	2,525	1,136	160	72
Belleair, FL	4.5	1,023	904	227	201
Siesta Key, FL	27.0	6,817	2,502	252	93
Manasota, FL	4.5	1,264	748	281	166
Ft. Meyers, FL	2.6	5,685	2,376	2,187	914
Naples, FL	8.6	12,204	6,432	1,419	748
Marco I., FL	7.9	5,901	4,166	747	527
	Mean Single Density: 377 Standard Deviation: 282 Standard Deviation of the Mean: 85				
South Atlantic					
Key Biscayne, FL	1.3	4,635	1,928	3,433	1,428
Lauderdale-By-Sea, FL	0.4	2,254	699	5,123	1,589
Palm Beach, FL	3.2	8,664	3,249	2,708	1,015
Vero Beach, FL	6.6	8,983	5,408	1,361	819
Cocoa Beach, FL	4.2	6,246	2,942	1,847	700
Daytona Beach, FL	3.0	1,267	212	422	71
Fernandina, FL	9.9	3,356	2,544	339	257
St. Simona, GA	7.4	3,400	2,591	459	350
Folly Beach, SC	1.9	1,128	774	594	407
Hilton Head, SC	43.2	9,768	7,922	226	183
Myrtle Beach, SC	16.8	10,107	5,508	602	328
Nags Head Area, NC	9.0	4,632	4,025	515	447
Wrightsville, NC	5.8	2,251	1,015	388	175
Long Bay, NC	5.3	2,967	2,314	560	437
	Mean Single Density: 586 Standard Deviation: 469 Standard Deviation of the Mean: 130				

Table 13. Building Densities for a Sample of Coastal Barriers (Continued)

Site	Area (mile^2)	Housing Units	Single Units	Units/mile^2	
				Housing Density	Single Density
Mid-Atlantic/Northeast					
Va. Beach, VA	144.5	92,032	74,362	637	515
Ocean City, MD	4.5	18,221	3,116	4,049	692
Rehobeth, DE	1.9	3,111	1,593	1,637	838
Beach Haven, NJ	1.0	2,379	1,734	2,379	1,734
N. Beach Haven, NJ	1.7	5,326	3,920	3,133	2,306
Ship Bottom, NJ	0.6	1,781	1,322	2,968	2,203
Surf City, NJ	0.7	2,530	1,801	3,614	2,573
Sea Isle, NJ	2.3	4,595	2,762	1,998	1,201
Wildwood, NJ	4.3	16,664	8,267	3,875	1,922
Seaside Heights, NJ	0.4	2,728	1,004	6,820	2,510
Ocean Beach, NJ	0.8	4,022	3,877	5,028	4,846
Long Beach, NY	2.0	15,203	5,123	7,602	2,562
Atlantic Beach, NY	0.4	975	760	2,438	1,900
Narragansett, RI					
Pier	2.6	1,576	953	606	367
Town of	3.8	6,587	5,395	1,733	1,420
W. Yarmouth, MA	12.4	784	417	63	34

Mean Single Density: 1726
Standard Deviation: 1177
Standard Deviation of the Mean: 294

(15) Road_Mileage = Length + LBI_Secondary_Road_Density * Density / LBI Density * Area

where:

(16) LBI_Secondary_Road_Density = (LBI Roads - LBI Length) / LBI Area,

and Area and Length refer to the barrier island under analysis. Equation (15) says that if density is zero, the road mileage is equal to the length of the island in question. If the island is twice as long as LBI and has the same width and density, the toad mileage is twice that of LBI. If the island has the same length but twice the area, the road length is not quite double that of LBI, since secondary roads are double but the primary road is the same length.

The secondary road density estimated by Weggel et al. is 14.3 miles per square mile. Weggel et al. also estimate the building density at 1949 per square mile; however, because only 73% are single-family houses, we adjust this downward to 1420, to be consistent with our approach of using census data for single family houses. Because the area of the island is 7.4 square miles, equation (IS) becomes:

(17a) Road Mileage = Island_Length + 0.01007042 * Density * Area,

or,

(17b) Road_Mileage = Island_Length + 0.01007042 * Single_Houses.

In the discussion of the case study, we noted that the cost for elevating houses and infrastructure worked out to $4S7, $8S6, and $1358 million for the 50-, 100-, and 200-cm scenarios, respectively. Because most of these costs apply to rebuilding infrastructure along roadways, we assume that the costs are proportional to road mileage. Given the island's 124 miles of roads, we multiply equation (17b) by the cost per mile of road for each of the scenarios, and we get:

(18a) Cost(SO cm) = 3,685,000 * Length + 37,109 * Buildings

(18b) Cost(100 cm) = 6,903,000 * Length + 69,518 * Buildings

(18c) Cost(200 cm) = 10,952,000 * Length + 110,287 * Buildings.

The intercept term, ranging from $3.7 to $11 million per mile, appears reasonable, when one considers that the roads are being replaced more than once in the high scenarios. However, the cost of $37-410 thousand per single house seems somewhat high at first glance. The cost results in part because Weggel et al. assume that communities would rebuild roads to normal engineering standards; however, this assumption is offset by the assumption that no other infrastructure would be necessary.

The cost does not seem quite so high if one remembers that the costs are incurred continuously over the course of a century;. even in the high scenario, it is less than one thousand dollars per year per building. Moreover, the co-efficient also includes costs attributable to multi-unit housing and would be 25% less if we included all buildings.

Because we have sampled for density, we rewrite equation (18) as follows:

(19a) Cost(50 cm) = 3,685,000 * Length + 37,109 * Area * Density

(19b) Cost(100 cm) = 6,903,000 * Length + 69,518 * Area * Density

(19c) Cost(200 cm) = 10,952,000 * Length + 110,287 * Area * Density.

Although the 200-cm scenario involves raising the entire island, the 50- and 100-cm scenarios might only require that the low bay sides be raised. Therefore, we need to scale the equation to account for the part of the island that would be raised. We do this by multiplying the equations by the ratio bayside area/area and dividing by the value of that ratio for Long Beach Island, 0.56. (Thus, for Long Beach Island, the equation is unchanged.)

(20a) Cost(50 cm) = 6,580,4000 * Length * Bayside_Area / Area + 65,947 * Bayside_Area * Density

(20b) Cost(100 cm) = 12,328,000 * Length * Bayside_Area / Area + 123,542 * Bayside_Area * Density

Because ocean as well as baysides would have to be raised in the 2-meter scenario, we do not bother to-scale this equation, and simply use equation (19c).

We also use the unscaled equation (19b) as an alternative to equation (20b) for the 1-meter scenario, to account for the possibility that ocean sides of barrier islands might have to be raised even with a 1-meter rise. Leatherman assumed this to be the case, largely because for many islands, much of the land above 5 ft NGVD is within 2 feet of this contour. However, for Long Beach Island and other coastal barriers, most of. the ocean side is above 8 ft NGVD. (Even land at the 10-ft contour might have to be raised with a 1-meter rise. Most of the islands with little land below 5 ft NGVD are along the Atlantic Coast. With a typical spring tidal range of 7 feet (and the fact that sea level is 6 inches above the NGVD reference elevation), land at the 10-foot contour is only 6 feet above spring ocean tide; with a 4-foot relative rise, it would only be 2 feet above the ocean's spring high tide. If the dunes were eroded by a prolonged northeaster, such low elevations of ocean side lots would greatly increase the risk of an inlet breach. If bay sides of barrier islands were already being raised, local officials recognizing that the sea would continue to rise after the year 2100 might conclude that raising ocean sides would be worthwhile as well.)

<u>Results of Extrapolation</u>

Table 14 illustrates our estimates of the non-sand costs of elevating barrier islands in place. For a 50 cm rise in sea level, Gulf coast barrier islands account for over 50% of the $U billion cost, largely due to their lower elevations. By contrast, for a 2-meter rise, the Mid-Atlantic and Northeast would account for over 50% of the $96 billion cost because they are on average the most densely developed. Our estimates imply a cost elasticity of 1.6.

Table 14. Cost of Elevating Roads and Structures Assuming That Costs are Proportional to-Building Density

	Gulf	South Atlantic	Mid Atlantic & Northeast	USA*
Shoreline Miles**	565	522	511	1,598
Bayside Area (mi2)	181	24	30	235
Oceanside Area (mi2)	325	167	204	696
Single Unit Building Density				
Mean	377	586	1726	nc
Standard Deviation	282	469	1177	nc
Total Cost (Billions of 1986 Dollars)				
50 cm	5.8	1.4	3.6	10.8
100 cm	10.9	2.6	7.2	20.7
100 cm (Alt Cost)	17.2	11.4	28.1	56.6
200 cm	27.2	18.1	50.1	95.4
Sampling Error				
50 cm	1.0	0.19	0.57	1.17
100 cm	1.9	0.37	1.09	2.22
100 cm (Alt Cost)	3.0	1.63	4.75	5.85
200 cm	5.6	2.64	7.60	9.86

Cost (50 cm) = 6,580,400* Length * Bayside_Area/Area + 65,947 * Bayside_Area * Density
Cost (100 cm) = 12,327,000 * Length * Bayside_Area/Area + 123,542 * Bayside_Area * Density
Alt Cost (100 cm) = 6,903,000 * Length + 69,518 * Area * Density
Cost (200 cm) = 10,952,000 * Length + 110,287 * Area * Density

* Results are for the Atlantic and Gulf Coasts only; the Pacific Coast has no barrier islands. Sampling error is based solely on the variation of building density.

** Shoreline lengths are from Leatherman and refer to developed as well as developable sandy ocean shorelines.

CHAPTER 7

SUMMARY AND CONCLUSIONS

FINAL CAUTION

This paper has discussed the methods and results of four studies and our own analysis of the nationwide impact of a rise in sea level of 50-200 centimeters by the year 2100. The analysis was structured to enable consideration of three broad policy options: protect all shores, protect no shores, and protect only the areas that were developed by the middle of the 1980s.

It is the nature of first-cut national assessments to underestimate the cost of any undertaking, and this study is no exception. We have not identified every important cost; we have not estimated the magnitude of every cost we have identified; and we use assumptions that tend to understate the impact at each step of the calculations.

The estimates for barrier island rai 'sing are conservative because they assume (1) today's level of development and (2) do not consider the sand losses caused by major storms. The estimates for protecting sheltered shorelines are conservative because the complete cost of defending land from inundation would generally be greater than $500 per foot of shoreline; they only evaluate the cost of defending areas that are densely developed today, and our assumptions understate the portion of shorelines that would require levees.

We did not attempt to estimate the cost of protecting water supplies from saltwater intrusion or the cost of protecting lowlands from flooding. Nor did we examine the cost of saving Louisiana's coastal wetlands or of rebuilding municipal, drainage systems.

Although the study provides nationwide estimates of wetland loss for three alternative policy options, it only provides a partial cost estimate for protecting currently developed areas. Future studies will have to assess the value of the (currently) undeveloped land that would be lost, as well as the economic losses that would occur from the loss of coastal wetlands.

Consideration of all three policy options should be conducted for specific areas; but nationwide cost estimates for the no-protection and total protection options would not be particularly meaningful. The no-protection costs would assume an eventual abandonment of the nation's beach resorts, as well as major portions of coastal cities such as Miami, Charleston, New York, and Boston--such an abandonment does not seem plausible given the relatively low cost of shore protection. The total-protection cost would assume a complete armoring of all U.S. tidal shorelines, which again does not seem reasonable.

SUMMARY RESULTS

Tables 15 and 16 summarize the nationwide and southeast-wide results of the papers comprising this volume. Fourteen thousand square miles of land could be lost to the sea from a 1-meter rise if shores are not protected, with dry and wet land each accounting for about half the loss. For approximately $100 billion, a thousand square miles of currently developed areas (accounting for about 7% of the threatened land) could be protected from inundation, but the loss of coastal wetlands would be greater.

Our estimates suggest that the cumulative cost of shore protection would be approximately $140,000 per acre. Thus, at the national level, protecting developed coastal areas appears to be cost-effective. Even if one merely compares this figure with the value of land and structures on barrier islands and coastal cities, these areas appear worth protecting. But this cumulative estimate implies that even at the end of the century, the annual cost of protection would be about

Table 15. Summary of Nationwide Results

	50 cm	100 cm	200 cm
If No Shores Are Protected			
Land Lost			
Dryland Lost (sq mi)	3315-7311	5123-10330	8191-15397
Wetlands Lost (%)	17-43	26-66	29-76
Value of Lost Property ($ bill)	Y	Y	Y
Cost of Coastal Defense ($ bill)			
Open Coast	0	0	0
Sand	0	0	0
Elevate Structures	0	0	0
Sheltered Shores	0	0	0
If Developed Areas Are Protected			
Land Lost			
Dryland Lost (sq mi)	2200-6100	4100-9200	6400-13500
Wetlands Lost (%)	20-45	29-69	33-80
Value of Lost Property ($ bill)	Y	Y	Y
Cost of Coastal Defense ($ bill)	15-20f	27-41f	58-100f
Open Coast			
Sand	9-13	21-57f	75-115
Elevate Structures	5-13	11-33	30-101
Sheltered Shores	5-13	11-33	30-101
If All Shores Are Protected			
Land Lost			
Dryland Lost (sq mi)	0	0	0
Wetlands Lost (%)	38-61	50-82	66-90
Value of Lost Property ($ bill)	0	0	0
Cost of Coastal Defense ($ bill)	?	?	?
Open Coast			
Sand	15-20f	27-41f	58-100f
Elevate Structures	9-13	21-57f	75-115
Sheltered Shores	?	?	?

Note: All dollar figures are in billions.

Symbols:
- Y signifies value that Yohe will calculate in future report.
- ? signifies value not currently being assessed.
- F Interval represents estimates not based on alternative formulae. All other intervals represent statistical uncertainty, except for totals, which contain both.

Table 15. Summary of Southeastern Results

	50 cm	100 cm	200 cm
If No Shores Are Protected			
Land Lost			
Dryland Lost (sq mi)	2300-5900	3200-7600	4800-10800
Wetlands Lost (%)	22-48	30-75	37-88
Value of Lost Property ($ bill)	Y	Y	Y
Cost of Coastal Defense ($ bill)			
Open Coast	0	0	0
Sand	0	0	0
Elevate Structures	0	0	0
Sheltered Shores	0	0	0
If Developed Areas Are Protected			
Land Lost			
Dryland Lost (sq mi)	1900-5500	2600-6900	4200-10100
Wetlands Lost (%)	24-50	34-77	40-90
Value of Lost Property ($ bill)	Y	Y	Y
Cost of Coastal Defense ($ bill)	19-28	42-75	127-174
Open Coast			
Sand	10-15f	19-30f	44-74f
Elevate Structures	5-9	10-40f	60-75
Sheltered Shores	2-5	5-13	9-41
If All Shores Are Protected			
Land Lost			
Dryland Lost (sq mi)	0	0	0
Wetlands Lost (%)	38-63	47-90	68-93
Value of Lost Property ($ bill)	0	0	0
Cost of Coastal Defense ($ bill)	?	?	?
Open Coast			
Sand	15-20f	19-30f	44-74f
Elevate Structures	5-9	10-40f	60-75
Sheltered Shores	?	?	?

Note: All dollar figures are in billions.

Symbols:
- Y signifies value that Yohe will calculate in future report.
- ? signifies value not currently being assessed.
- F Interval represents estimates not based on alternative formulae. All other intervals represent statistical uncertainty, except for totals, which contain both.

$3,000 per acre--hardly a welcome prospect for coastal property owners but nevertheless, one well worth bearing in order to maintain the property.

But cost-effectiveness is not the sole criterion society should use to determine whether our shores should be protected from the effects of a rising sea; the value of resources like wetlands that might be lost if we protect our more tangible economic assets should be considered as well. Fortunately, it might be possible to protect both. The effort to protect coastal wetlands would be most successful if focused upon areas that are not yet densely developed. Abandoning developed areas would only increase the area of surviving wetlands by 5 to 10% -- but at great cost. By contrast, limiting coastal protection to areas that are already developed (and allowing currently undeveloped areas to flood) would increase the area of surviving wetlands by 40 to 100%.

NEXT STEPS

Toward Better National Assessments

Although our nationwide estimates are based on samples of coastal sites, we have analyzed the implications of these results only at the national level, with the exception of the Long Beach Island case study. Although this is probably adequate for providing national policy makers with a sense of the magnitude of the threat from global warming and the need to develop anticipatory policies, it does little to suggest what those policies might be.

Once Yohe's assessment of coastal property values is complete, we will have a nationwide data base that will be adequate for conducting preliminary economic analyses of coastal policy options. For each sea level rise scenario, it will be possible to estimate whether and for how long particular coastal sites would be worth protecting (ignoring the value of wetlands, which market forces generally do). Such assessments will make it possible for national analyses to use a more realistic management scenario which assumes that all areas will be protected that are worth protecting; such a scenario will almost certainly fall between our total and standard protection scenarios.

Additional refinements in shore-protection cost estimates should focus on alternatives to raising barrier islands on the open coast and explicitly incorporating drainage costs in areas that would require levees. The former is necessary because island migration and levees may be more viable for some communities on the open coast; the latter is necessary because it is potentially as significant as construction of levees.

Estimates of the value of lost property will also have to be improved. Our proposed market-based shore-protection scenario will substantially understate the dryland protected and the wetlands lost as long as we assume today's level of development. r Particularly in the Southeast, there is considerable low-lying forest and farm land that may be developed in the next thirty to one hundred years.

Toward Protecting Coastal Wetlands

Because a substantial acceleration in sea level rise is still decades in the future, we have argued that it is still too soon for society to implement most of the responses that sea level rise will eventually necessitate, but that one important exception is the protection of coastal wetlands (Titus, 1984; Titus, 1986; and Titus, 1988). Our hypothesis has been that coastal states outside Louisiana could maintain most wetland shorelines and minimize the loss of wetland acreage most efficiently by enacting a policy of "presumed mobility' that required that areas that are developed in the future (and perhaps a limited number of areas that are currently lightly developed) revert to nature 75-100 years hence if the sea rises enough to inundate them. There are many ways of implementing such a policy (e.g., restrictions on bulkhead reconstruction, state regulations, long-term leases, conditional land ownership), but the success of this option requires that it be implemented soon.

In our view, presumed mobility is legally, economically, and administratively more feasible than the alternative of prohibiting coastal development. First, prohibitions of development are often ruled as contrary to the "due process" clause of the Constitution. By contrast, requirements to yield property to the state as shores erode have been part of the riparian laws of many states since colonial times; bulkheading restrictions are commonplace; and the courts have found that a coastal management action is not a "taking" if the impact is a negligible fraction of a property's value. (Note: the present value of losing a $100,000 property fifty years hence is less than $1,000, and one-hundred years hence, less than $10.)

The latter aspect also explains why the presumed mobility policy would be more economically feasible than prohibiting development. To purchase a few million acres of land that might be wetlands with a one or two meter rise today, would cost tens of billions of dollars; and it would be a poor investment if the greenhouse effect were curtailed and the sea did not rise as projected. By contrast, some ways of implementing the presumed mobility approach (e.g., bulkhead regulations) would require little if any public expenditures; even eminent domain purchases of the option to take over property as sea level rises would be at most a few percent of the property values. If sea level does not rise as projected, the investment to protect coastal wetlands would be lost, just as farmers hedging against decreases in crop prices lose their investments in commodity options if prices rise and homeowners lose the value of their fire insurance premiums if their houses do not burn. In either event, economic theory generally finds hedging and insurance to be rational investments.

Finally, the presumed mobility approach is more administratively feasible because governmental decisions are confined to setting an environmental constraint--the long-term protection of wetlands--rather than dictating the methods by which private landholders meet the constraint. Unlike prohibitions of development, one must concede the eventuality of sea level rise before opposing a policy of presumed mobility. Moreover, preventing development of coastal lowlands would require drawing a line on a map beyond which the land would not be developed; drawing the line would require a decision regarding what level of sea level rise to anticipate, which would in turn require policy makers to (1) rely on a projection of sea level rise, and (2) pick a year after which the policy would be ineffective. By contrast, presumed mobility allows (in fact, requires) real estate markets to incorporate the assessments of buyers and sellers regarding how much the sea will rise and the present value of losing land at some future date.

So far, our argument in favor of the presumed mobility approach has been nothing more than a logical hypothesis; it has not been possible to estimate the practical significance of our arguments. The State of Maine has extended its coastal protection policies to include long-term mechanisms to ensure the survival of coastal wetlands as sea level rises; but no one else has yet followed suit. Whether this is because coastal policy makers disagree with our hypothesis or they simply feel that the matter is not sufficiently urgent to require action, we believe that they need an assessment that estimates costs, remaining wetland acreage, and percentage of the coast with a band of at least (for example) 100 meters of wetlands, for various policy options and implementation dates.

We are now close to having sufficient geomorphic and engineering data to conduct such an assessment for a sample of 46 sites throughout the nation; but we still need projections of economic development for the areas. Moreover, economic models have to be developed to project both annual economic losses and current impacts on property values for a given time profile of the probability distribution of future sea level rise. These models will have to address strategies for physical and economic depreciation of properties. Property owners certain to lose their property in five to ten years would allow their properties to physically depreciate by avoiding major repairs. Owner-occupied property likely to be inundated 20-30 years later could be sold to rental investors who viewed the future more than twenty years hence as irrelevant. People concerned about permanent family ownership of property would tend to buy property in areas that were likely to be protected, but fairly modest price differences would induce investors to purchase property even if inundation were only 20-30 years away. Nevertheless, these strategies would not avoid all of the losses experienced by long-term property owners, who might have attachments to a community or might have invested in additions that command little premium on the rental market.

Incorporating these issues appears manageable. We have an opportunity to evaluate a policy whose benefits may be an order of magnitude greater than the costs. We hope that such an assessment can be undertaken soon.

Because the situation is very different than for the rest of the nation's coast, this report has not focused on Louisiana. Unlike wetland loss elsewhere, the implications of sea level rise for this coastal state appears almost certain to require federal action, because the federal government manages the flow of the Mississippi River. A recent EPA/Louisiana Geological Survey report outlined the analysis necessary to evaluate options to protect Louisiana's coastal wetlands. With 40% of the nation's coastal wetlands at risk and the federal government preventing freshwater and sediment from reaching the marshes and swamps, wetland loss in Louisiana cannot realistically be viewed as the parochial concern of a single state.

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APPENDIX 1.

Proof that the Ratio of Costs in the Year 2100 for different sea level rise scenarios is a conservative approximation of the ratio of total costs, assuming the Weggel formula.

First, we simplify notation by letting x(t) and y(t) represent the costs of the 1 and 2 meter scenarios, and A represents the ratio x(2100)/y(2100). It is commonly known that if x(t) $\geq$ A * y(t) for t over a given range (in our case 1990 to 2100), then,

(A1) $$\int_{t=1986}^{2100} x(t)dt \,/ \int_{t=1986}^{2100} y(t)dt \geq A$$

Therefore, x(2100)/y(2100) is a conservative estimate provided that x(t)/y(t) is in fact greater than x(2100)/y(2100) for t<2100, which we now show.

First, we note that sea level rise accelerates over time, which means that,

(A2) SLR_lm(t)/SLR_2m(t) > SLR_lm(2100)/SLR_2m(2100),

throughout the period 1986 to 2100. We define the latter ratio (for 2100) as B, which is less than one. Therefore, recalling that,

(A3) $$x(t)/y(t) = \frac{((S+SLR\_lm(t))/5)^{1.5}-1}{((5+SLR\ 2m(t))/5)^{1.5}-1}$$

We substitute B*SLR 2m(t)<SLR-lm(t), and get,

(A4) $$x(t)/y(t) > \frac{((5+B*SLR\_2m(t))/5)^{1.5} - 1}{((5+SLR\_2m(t))/5)^{1.5} - 1}$$

For clarity, we redefine SLR_2m(t) as z(t),

(A5) $$x(t)/y(t) > \frac{((5+B*z(t))/5)^{1.5} - 1}{((5+z(t))/5)^{1.5} - 1}$$

Since z(t) is monotonically increasing, and B is positive but less than 1, it is clear that x(t)/y(t) is monotonically decreasing. Therefore, x(t)/y(t) is in fact greater than x(2100)/y(2100) for all years before 2100, and the assertion is proven.