Originally published December 1989 by the U.S. EPA Office of Policy, Planning, and Evaluation

NATIONAL ASSESSMENT OF BEACH NOURISHMENT REQUIREMENTS- ASSOCIATED WITH ACCELERATED SEA LEVEL RISE

by

Stephen P. Leatherman
Laboratory for Coastal Research
University of Maryland
1113 Lefrak Hall
College Park, MD 20742

Contract No. 68-01-72-89

CONTENTS

Page

CHAPTER 1

INTRODUCTION[1]

A significant portion of the United States population lives within the coastal zone, with many buildings and facilities located at elevations less than 3 meters (10 feet) above sea level. These structures are presently subject to damage during storms, and this hazard has grown increasingly serious as sea levels have risen during the twentieth century. Greenhouse-induced warming is expected to raise water levels at. historically unprecedented rates, resulting in increased beach erosion and flooding.

Despite these potential hazards, the coastal population is burgeoning. In fact, development in the coastal zone is proceeding at rates that more than double inland construction. Hundreds of thousands of beachfront structures (exquisite single-family houses, high-rise -condominiums, and elegant, hotels) have been built within a few hundred feet of an eroding ocean shore. Beachfront property is some of the most valuable real estate in the country, exceeding $20,000 per linear foot of shoreline along the U.S. mid-Atlantic coast.

The present dilemma and developing disaster have resulted from the tremendous investment in coastal property at a time when most sandy beaches nationwide are eroding. Best estimates are that 90 percent of the U.S. sandy beaches are presently experiencing beach erosion (Leatherman, 1986). Accelerated sea-level rise will increase erosion rates and associated problems.

Public attention is yet to be critically focused on the beach erosion problem. The present (1988) drought and heat wave have brought about a dramatic awakening and interest of citizens in the greenhouse effect and climate change. Hopefully, a coastal disaster along an urbanized beach will not be necessary to promote public awareness of the sea level rise phenomenon and its attendant impacts.

Sea level is a primary control on shore position, which, in human terms, translates to beach erosion when water levels are rising. While weather is subject to large-scale variations and hence climate change trends are difficult to measure, rising sea levels are relatively easy to discern and can be thought of as the dipstick of climate change, reflecting the integration of many earth surface processes.

There are three general responses to accelerated sea level rise: retreat from the shore, armor the coast, or nourish the beach. Beach nourishment is the focus of this report, wherein sand is artificially placed on the beach. Other tactics for combatting the sea level rise/coastal erosion problem are discussed elsewhere in this volume. The proper shore protection response is site-specific on a community or coastal sector basis due to large differences in environmental and socioeconomic factors. The abandonment alternative is not realistic for urbanized beaches. For less developed areas along eroding shorelines, planning decisions are less clear cut. Therefore, the costs and benefits of stabilization vs. retreat must be carefully considered as the cost in either case is likely to be quite high (National Research Council, 1987).

The principal approach today of protecting coastal property and maintaining recreational beaches is beach nourishment. Engineering structures, such as groins and seawalls, have often been shown to cause detrimental effects on adjacent beaches. Also, their construction and maintenance costs are quite high. Therefore, coastal communities have come to rely upon a "soft" engineering solution -- beach nourishment, since it is environmentally sound, aesthetically pleasing, and up-to-this-time, economically feasible. However, the projected accelerated sea level rise will cause more rapid rates of beach loss and could make even this alternative too costly for many resort areas along the United States coastline.

---

[1] Although the information in this report has been funded wholly or partly by the U.S. Environmental Protection Agency under Contract No. 68-01-72-89, it does not necessarily reflect the Agency's views, and no official endorsement should be inferred from it.

OBJECTIVE

The overall objective of this research is to estimate the cost to nourish all the major recreational oceanic beaches in the U.S., given various sea level rise scenarios. It is clear that developed coastal resort residents would prefer not to move back and abandon the coast and will attempt to stabilize the shore through beach fill projects. The approach is to place, enough sand on the beach to maintain stable (nonretreating) conditions with rising sea levels. The quantity of sand required "to hold the line" is evaluated under various sea level rise scenarios (rise/year combinations) at foot intervals up to a 10-foot rise situation by the year 2100.

REPORT OUTLINE

This Introduction is followed by a general Methodology section. The beach nourishment analysis were undertaken at the community level, from which state and national totals were determined. Delray Beach, Florida, was selected as a case study to illustrate the type of analysis conducted for each area. Finally, the national results are presented. Of the approximately 7,000 miles of sandy shoreline in the U.S., 1,920 miles of beaches were evaluated in this study. These areas are considered to be the principal recreational beaches in the country.

CHAPTER 2

METHODOLOGY

STUDY SITES

This report focuses on the twenty-one coastal states in the United States. Alaska is excluded because of its undeveloped nature. Some states have only one to a few coastal resort areas (e.g., Ocean City in Maryland), while others, particularly Florida and New Jersey, are known for their many recreational beaches. The major recreational beaches in each state are examined; state averages for nourishment needs are then tabulated from the site-specific calculations. Therefore, cost estimates of beach fills are made based on local (community or physiographic) conditions to produce statewide and national assessments.

DATA SOURCES

The last national assessment of shore erosion and associated planning implications was undertaken by the U.S. Army Corps of Engineers in 1971. Their national survey, based on District Corps office reports, indicated the prevalence of shore erosion. In addition, there are numerous site-specific reports and information available for various locales. These data were assembled and analyzed to extract information pertinent to the study. Corps District personnel and State Coastal Zone Management (CZM) officials were also queried for any up-to-date information and insights. Specifically, the basic information for analysis was largely obtained from the following sources: U.S.G.S., topographic maps for areal measurements and offshore contours, National Research Council (1987) report for sea level rise scenarios, supplemented by estimates from Hoffman et al (1986), baseline relative sea level rise rates for U.S. coast (Lyles et al., 1987), and CERC Inner-Continental Shelf Studies (ICONS) data sets on offshore sand resources.

COASTAL SEGMENTATION

The coast in each state is divided into three categories: (1) publicly owned, undeveloped; (2) privately owned, undeveloped, and (3) already developed. Roughly one-third of the U.S. coast falls into each of these categories. Publicly owned, undeveloped areas (e.g., state parks, national seashores, and NASA installations) will most likely never be developed, but some, areas may be nourished. In general, these areas are not considered in the nourishment assessment, unless beach fill has already been undertaken and is likely to continue (e.g., Huntington Beach State Park, SC).

Most of the areas contained in the privately owned, undeveloped coastal area category are identified in the 1983 U.S., Congress COBRA legislation, and usually are excluded from receiving federal assistance in shoreline stabilization by law. However, these areas still have the potential to be developed, and are therefore included in the national assessment. Inclusion of these locales represents a worst case scenario in terms of the total amount of area needing nourishment.

Developed areas have already been urbanized or are already somewhat developed and are likely to be extensively developed in the future. Beaches that have been nourished in the past or have undergone full-scale urbanization are the best candidates for further restoration. Areas are delimited along the coast by jurisdictional (e.g., town, city) boundaries or natural demarcations (e.g., inlets) into geomorphic units.

CLOSURE DIMENSIONS

Offshore closure depth is specified for each area on the basis of Hallerineier's (1981) determinations for the U.S. coast. Hallermeier's (1981) approach relies upon statistical wave data, which is available for the entire U.S. coast, and his work represents the state-of-the-art in the field. Some may feel that the derived values for closure depth are too conservative in certain areas. In this case, a simple ratio of utilized and preferred values can be used to calculate higher sand volumes and costs.

The U.S. Geological Survey 7.5-minute quadrangles, supplemented by National Ocean Service nautical charts, were used to determine the horizontal distance offshore to closure depth for each coastal sector. This data source was selected since U.S.G.S. quadrangles (1:24,000 scale) are the most commonly utilized maps in the country, depicting both surficial (e.g., urban development and topography) features and offshore contours.

SEA LEVEL RISE SCENARIOS

A total of six sea level rise (SLR) scenarios are considered in this analysis, evaluated from 1 to 10 feet at 1-foot intervals but without the time exceeding year 2100. These scenarios are based on previous studies by the National Research Council (1987) and the U.S. Environmental Protection Agency (see Titus and Greene this volume). The total component of rise can be calculated as follows: $T(t) = (0.0012 + M/1{,}000)t + tb^2$, where M is the local (isostatic) factor (in mm/yr) and b describes the concaval upward slope of the quadratic equation. Estimates of M from Lyles et al. (1987) can be obtained from Table 1 as determined by NRC (1987), and values of the coefficient b are listed in Table 2 for the six scenarios.

SAND VOLUME DETERMINATIONS

The direct approach of "raising the beach/nearshore profile" is utilized because of its straightforward application. The beach to offshore closure depth distance (d) represents the Active profile dimension. For every increment (x) of sea level rise, the volume of sand required to "raise the profile" simply corresponds to xd per unit of shoreline length. This approach overcomes objections to the Bruun Rule formulation regarding on/offshore sand transport. Also, other methodologies require considerably more data (e.g., Trend Analysis necessitates knowledge of historical shoreline change and the Sediment Budget Model involves site-specific information on transport rates; Leatherman, 1985). In this analysis, longshore losses are shown separately in the tables so that the sand required to mitigate accelerated sea level rise, alone, is clearly stated.

As sea level rises, the land surface becomes relatively lower with respect to mean water level, resulting in increased frequency and more severe coastal flooding. For barrier islands, the decision will likely be. made at some point to raise -the barrier elevations. to overcome or lessen the effects of this problem. It is assumed that after 1 foot of sea level rise, coastal communities will start raising the bayside areas of the island, which are less than 5 feet above mean sea level. Prior to this point, it can be argued that the cost and nuisance of such actions would dictate inaction, and people would tolerate the increased flooding. By the time a 4-foot rise in mean sea level is achieved, the entire barrier surface, including the dunes but excluding wetlands, will have been raised in concert with water levels to prevent storm overtopping. Therefore, the procedure involves calculation of the elevational distribution above and below the 5-foot (MSL) elevation to compute the area and hence volume of sand required with different scenarios of sea level rise. Some barrier islands and mainland areas had general elevations above the 15-foot contour line. No mitigating action was deemed necessary for these areas.

SAND RESOURCE AVAILABILITY

Once the quantities of sand required to maintain the recreational beaches for various SLR scenarios have been established, a determination of available sand resources available to match this projected need must be undertaken. The preferred borrow site areas are generally located offshore for most states. Backbarrier lagoons and bays have been utilized in the past for small quantities of material, but environmental objections and incompatibility of material because of size have precluded further use of such sources, Mining of mainland sand pits has been employed locally in some areas, but again the resources are limited and this type of activity is not permitted in most states.

Table 1. Relative Sea Level for the United States Coast, 1850-1986*

Location	Trend		Location	Trend	
	mm/yr	ft/yr		mm/yr	ft/yr
Atlantic Coast			Gulf Coast		
Eastport, ME	2.7	.009	St. Petersburg, FL	2.3	.007
Bar Harbor, ME	2.7	.009	Cedar Key, FL	1.9	.006
Portland, ME	2.2	.007	Pensacola, FL	2.4	.008
Seavey Is., ME	1.8	.006	Grand Isle, LA	10.5	.034
Boston, MA	2.9	.010	Eugene Island, LA	9.7	.032
Woods Hole, MA	2.7	.009	Sabine Pass, TX	13.2	.043
Newport, RI	2.7	.009	Galveston, TX	6.4	.021
Providence, RI	1.8	.006	Galveston, TX	7.5	.024
New London, CT	2.1	.007	Freeport, TX	14.0	.046
Bridgeport, CT	2.1	.007	Rockport, TX	4.0	.013
Montauk, NY	1.9	.006	Padre Island, TX	5.1	.017
Port Jefferson, NY	2.7	.009	Port Isabel, TX	3.1	.010
Willets Pt., NY	2.4	.008			
New Rochelle, NY	06	.002	Pacific Coast		
New York, NY	2.7	.009	San Diego, CA	2.1	.007
Sandy Hook, NJ	4.1	.014	La Jolla, CA	2.0	.007
Atlantic City, NJ	3.9	.013	Newport, CA	1.9	.006
Philadelphia, PA	2.6	.008	Los Angeles, CA	0.8	.003
Lewes, DE	3.1	.010	Santa Monica, CA	1.8	.006
Baltimore, MD	3.2	.010	Port San Luis, CA	1.2	.004
Annapolis, MD	3.6	.012	San Francisco, CA	1.3	.004
Solomons Is., MD	3.3	.011	Alameda, CA	1.0	.003
Washington, DC	3.2	.011	Crescent City, CA	-0.6	-.002
Kiptopeke, VA	3.1	.010	Astoria, CA	-0.3	-.001
Hampton Roads, VA	4.3	.014	Neah Bay, CA	-1.1	-.004
Portsmouth, VA	3.7	.012	Seattle, WA	2.0	.006
Wilimington, NC	1.8	.006	Friday Harbor, WA	1.4	.004
Charleston, SC	3.4	.011	Nawiliwili, HI	2.0	.006
Ft. Pulaski, GA	3.0	.010	Honolulu, HI	1.6	.005
Fernandina, FL	1.9	.006	Hilo, HI	3.6	.012
Mayport, FL	2.2	.007			
Miami Beach, FL	2.3	.008			
Key West, FL	2.2	.007			

Inlet sand shoals (termed "ebb tidal deltas") often contain large quantities of beach sand and are located in close proximity of important resort areas, particularly in the State of Florida. Future plans for dredging of these inlets and outer shoals for ship navigation should include a provision for sand placement on adjacent or specified beach areas, rather than dumping sand far offshore in deep water. Unfortunately, some inlet material is chemically polluted, particularly in the New York-New Jersey metropolitan areas, and there is also the concern of sand drawn down from adjacent beaches if extensive sand dredging and shoal removal are realized. In fact, the large ebb tidal delta off Ocean City, Maryland (8 million cubic yards of clean beach sand) probably will not be used in the forthcoming beach restoration project because of concerns of accelerated, post dredging erosion of adjacent beach areas. Therefore, only offshore borrow sites are considered in this analysis as ebb-tidal deltas are generally too small regarding sand volumes or clouded by political concerns (unless specifically recommended for usage by state authorities).

Offshore sources along the Atlantic Coast were delineated by a series of studies undertaken in the recent past by the U.S. Army Corps of Engineers Coastal Engineering Research Center (CERC). The Inter-Continental Shelf (ICONS) study involved 0 the states from New York to Florida, and these reports are used to obtain a good estimate of available sand reserves. This information is supplemented for the rest of the coast and updated by Corps District reports for specific areas. In addition, the U.S.G.S. and M.M.S. (Minerals Management Services) in association with various state geological surveys (e.g., Louisiana, Maryland, and Maine) have expanded and updated these inventories.

BEACH NOURISHMENT COSTS

Sand costs are estimated for the range of alternatives (e.g., various SLR scenarios evaluated at particular years when a certain sea level has been achieved). Values are based on current rates per cubic yard of material. A sand cost function was developed from past dredging experience and applied to each coastal sector. It is clear that as the less expensive, closer-to-shore sand supplies are exhausted, the costs will rise as a step-function (approximately $1.00 per cubic yard per mile farther offshore as booster pumps are added). The "base rates" vary regionally so that the actual costs are site-specific. This study gives us the ability to predict for the first time the nourishment requirements for various SLR scenarios and associated costs for individual resort areas, resulting in statewide and national estimates.

FLORIDA CASE STUDY[2]

The Delray Beach area along the Florida Atlantic coast was chosen as the case study to illustrate the type of analysis conducted in this report for coastal communities nationwide. The Delray Beach area in Florida is heavily developed and requires analysis at all levels addressed in this report; profile nourishment, backbarrier and oceanside elevation raising, sand volume requirements, offshore sediment supplies, and associated dredging costs. In addition, Delray Beach has been nourished in the past (1973, 1978, and 1984), and the state of Florida proposes to continue such projects in the future (Florida DNR, 1988).

Delray Beach is located in southeast Florida in rapidly growing Palm Beach County. It shares boundaries to the north and south with Boynton Beach and Boca Raton, respectively. The beach area functions as a barrier island as it is fronted by the Atlantic Ocean to the east and the Intracoastal Waterway to the west. The barrier is rather low-lying, with maximum elevations approximately 1S feet in the dune line. The barrier varies in width, but averages 1800 feet along its length. The beaches in this locale are composed of medium to -coarse shelly sands and are underlain by similarly composed coquina. rock (Florida DNTR, 1988).

WAVE CLIMATE AND CLOSURE DEPTH SELECTION

Closure depth represents the seaward limit of significant sediment transport along a beach profile and is the offshore extent to which beach nourishment should occur. Nourishment of the beach profile to this distance is imperative for the success and longevity of beach replenishment projects; otherwise, wave action will rapidly rework the new

---

[2] This section was authored by Ms. Cary Gaunt, Laboratory for Coastal Research, University of Maryland.

sediment (which can appear as beach erosion to the casual observer), moving a portion of it offshore to attain profile equilibrium.

With. these considerations in mind, a technique was developed (Hallermeier, 1981) to determine closure depths at various coastal locations in the U.S. based on local sand characteristics and summary statistics of annual wave climate (Table 3). The results of Hallermeier's work were used in this study to determine the appropriate offshore extent of proposed beach nourishment. When Hallermeier's (1981) predictions were not available for a particular study area, approximate closure depths were extrapolated from the closest given locations.

Hallermeier defined two offshore limits in his work, d_l and d_j. The di limit was used to estimate closure depths for this report, as it (d_l) represents the "maximum water depth for sand erosion and seaward transport by an extreme yearly wave condition, and corresponds to a seaward limit of appreciable seasonal profile change" (Hallermeier, 1981). The d_j value, on the other hand, corresponds to an offshore depth where "expected surface waves are likely to cause little sand transport" (Hallermeier, 1981). Therefore, to ensure inclusion in the active profile, sand introduced by beach nourishment should be added out to the offshore depth, d_1. Hallermeier's (1981) recommended applications for the seaward limit also suggest using dd_1 values as the offshore limit for beach nourishment projects. Although extreme storm events may move sand beyond the di location, this report assumes that beach nourishment projects are based on average wave conditions.

The closure depth used for Delray Beach was 4.2 meters. This depth was determined from Hallermeier's (1981) work for Boca Raton, Florida (Table 3), the municipality immediately adjacent to southern Delray Beach. The area is subject to a mild wave climate (average height of LS9 feet) and closure depths are relatively shallow and near the shore as a result.

After determining closure depths, United States Geological Survey (USGS) topographic maps (7.5- minute series) were -used to estimate the distance from the shoreline to these depths. For example, the bathymetric points closest to 4.2 meters were located on the U.S.G.S. map for Delray Beach and measured as an average of 600 feet offshore. This distance was used in the calculations to determine the area of beach profile nourishment (i.e., length of beach to be nourished multiplied by offshore distance of closure depth = beach profile area to be nourished).

AREA MEASUREMENTS

The initial response to rising sea levels is beach profile nourishment. Following this preliminary measure, it is possible that low-lying areas of the barrier may be raised to a higher elevation by sediment input to prevent submergence. This report assumes that backbarrier elevations are raised after I foot of sea level rise and that oceanside elevations are raised after 4 feet of sea level rise.. Sediment volumes needed to raise these barrier elevations were approximated in the following manner:

- U.S.G.S. topographic maps (7.5-minute series) were obtained for each study area.

- Backbarrier areas less than 5 feet above MSL were delineated.

- Oceanside areas greater than 3 feet, but less than 1S feet above MSL, were delineated, unless the higher elevation represented a dune line. If a dune line was shown, it was included in the oceanside area measurement, as it is likely that dune.elevations would be raised in concert with beach elevations to maintain the storm buffer.

- Area measurements for each delineated backbarrier and oceanside location were estimated using an engineer's ruler and the map scale. All area measurements represent the average width and length for the delineated locations. Only buildable (i.e., not marshy) areas were included. Small, isolated locations were not included, as the maintenance (e.g., dredging) costs would likely exceed associated economic benefits.

When tabulating final results, calculations for physiographically similar locations often were lumped together. Thus, the Delray Beach profile, backbarrier, and oceanside areas were summarized with the results of Boynton and Highland Beaches and Boca Raton to give the final results:

- Profile Nourishment: 1.693 million cubic yards of sand needed for. one foot of sea level rise (SLR);
- Backbarrier Elevations: 0.946 million cubit yards of sand needed for one foot of elevation raising;
- Oceanside Elevations: 3.217 million cubic yards of sand needed for one foot of elevation raising.

Table 4 summarizes the above results for varying SLR scenarios.

Sand volume estimates like those given above were derived for all developed and developable coastal localities. These individual site results were then cumulated as statewide totals. Table 5 provides an example summary for the Florida (Atlantic) coast.

SAND SOURCES AND ASSOCIATED COSTS

The U.S. Army Corps of Engineers was involved in the late 1960s to mid-1970s in an inventory of the morphological and sediment characteristics of the Inner Continental Shelf (ICONS Studies) in an effort to locate sand suitable for beach nourishment endeavors. Using high-resolution seismic reflection surveys and sediment coring techniques, they performed a preliminary assessment of offshore borrow sites -suitable for the restoration of nearby beaches (Duane and Meisburger, 1969) The ICONS surveys were the primary sources used in this report to locate sand sources suitable for future beach nourishment projects.

Table 4.* Sand Volume Requirements for Boynton Beach to Boca Raton, FL (including Delray Beach) to Raise the Beach/Nearshore Profile and Barrier Elevations with Sea Level Rise**

Sea Level Rise (feet)	Beach/Nearshore Profile (million yd^3)	Barrier Elevations (million yd^3)		Total (million yd^3)
		Backbarrier	Oceanside	
1	1.693	0	0	1.693
2	3.386	09.46	0	4.332
3	5.079	1.892	0	6.971
4	6.772	2.838	3.217	12.827
5	8.465	3.784	6.434	18.683
6	10.158	4.730	9.651	24.539
7	11.851	5.676	12.868	30.395
8	13.544	6.622	16.085	36.251
9	15.237	7.568	19.302	42.107
10	16.930	8.514	22.519	47.963

* Excerpted Table 30 from Florida (Atlantic) Report.
** Shore length considered for nourishment is 14.43 miles.

Table 5.* Summary of Sand Volume Requirements for the Atlantic Coast of Florida to Raise the Beach/Nearshore Profile and Barrier Elevations with Sea Level Rise

Sea Level Rise (feet)	Beach/Nearshore Profile (million yd^3)	Barrier Elevations (million yd^3)		Total (million yd^3)
		Backbarrier	Oceanside	
1	76.981	0	0	76.981
2	153.962	22.358	0	176.320
3	230.943	44.716	0	275.659
4	307.924	67.074	85.219	460.217
5	384.905	89.432	170.438	644.775
6	461.886	111.790	255.657	829.333
7	538.867	134.148	640.876	1,013.891
8	615.848	156.506	426.095	1,198.449
9	692.829	178.864	511.314	1,383.007
10	769.810	201.222	596.533	1,567.565

* Excerpted Table 32 from Florida (Atlantic) Report.

For example, the Florida Atlantic coast was studied as a part of the ICONS program. Surveys were taken covering the following areas:

- Miami to Palm Beach (Duane and Meisburger, 1969)
- Palm Beach to Cape Kennedy (Meisburger and Duane, 1971)
- Cape Canaveral (Field and Duane, 1974)
- Cape Canaveral to Georgia (Meisburger and Field, 1975)

Table 6 briefly characterizes sand located by the ICONS studies. These maps and data contained in the ICONS reports were used to identify the offshore locations of sand suitable for beach replenishment. For example, Field and Duane (1974) define sand suitable for beach nourishment in the Cape Canaveral area as "medium to coarse, well-sorted quartz size-mollusk sand." Seismic profiling and coring suggest that such sand sources lie in large offshore shoals such as Chester Shoal, which contains an estimated sand quantity of 8.8 x 106 yd^3. Table 7 summarizes all reported Florida Atlantic sand reserves in terms of offshore location, quantity, and associated nourishment cost. The data provided in Table 7 were paramount in calculating final sand costs associated with beach nourishment.

Initial dredging costs for the Florida Atlantic coast were established at $4.00 per cubic yard, based on Bruun (198S). Bruun's paper examined some beach nourishment projects in Florida, where he noted that project costs ranged between,$3 and 5.00 per cubic meter ($2.27-3.78 per cubic yard), with costs recently increasing. It is likely that dredging costs will continue to increase with future beach restoration projects, thus the higher figure of $5.00 per cubic meter (approx. $4.00 per cubic yard) was used to provide preliminary estimates of future sand costs for beach nourishment..

The $4.00 per cubic yard value was used only for sand reserves located within one mile of the shore, as dredging costs increase with greater distance offshore. The Army Corps of Engineer's "rule of thumb" for dredging cost escalation is $1.00 per cubic yard for each, additional,- mile offshore (Weggel, personal communication, 1987). This rule only applies for sand reserves within 5 miles of the shore when a floating pipeline dredge system is used to pump the sand directly to the beach. Beyond 5 miles, the sand must be moved in two stages; dredging onto a ship for transport to the mainland, followed by truck hauling to location. Costs for this process are not clearly known, but it is estimated that at least \$2.00 per cubic yard would be added to the highest floating pipeline cost. This rate is used for all cost calculations requiring sand beyond 5 miles. Table 7 summarizes sand costs based on offshore location for the Florida Atlantic coast.

Given data on offshore sand reserves and associated dredging costs, it is possible to project future costs of beach nourishment projects given various SLR scenarios. This report examines six SLR scenarios and projected costs at 20-year intervals (2000-2100) given relative sea level rises (RSLR) for each state. Table 8 indicates the RSLR for the Atlantic coast of Florida for each scenario and year studied. These RSLR estimates were multiplied by the amount of area contained in the beach profile, backbarrier, and oceanside locations to provide estimates of sand volumes needed for nourishment (Table 9). Recall that beach profiles are nourished immediately, backbarrier elevations are raised after 1 foot of SLR, and oceanside elevations are raised with 4 feet of rise. An example calculation for the state of Florida (Atlantic) is given as follows (using RSLR Scenario IV and the year 2100):

- Projected RSLR for Scenario IV by 2100 is 6.94 feet (Table 8)

- Multiply projected RSLR by the appropriate volume of sand needed to nourish 1 foot of each barrier area -

  -6.94 feet (RSLR) x Table 5 value for Beach/Nearshore Profile (76.981) = 534.248- million yd^3
  -[6.94 feet (RSLR) - 1 foot] x Table 5 value for backbarrier elevations (22.358) = 132.806 million yd^3
  -[6.94 feet (RSLR) - 3 feet] x Table 5 value for oceanside elevations (85.219) = 335.762 million yd^3

- Add the sand volumes given above (534.248 + 132.806 + 335.762 = 1,002.818 million yd3) to derive the total sand volumes needed to protect the barriers from encroaching seas (Table 9).

Table 6. ICONS Survey Results - Potential Offshore Sources of Sediment for Beach Nourishment

	Study Area	Amount Available (million yd^3)	Type	Suitability
I.	Miami to Palm Beach (Duane and Meisburger, 1969)			
	a) south of Boca Raton	201; located in offshore troughs	Mostly calcerous	Possibly suitable for short-term projects, but are easily degraded in turbulent littoral zone and may become to fine for long-term projects.
	b) north of Boca Raton	380; thickly blanketed over portions of the shelf	50-50% quartz and calcerous sediments	Too fine for successful nourishment of area's beaches; not included in nourishment assessment.
II.	Cape Canaveral (Field and Duane, 1974)	approx. 130; large south-trending, cape associated shoals	medium to coarse, well sorted quartz-mullusk sand	Well suited for nourishment. Surveyed areas show the following sand quantities: - Ohio-Hetzel Shoal (76.1 x 10^6 yd^3) - Chester Shoal (8.8 x 10^6 yd^3) - Southeast Shoal (15.2 x 10^6 yd^3) Volumes of suitable sand in unsurveyed areas of Chester and Southeast Shoal are likely an order of magnitude larger.
III.	Cape Canaveral to Georgia (Meisburger and Field, 1975)	minimum of 295; ten potential borrow sites (possibly 21 more sites) are identified, with each having a sand reserve from 5-178; total volumes are unknown - more study needed; located in linear shoals.	Fine to very quartz sand in shoreface; seaward of shoreface, sand is fine to medium, well sorted, predominantly quartz sand	Suitable sand was identified in the following locations: - Jacksonville (5.01 x 10^6 yd^3) - Mickler Landing (178.0 x 10^6 yd^3) - St. Augustine (7.4 x 10^6 yd^3) - Marineland (39.0 x 10^6 yd^3) - Ormond Beach (66.0 x 10^6 yd^3) Further study may show significantly more sand available.

After determining sand volumes needed for each SLR scenario and associated year, nourishment costs are calculated. Initial dredging costs were used to determine final costs until all sediment supplies within one mile of the shore were exhausted. In the case of Florida, $4.00 per yd3 was used to project costs for the first 66 million yd3 of sediment (see Table 7). After exhausting these nearby sand reserves, the cost escalation function was employed for sand each additional mile offshore. For example, FloriMs Scenario IV projects that by the year 2100, 1,002.818 million yd3 of sand will be needed for beach nourishment. All of Florida's recorded offshore sand reserves would be exhausted by such a request; however, costs were calculated assuming the availability of sand. A sample cost calculation is given as follows:

Scenario IV, year 2100

1,002.818 yd^3
\- 66.000 yd^3 @ \$4.00/yd^3 (sand w/in 1 mile; see Table 7)
936.818 yd^3
\- 87.000 yd^3 @ \$5.00/yd^3 (sand 1-2 miles; see Table 7)
849.818 yd^3
\- 122.300 yd^3 @ \$6.00/yd^3 (sand 2-3 miles; see Table 7)
727.518 yd^3
\- 48.000 yd^3 @ \$7.00/yd^3 (sand 3-4 miles; see Table 7)
679.518 yd^3 @ \$10.00/yd^3 (sand >5 miles; see Table 7)

Table 7. Sand Reserves and Approximate Associated Dredging Costs for the State of Florida (Atlantic Coast)

Distance Offshore (miles)	Sand Amount (million yd^3)	Cost per yd^3 (\$)	Total Cost (million \$)
<1 mile	66	4.00	264
1-2	87	5.00	435
2-3	122.3	6.00	766.8
3-4	48	7.00	336
4-5	-	8.00	-
5-6	199.2	10.00*	1992
6-7	-	10.00*	-
7-8	97.6	10.00*	976
8-9	-	10.00*	-
9-10	15.2	10.00*	152
10-11	76.1	10.00*	761
11-12	39.0	10.00*	390
12-13	-	10.00*	-
13-14	175	10.00*	1750

* At distances >5 miles offshore, it is highly unlikely that a floating pipeline dredge would be used. Rather, sand would probably be moved in two stages; dredging into a ship for transport to the mainland, followed by truck hauling to location. Costs for this process are not clearly known, but it is estimated it would add at least \$2.00 per yard^3 to the highest floating pipeline cost.

Table 8. Amount of Sea Level Rise for Various Year/Scenario Combinations (in feet)*

Scenario

Year	I	II	III	IV	V	VI
2000	.12	.14	.17	.19	.22	.24
2020	.35	.50	.64	.79	.93	1.08
2040	.66	1.03	1.39	1.76	2.13	2.50
2060	1.04	1.73	2.42	3.11	3.80	4.49
2080	1.49	2.60	3.72	4.84	5.95	7.06
2100	2.01	3.65	5.30	6.94	8.57	10.22

Table 9. Sand Volumes Required to Raise the Beach/Nearshore Profile and Barrier Elevations for the Florida Atlantic Coast (million yd^3)

Scenarios

Year	I	II	III	IV	V	VI	LST*
2000	9.238	10.777	13.087	14.626	16.936	18.475	2.800
2020	26.943	38.490	49.268	60.815	71.592	83.139	6.800
2040	50.807	79.290	107.004	135.487	189.234	225.989	10.800
2060	80.060	133.177	218.042	286.586	355.130	550.650	14.800
2080	114.702	235.921	347.183	615.246	820.105	1024.964	18.800
2100	1177.314	340.230	700.142	1002.818	1303.647	1608.168	22.800

*LST is longshore sediment transport. Average annual rates vary along the Florida Atlantic Coast so a representative figure of 20,000 yd^3 is used for illustrative purposes.

Given the above, total sand costs for Scenario IV, year 2100, for the Florida Atlantic coast are $8,563.980 million dollars (Table 10).

Tables 9 and 10 also provide sand volume and cost estimates based on average annual longshore transport rates (200,000 yd3/year) for the Florida Atlantic coast. It is obvious from these figures that sand removed from the system by longshore transport is insignificant compared to that required to compensate for accelerated sea level rise.

Sand costs for the Atlantic coast of Florida were derived assuming equal access to offshore sand reserves for all coastal locations, as it was beyond the scope of this research to evaluate sand supplies and costs on a site- specific basis. In reality, suitable borrow material is scattered along the coastline; some areas have sand directly offshore, while other sites are far removed from available supplies. Therefore, the equal access assumption made in this report may underestimate true sand costs, as sand hauling to distant locations is not adequately examined.

Table 10. Cost of Raising the Beach/Nearshore Profile and Barrier Elevations for the Florida (Atlantic) Coast ($ millions)*

Year	I	II	III	IV	V	VI	LST*
2000	36.952	43.108	52.348	58.504	67.744	73.900	11.200
2020	107.772	153.960	197.072	243.260	291.960	349.695	27.200
2040	203.228	330.450	469.020	611.435	916.404	1136.695	43.200
2060	334.300	599.885	1089.252	1511.802	2087.100	4042.300	59.200
2080	507.510	1196.526	2007.630	4688.260	6736.850	8785.440	75.200
2100	844.884	1938.100	5537.220	8563.980	11572.2730	14617.480	91.200

* These cost figures assume that the borrow sand is fully compatible in size with the native sand and will remain on the active beach profile; this is a conservative assumption.

** LST is longshore sediment transport (see footnote for Table 7).

CHAPTER 3

NATIONWIDE RESULTS

The U.S. coastline can be divided on the basis of physiographic regions for discussion purposes. The New England states typically have small sandy beaches, often consisting of sand spits. Massachusetts has the largest number of such recreational beaches (Table 11), but those along the Rhode Island coast are perhaps the most urbanized and have been subject to severe damage during historical hurricanes.

The Mid-Atlantic coast, which extends from New York to Virginia, is in general the most urbanized shore in the country except for parts of Florida and southern California. The recreational beaches in New York and northern New Jersey serve as the playgrounds for some 15 million people in the greater New York metropolitan area.. Presently, pollution from human waste is adversely impairing their recreational value, but beach erosion has been a chronic problem, and many nourishment projects have already been completed and others are planned. Farther south, there are more open stretches of coast (parklands, reserves, etc.) so that the approach of holding the line by beach fill would be city-specific (e.g., Virginia Beach, VA, Ocean City, MD) rather than island-wide (e.g., Long Beach Island, NJ).

The U.S. southeastern coast (North Carolina to Florida) is the least urbanized along the Atlantic coast, but this area has the largest growth potential because of the greatest availability of beachfront property. The Outer Banks of North Carolina constitute a long chain of barrier islands with development spread out over long distances (Table 11). While an increasing number of multi-story condominiums are being built, the traditional type building is the wooden, single-family house that can be readily moved. Therefore, the retreat alternative becomes more attractive than beach stabilization in many areas. * This alternative is plausible to a less extent in South Carolina and Georgia, but many islands are already too urbanized for this approach (e.g., Hilton Head, S.C.). Also, the barrier islands in the Georgia bight (southern South Carolina to northern Florida) are generally higher in elevation, much wider, and more stable than the microtidal barriers found elsewhere along the Atlantic coast (Leatherman, 1988).

Florida should be considered separately from the others as its immense coastline is the single most important feature of the state. Almost 300 miles are considered for beach nourishment along the Atlantic coast, and about 250 miles on the Gulf will require sand fill with accelerated sea level rise. It could be argued that Florida has the most important beaches in the United States because it serves as a national and even international resort area. Recreational beaches are the number one source of revenue, and state officials are considering spending tens of millions of dollars each year for beach nourishment. The Miami Beach project, completed in 1980 at a cost of $65 million for 10 miles of beach, perhaps represents the scale and magnitude of future such projects along this rapidly urbanizing coast, which is becoming dominated by the high-density, high-rise type of development.

The Gulf Coast is the lowest-lying area in the U.S. and consequently is the most sensitive to small changes in sea level. One of the earliest extensive beach nourishment projects undertaken in the U.S. was in Harrison County, Alabama, in the 1950s. The beaches have greatly narrowed since this time, and renourishment is now required. Louisiana has the most complex coastline in the region and also has the distinction of having the most rapid rate of beach erosion in the nation. While a number of islands are included on the state list for nourishment (Table 11), much of this proposed work will probably never be undertaken since it is uneconomical under today's conditions. There are only two recreational beaches in the State of Louisiana-- Grand Isle and Holly Beach. While Grand Isle was recently nourished, it is unlikely that the economics (relative high cost of sand fill vs. value of property to be protected) will make future projects feasible with accelerated sea level rise. Texas has the most extensive sandy coastline in the Gulf, but much of the area is little inhabited. Clearly the City of Galveston will be maintained, but the nearly century-old seawall has been most effective in this regard largely at the expense of the beach. Elsewhere, beach nourishment is probably not the most viable alternative as much land on the barrier islands is generally available for relocation.

Table 11. Sites Investigated for Stand Fill with Sea-Level Rise

State/Site		Miles of Shoreline	Sand Volume Needed (million yd^3)		
			Profile	Bayside	Oceanside
Maine - Higgins Beach		0.62	0.303	–	–
State Total		30.87		–	3.139
New Hampshire beaches (Total)		8.91	5.229	–	1.220
Massachusetts -	Humarock Beach	2.75	0.967	–	–
	Siasconset	1.70	0.333	–	–
State Total		100	27.390		137.984
Rhode Island beaches (Total)		27.42	6.970	–	3.308
Connecticut beaches (Total)		63.51	43.467	–	7.663
New York -	Southhampton Beach	7.05	2.756	–	–
State Total		120	46.910	3.168	30.272
New Jersey - Long Beach Island		18.03	5.289	3.778	2.936
State Total		125	26.668	26.180	20.362
Delaware -	Rehoboth Beach	1.55	0.243	–	–
	Dewey Beach	1.59	0.249	0.132	0.189
	Bethany/South Bethany	2.95	0.462	–	1.095
	Fenwick Island	1.12	0.175	0.262	0.219
	North Bethany	2.73	0.426	–	–
State Total		9.94	1.555	0.394	1.503
Maryland -	Ocean City (Total)	8.94	2.447	–	4.124
Virginia -	Wallops Island	5.89	5.759	–	0.691
	Virginia Beach	5.89	1.728	–	3.995
	Sand Ridge	5.21	2.241	–	1.268
State Total		16.99	9.728		5.954
North Carolina -	Currituck Banks	2.84	1.667	–	1.944
	Currituck Spit	29.47	17.288	–	14.403
	Nags Head Area	19.82	11.627	–	7.935
	Buxton	0.95	0.556	–	0.611
	Bogue Banks	22.67	6.207	0.519	0.241
	Topsail Island/Beach	21.14	4.547	1.176	1.326
	Lee Island Complex	3.60	0.774	0.141	0.281
	Figure Eight Island	3.64	0.774	0.096	0.356
	Wrightsville Beach	4.36	0.852	–	0.852
	Wilmington Beach area	6.44	1.133	–	1.007
	Long Bay area	25.57	4.500	–	–
	Bald Beach/Island	2.46	0.433	–	–
State Total		142.96	50.358	1.932	28.956

State/Site		Miles of Shoreline	Sand Volume Needed (million yd^3)		
			Profile	Bayside	Oceanside
South Carolina -	The Strand	20.45	3.000	–	7.600
	Myrtle Beach	9.19	2.007	–	0.581
	Magnolia Beach	5.19	0.879	–	1.411
	Pawley's Island	3.30	0.472	–	0.129
	Debidue Beach	3.66	0.979	–	1.098
	Capers Island	3.03	2.370	–	1.538
	Dewees Island	2.27	2.756	–	0.524
	Isle of Palms	1.02	6.380	–	2.839
	Sullivan's Island	3.69	3.900	–	1.499
	Folly Beach	5.25	7.848	–	1.106
	Kiawah Island	7.42	9.364	–	5.448
	Seabrook Island	2.14	2.427	–	4.134
	Edisto Beach	5.51	4.850	–	1.636
	Hunting Island	5.70	13.601	–	3.096
	Fripps Island	2.71	4.634	–	1.766
	Hilton Head	12.75	39.134	–	9.593
State Total		93.28	104.601	–	43.998
Georgia -	Tybee Island	2.65	2.738	–	1.400
	Sea Island	3.46	3.579	–	1.084
	St. Simons Island	2.54	2.620	–	0.759
	Jekyll Island	7.44	7.685	–	6.129
State Total		16.09	16.622	–	9.372
Florida -	Amelia Island	10.83	3.178	–	1.271
	Seminole/Manhattan Beaches	2.78	0.762	–	0.436
	Jacksonville area	5.83	1.597	–	2.384
	Ponte Vedra-Vilano Beach	23.90	6.076	–	4.674
	Anastasia Island	10.13	3.170	–	2.378
	Summer Haven - Beverly Beach	14.96	3.511	–	3.511
	Flagler Beach	5.26	1.440	–	1.133
	Ormond Beach area	12.42	3.887	–	6.439
	Daytona Beach	8.14	2.548	–	3.602
	Wilbur-by-the-Sea	5.25	1.640	–	1.128
	New Symrna Beach	4.15	1.379	–	1.839
	South of Symrna Beach	17.33	5.761	–	3.816
	Cocoa Beach	8.86	3.120	–	6.413
	Eau Gallie Beach	11.10	3.038	3.630	9.767
	South of Melbourne Beach	28.12	7.700	4.467	8.867
	Vero Beach/Riomar	3.96	1.084	1.037	1.998
	South of Vero Beach	15.26	4.179	1.490	1.987
	Hutchinson Island	13.31	3.645	0.956	1.687
	Jupiter Island	10.10	2.764	0.387	2.307
	South of Jupiter Island	11.78	1.843	0.567	3.869
	Palm Beach - Lake Worth Inlet	15.50	2.427	0.660	3.306
	Boynton & Delray Beaches	14.43	1.693	0.946	3.217
	Deerfield & Hillsboro Beaches	5.36	0.838	–	1.220
	Pompano Beach	3.84	0.752	–	1.353