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THE COST Of DEFENDING DEVELOPED SHORELINES ALONG SHELTERED WATERS OF THE UNITED STATES FROM A TWO METER RISE IN MEAN SEA LEVEL

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CHAPTER 1

INTRODUCTION[1]

Mean sea level is rising in those regions of the world not previously or recently glaciated, not near present plate boundaries, and not currently subjected to man-caused subsidence. The rise in sea level is eustatic in nature and worldwide records suggest an overall rise of about 12 cm over the last 100 years (Fairbridge & Krebs, 1962; Gornitz et al., 1982).

Measurements of sea level rise along the coastal, margins of the United States show substantial local variability, but reasonable averages over the last century suggest a 30-cm rise along the East Coast of the U.S., an 11-cm rise along the West Coast, and rises ranging from 20 to 100 cm per century along the Gulf of Mexico.

The above estimates of sea level rise are averages based on analysis of available records gathered at specific locations such as New York, New York, and Atlantic City, New Jersey, over recent decades as well as readings made at tide gaging stations currently in operation. The estimates filter out the shorter term (2-7 years) meteorological fluctuations.

Geological data support the observed indications of recent sea level, rise. -and suggest a fluctuating but persistent rise over the last 1500 years with even more rapid rates of rise extending back over the last 6000 years (Fairbridge, 1961).

Beyond past and present rates of rise, there is a growing belief, based on theoretical evaluations of the potential causes of sea level rise, that a sustained or, more likely, an accelerated rate of sea level rise can be expected in the future.. The cause of the projected rise is global warming due to the "greenhouse" effect (assisted by ozone depletion), which leads to melting of Alpine glaciers, ice sheets, and ice caps on a global scale, accompanied by thermal expansion of the oceans.

Projections of future sea levels vary based on the assumptions used. Estimates of the global rise by the year 2100 generally are between 50 and 200 cm, although Hoffman (1985) concludes that a 35O-cm rise is possible (Titus, 1986; Revelle, 1983; Meier et al., 1985). Because of the quantitative uncertainties and probabilities involved in such a prediction, the Committee of Engineering Implications of Changes in Relative Mean Sea Level (National Research Council, 1987) suggests that three plausible variations in eustatic sea level rise be assumed for design purposes, all of which project an increasing rate of rise relative to the present and produce rises of 50, 100, and 1SO cm by the year 2100.

Even recognizing that tide-gage data are subject to influences that tend to "degrade the data!' and that estimates of the future eustatic sea level are based on estimates of factors such as glacial thickness that are not well known, the projections of accelerated sea level rise cannot be disregarded.'In the United States there is an enormous and growing investment of population, facilities, and real estate in the zone along the Atlantic, Pacific, and Gulf of Mexico coastal margins. Moreover, the postulated climatic and oceanic models on which increasing rates of eustatic sea level rise are based are, sufficiently well developed to assume that the physical and financial risks to coastal communities, facilities, and environments can be realistically estimated, and that many areas are vulnerable to undesirable changes caused by-a rising sea level.

The effects of sea level rise on the coastal zone would include effects on physical processes such as: changes in weather patterns; higher storm surges; increased storm damage;'shoreline erosion; increased flood frequencies due to

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backwater effects; changes in river courses and flow rates; increased sedimentation; shoaling and scouring in inlets; increased need to dredge waterways; loss of agricultural land; increased landslides; changing offshore current speeds and directions; land subsidence; higher waves; and more frequent barrier island washover. There could be major influences on systems, facilities, and infrastructure such as: buried utilities, subway systems, municipal storm and sanitary sewers, transportation systems (roadways, railways, etc.), water treatment plants, landfills, drainage patterns, water supply systems, ground water supplies, bridges, and coastal navigation and harbor improvements. Construction-related activities impacted might include: dredging, tunnelling, drainage, elevated water tables and dewatering, foundation elevations, tidal energy projects, increased construction costs, and beach nourishment sand sources. Environmental impacts include: changes in wetland area boundaries, saltwater intrusion, increased energy consumption for pumping, ecological changes, evaporation ponds, coastal vegetation, inundation, and loss of habitat. Socioeconomic effects include: the public's response to rising sea level, flood insurance costs, impact on tax base, sources of compensation for losses, legislation, government versus personal responsibility for costs, the decision making processes, emergency planning and responses, identification of future problems, water rights, and the financial resources needed to respond to the rising sea. Finally, it will be necessary to re-map and survey coastal areas and to obtain new bathymetry for the near offshore.

Responses and response strategies developed when confronted with sea level rise can include some or all of the following: constructing dikes, bulkheads, sea walls, revetments, groins, beach nourishment, construction of offshore breakwaters, storm surge barriers, dikes and polders. All of these represent an effort to resist the landward advance of the sea. In addition, there is always the alternative of abandoning some areas and structures or relocating structures on higher ground.

In the present study, the effects of sea level rise at six index sites in the United States were evaluated. The index sites were: the metropolitan New York City area; the Long Beach Island, New Jersey, area; the Corpus Christi, Texas, area; the Dividing Creek, New Jersey, area (a sparsely developed area); the south San Francisco Bay, California, area; and the Miami/Miami Beach, Florida, area. Using shoreline length, ground elevation distributions, and degree of development data, the six sites were evaluated in terms of the type of response judged to be most appropriate. The cost of responding to sea level rise was determined based on certain consistent assumptions. The response strategies can be categorized as follows:

1. Abandon those low-lying areas with little development and having a limited economic base.
2. Raise dwellings and other structures where appropriate.
3. Move isolated, structurally sound dwellings and other structures to new locations at higher. elevation.
4. Surround low-lying economically developed areas with a dike; install a seawater seepage control system, an interior drainage system, and storage and pumping facilities to maintain drainage.

Costs for each of the above alternatives were developed by establishing unit costs for each element of a response strategy and then applying those costs to an assumption as to how each individual index site might respond to sea level rise. For example, in sparsely developed areas, isolated structures identified on United States Geological Survey (USGS) quadrangle maps were counted, and the cost of moving some fraction of them was estimated. (Because much of the data on building locations on the USGS quads is outdated, the number of buildings obtained from the quads was interpreted as only an indicator of the number of buildings present.) The cost to construct a dike around isolated communities and to provide an interior drainage system was estimated for areas with a reasonable level of economic development. The cost of raising and/or replacing roads that would connect such isolated areas with high land was also estimated. The cost of raising existing bulkheads and the cost of providing new bulkheads was estimated for those areas where such a response was bulkheads have a relatively short lifetime and need to be replaced periodically. Thus an accelerated sea level rise will result in a shorter lifetime and more frequent replacement. Such costs can be significantly reduced if sea level rise is anticipated in the initial design.)

The cost of responding to sea level rise for the total U.S. shoreline was determined by extrapolating costs for the six index sites to the rest of the U.S. coast. Costs at the six index sites were correlated with topographic and economic development factors, and then digitized topographic data obtained from USGS quad sheets were used to extrapolate costs to 78 additional sites around the U.S. shoreline. The extrapolation techniques make use of information on shoreline lengths, the distribution of land elevations, and the level of development.

CHAPTER 2

SEA LEVEL RISE SCENARIO

The sea level rise scenario assumed for the present study is summarized by Titus (this volume). The assumption is that by the year 2100, sea level will be 2 meters (6.5 feet) above the level it would have attained had it continued to rise at its local historical rate. Thus, the historical rate is extrapolated to the year 2100, and an additional 2 meters are added. The historical rate of rise is assumed to continue linearly, while the uperposed 2-meter rise is assumed to increase parabolically. The general equation is given by,

$$RSL(t) = L(t) + 0.0012\ t + 0.0001434\ t^2 \qquad (1)$$

in which RSL(t) is the relative sea level, L(t) is a local sea level factor that includes the deviation of the local historical rate from the global rate (a local rate of rise based on historical tide gage records), and it is the number of years beyond the 1986 base year. For example, the rate of sea level rise in the Long Beach Island, New Jersey, area has been about 40 cm/100 years or 0.004 m/yr (Lyles et al., 1987); thus, the function $L(t) + 0.0012\ t = 0.004\ t$ and equation (1) for Long Beach Island becomes,

$$RSL(t) = 0.004\ t + 0.0001434\ t^2 \qquad (2)$$

Some of the analyses in the present study are not sensitive enough for the precise rate of sea level rise to become a factor in determining costs or for determining when certain actions in response to sea level rise will be triggered; however, for some detailed analyses the rates do enter into the cost calculations. For example, several alternatives were evaluated for Long Beach Island where the timing of certain actions depends on the stage of local sea level. On the other hand, several of the analyses simply assume that actions will be taken in response to sea level rise but the time when those actions are taken is not specified.

CHAPTER 3

INDEX SITE CONCEPT

To determine the cost of constructing dikes and other facilities to protect areas from inundation and from storm surge and wave damage, six index sites were selected for detailed study and used to develop correlations between data from those sites and data from other coastal sites around the continental U.S. The six sites were chosen to be a representative sample of the various types of coastal topography and development present in the U.S. with emphasis on developed areas where it is certain that some action to counter sea level rise will have to be taken. The sites were selected-from among those being analyzed by Park et al. (this volume). The sites included: a) sections of New York City and its environs; b) Long Beach Island, New Jersey; c) Dividing Creek, New Jersey; d) Miami and Miami Beach, Florida; e) Corpus Christi, Texas; and f) portions of California's south San Francisco Bay area. The boundaries of the specific areas studied were selected to correspond with areas covered by USGS quad sheets. The sites, the USGS quads analyzed, and their dates of latest revision are given in Table 1. In addition, a portion of one of these index sites, Long Beach Island, New Jersey, was singled out for a more in-depth analysis.

Table 1. Index Sites and Corresponding USGS Quad Sheets

Nominal Index Site	USGS Quad Sheets	Original Date	Photo Revision
New York, NY	Weehawken, NJ	1967	1981
	Central Park, NY	1966	1979
	Elizabth, NJ	1967	1981
	Jersey City, NJ	1967	1981
	Brooklyn, NY	1967	1979
	Arthur Kill, NJ	1966	1981
	The Narrows, NY	1966	1981
* Long Beach Island, NJ	Barnegat Light, NJ	1953	1972
	Long Beach NE, NJ	1951	1972-77
	Ship Bottom, NJ	1952	1972
	Tuckerton, NJ	1952	1972
	Beach Haven, NJ	1951	1972-77
Dividing Creek, NJ	Dividing Creek, NJ	1956	1972
	Cedarville, NJ	1956	1972-82
	Port Norris, NJ	1956	1972
	Fortescue, NJ	1956	1972
Miami, FL	North Miami, FL	1962	1969-72
	Miami, FL	1962	1969
Corpus Christi, TX	Oso Creek NE, TX	1968	1975
	Oso Creek NW, TX	1968	1975
	Port Ingleside, TX	1968	1975
	Crane Islands NW, TX	1968	1975
	Portland, TX	1968	–
	Corpus Christi, TX	1968	1975
San Francisco, CA	Palo Alto, CA	1961	1968-73
	Mountain View, CA	1961	1981
	Redwood Point, CA	1959	1980
	Newark, CA	1959	1980

* Index site selected for more detailed analysis of alternatives.

Three scenarios of a coastal community's response to sea level rise were evaluated for Long Beach Island. They included: a) moving the island landward by reclaiming land on the bay side of the barrier while allowing the ocean side to recede in response to erosion caused by higher sea levels; b) artificially raising the island's elevation in conjunction with moving the island landward; and c) constructing dikes around the island and installing an interior drainage system to handle both storm drainage and seawater seepage beneath the dike system. Under the first two scenarios, houses would be moved to newly reclaimed land or raised in response to raising the island. In the third scenario, the island would have a protective dike built around it and the houses would be left in place.

TOPOGRAPHIC AND SHORELINE LENGTH ANALYSES

Topography at the six index sites was analyzed using the USGS quad sheets to obtain basic ground elevation and shoreline length data. Specifically, the shoreline length was measured using a rolling map-measure while areas enclosed within various elevation contours were planimetered. As a result, the total shoreline length was determined for each quad sheet along with that portion of the shoreline that is presently protected by bulkheads. The area between various contours on the quad sheets was planimetered and the topographic characteristics determined by plotting the distribution of ground elevations. For example, the distribution of elevations for the New York City metropolitan area is given in Figure 1. In general, each site has a characteristic topographic distribution that determines its vulnerability to inundation by a rise in sea level.

New York Metropolitan Area, New York and New Jersey

The New York City metropolitan area is an intensively developed urban area characterized by heavily populated residential iareas as well as large-scale commercial and industrial development. It is perhaps the most intensely developed metropolitan area of the United States. It also has a long, heavily developed shoreline, most of which is already protected by structures such as bulkheads or revetments. Major metropolitan subdivisions include: Manhattan, Brooklyn, Queens, The Bronx, and Staten Island, New York; and Elizabeth, Jersey City, Union City, and Linden, New Jersey. In general, 26% of the land on the quads lies below the + 5 foot contour while 52% lies below the + 10 foot National Geodetic Vertical Datum (NGVD) elevation. (NGVD is sometimes referred to as the mean sea level datum of 1929.) On the other hand, there are few undisturbed wetlands on the quads (except for the wetlands along the west bank of the Hackensack River), so that erosion will be more of a concern than simple inundation. The distribution of land elevations planimetered from the quads is summarized in Table 2 and shown in Figure. 1. (The contour interval of the seven USGS quads that cover the study area is 10 feet so that the distribution of land elevations below the 10-foot contour cannot be determined from the quads. The digitized topographic data allowed a better resolution of elevations than the present analysis.) The USGS quads that cover the present study area include: Weehawken, Arthur Kill, Brooklyn, The Narrows, Jersey City, Elizabeth, and Central Park. Major bodies of water include the Hudson, Hackensack, East, Arthur Kill, and Kill van Kull Rivers; Newark Bay, the Verazzano Narrows, Upper Bay, Lower Bay, and the Raritan Bay. The shoreline lengths are given in Table 1. Table 3a is a partial summary of shoreline lengths by region. Table 3a does not include the total shoreline shown on all seven quads. Of the 220 miles of shoreline included in the study area, 155 miles (70%) are bulkheaded.

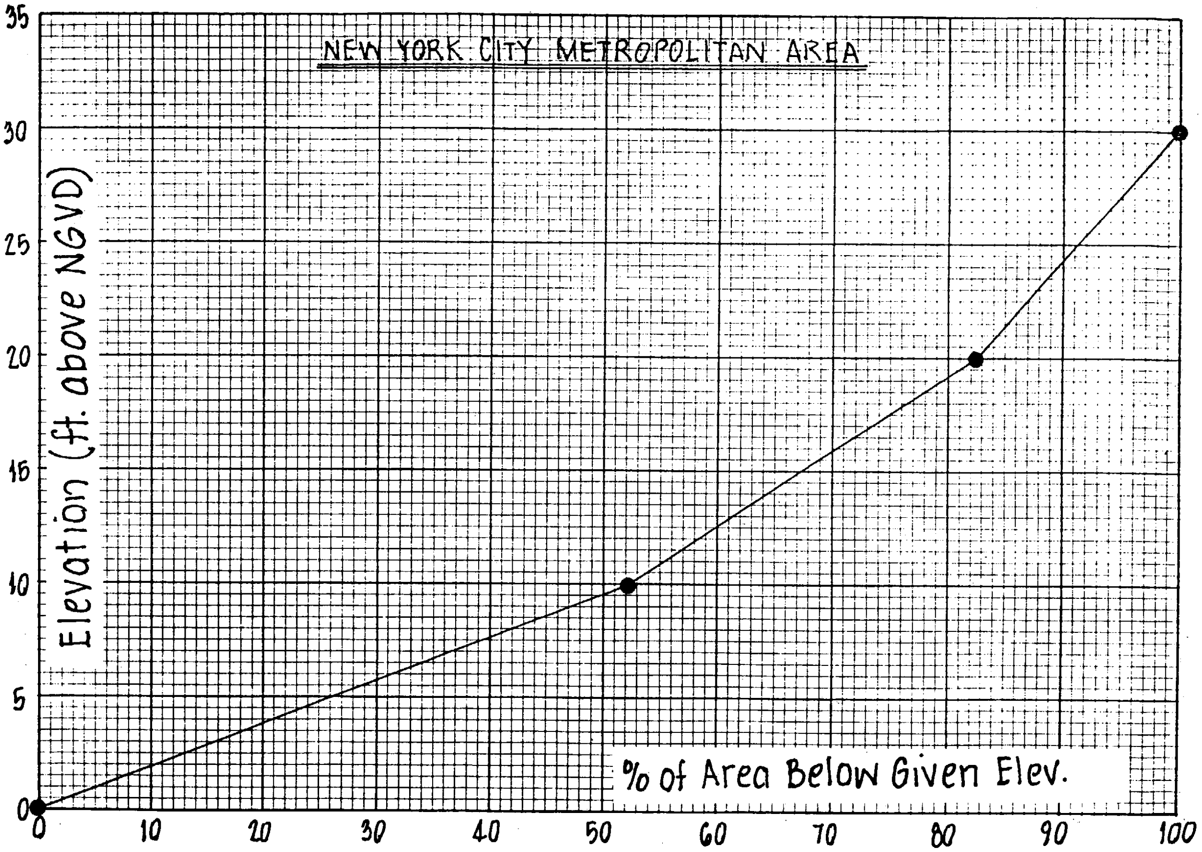


Figure 1 Distribution of Ground Elevations - New York City Metropolitan Area.

Table 2. Summary of Topographic Conditions at New York, New York

USGS Quad	Area (sq mi) Between Given Elevations (ft)			Total Area	Wetlands Area
	0<Z<10 *	10<Z<20	20<Z<30		
Weehawken	30.60	4.41	1.42	36.43	2.30
Arthur Kill	15.35	9.17	5.04	29.56	
Brooklyn	2.72	8.60	6.33	17.65	
The Narrows	2.94	2.15	1.65	6.74	
Jersey City	12.54	6.71	2.76	22.01	
Elizabeth	11.60	7.92	4.21	23.72	
Central Park	2.39	5.60	4.68	12.67	
Overall Totals					
Total	78.14	44.55	26.09	148.77	2.30
% of Total	52.5	30.0	17.5		
CUM %	52.5	82.5	100.0		

* Datum is NGVD.

Long Beach Island Area, New Jersey

Long Beach Island, New Jersey, is a sandy barrier island near the center of New Jersey's Atlantic Ocean shoreline. The island is located approximately 4S miles south of Sandy Hook and 5S miles north of Cape May and is bounded by Barnegat Inlet on the north and Beach Haven and Little Egg Harbor Inlets on the south. The island is about 23 miles long. The mainland behind the barrier island is bordered by extensive wetlands. There are also numerous wetlands islands in the bays behind the barrier island. The five USGS quads that cover the study area are: Barnegat Light, Long Beach NE, Ship Bottom, Tuckertoh, and Beach Haven. The distribution of elevations on the rive USGS quads is given in Table 4 and in Figure 2. Generally, the barrier island is at about the + 3.5-foot NGVD elevation with only a few scattered areas of high dunes where the elevation exceeds + 10 feet. (The demarcation between wetlands and fast land on the quads was assumed to be the + 3.5-foot NGVD contour.) Large areas of the mainland are below the +3.5-foot NGVD elevation, however. The overall topographic summary indicates that almost-50% of the land area is below + 3.5 feet NGVD; about 80% is below + 10 feet, and 93% is below 20 feet.

Shoreline lengths are summarized in Table 5. Long Beach Island's shoreline is about 55 miles long. About 23 miles front the Atlantic Ocean while the remainder is bay shoreline. The shoreline defined by the interface between the mainland and wetlands is about 33 miles long, while the outer wetlands shoreline is about 55 miles long.

Long Beach Island was selected for detailed analysis to investigate the cost of several alternative responses to sea level rise. This analysis is presented in a later section. A more detailed description of Long Beach Island is also presented there.

Dividing Creek, New Jersey

The Dividing Creek, New Jersey, area is a spaisely developed area bordering the Delaware. Bay near where the Maurice River discharges into the bay. The area considered in the present study is covered by four USGS Quads and is mostly composed of wetlands haying an elevation below + 5 feet NGVD; much of it is state-owned hunting lands. The USGS quads covering the area are: Dividing Creek, Cedarville, Port Norris, and Fortescue. The region is criss-crossed by small streams and drainage channels. There are several small communities in the area. They include the bayside towns of Fortescue and Gandys Beach, the town of Dividing Creek on the fast land behind the wetlands, and the towns of Laurel Lake and Cedarville on the Maurice River and Cedar Creek, respectively. Laurel Lake and Cedarville are mostly above + 10 feet NGVD, while significant portions of the remaining towns are below + 10 feet elevation. The distribution of land' elevations obtained by planimetering the USGS quads is summarized in Table 6 and shown in Figure 3. - About half -of the land area is below the + 5- foot contour (defined here as wetlands area), while fully 92% of the land area is below the 20-foot contour. The shoreline lengths on the four quads are summarized in Table 7. The shoreline length is about 97 miles and is defined here as the interface between the wetlands and Delaware Bay.' Dividing Creek is believed to. be typical of much of the undeveloped U.S. coastlines such as areas on the mainland behind barrier islands. For example, the mainland areas in North Carolina in sounds and bays behind the Outer Banks might be characterized by the level of development and wetlands of the Dividing Creek area.

Table 3. Summary of Shoreline Lengths - New York, New York

USGS Quad	Shoreline Length			Wetlands Shoreline (mi)
	Bulk. (mi)	Unbulk. (mi)	Total (mi)	
Manhattan Island				
Weehawken	0.89	0.15	1.04	
Central Park	13.79	5.59	19.39	
Jersey City	8.13	0.15	4.47	
Brooklyn	4.18	0	4.18	
Subtotal	23.19	5.89	29.08	
Staten Island				
Jersey City	8.13	0.52	8.65	
Elizabeth	4.18	1.57	5.74	2.09 *
Arthur Kill	4.03	17.89	21.92	
The Narrows	1.49	6.26	7.75	
Subtotal	17.82	26.25	44.07	2.09 *
Elizabeth				
Elizabeth	6.93	7.46	14.39	
Subtotal	6.93	7.46	14.39	
Jersey City - Union City				
Weehawken	20.43	0	20.43	27.89 *
Jersey City	2.23	1.49	3.72	
Elizabeth	10.89	1.49	12.38	
Subtotal	33.55	2.98	36.53	27.89 *

* Wetlands shoreline length not included in total shoreline length.

		Bronx - Queens - Brooklyn		
Weehawken	16.40	11.93	28.33	
Brooklyn	10.73	0	10.73	
Jersey City	43.11	9.09	52.20	
The Narrows	4.10	1.27	5.37	
Subtotal	74.34	22.29	96.63	
Total	155.83	64.87	220.70	29.98 *

Table 3A. Summary of Shoreline Lengths By Region

USGS Quad	Shoreline Length			Wetlands Shoreline (mi)
	Bulk. (mi)	Unbulk. (mi)	Total (mi)	
Jersey City	45.56	17.15	62.71	27.89 *
Brooklyn	36.98	1.71	38.70	
Bronx	6.70	4.29	11.63	
Queens	4.76	2.98	7.75	
Elizabeth	22.89	3.88	26.77	
Governors Is.	2.16	0	2.16	
Total	119.05	30.01	149.06	27.89 *

* Wetlands shoreline length not included in total shoreline length.

Table 4. Summary of Topographic Conditions on Long Beach Island and Adjacent Mainland, New Jersey

USGS Quad	Area (sq mi) Between Given Elevations (ft)					Total Area	Wetlands Area
	0<Z<3.5	3.5<Z<10	10<Z<20	20<Z<30	30<Z<40		
Long Beach Island							
Barnegat Light	0.014	0.589	0.037	0.021	0	0.661	0.234
Long Beach NE	0.023	0.476	0.101	0.015	0	0.615	0.021
Ship Bottom	0.075	2.580	0.188	0.023	0	2.866	1.212*
Tuckerton	0.096	0.963	0.078	0	0	1.137	2.562*
Beach Haven	0.216	1.645	0.273	0.005	0	2.138	0.216
Total	0.423	6.254	0.676	0.063	0	7.417	4.244*
% of Total	5.7	84.4	9.1	0.8		100.0	
Cum %	5.7	90.1	99.2	100.0			
Island Beach State Park							
Barnegat Light	1.452	0.373	0.538	0.116	0.020	2.500	1.452
Total	1.452	0.373	0.538	0.116	0.020	2.500	1.452
% of Total	58.0	15.0	21.6	4.6	0.8	100.0	
Cum %	58.0	73.0	94.6	99.2	100.0		
Mainland Behind Long Beach Island							
Ship Bottom	7.723	5.002	3.125	1.012	0	16.862	7.724
Tuckerton	12.950	2.282	1.819	2.066	0	19.117	12.950
Total	20.673	7.284	4.944	3.078	0	35.979	20.674
% of Total	57.5	20.2	13.7	8.6	0	100.0	
Cum %	57.5	77.7	91.4	100.0	100.0	100.0	
Overall Totals							
Totals	22.55	13.91	6.16	3.26	0.02	45.90	
% of Total	49.1	30.3	13.4	7.1	–	100.0	
Cum %	49.1	79.4	92.8	99.9	100.0		

* Includes wetlands areas on islands in bay behind Long Beach Island.

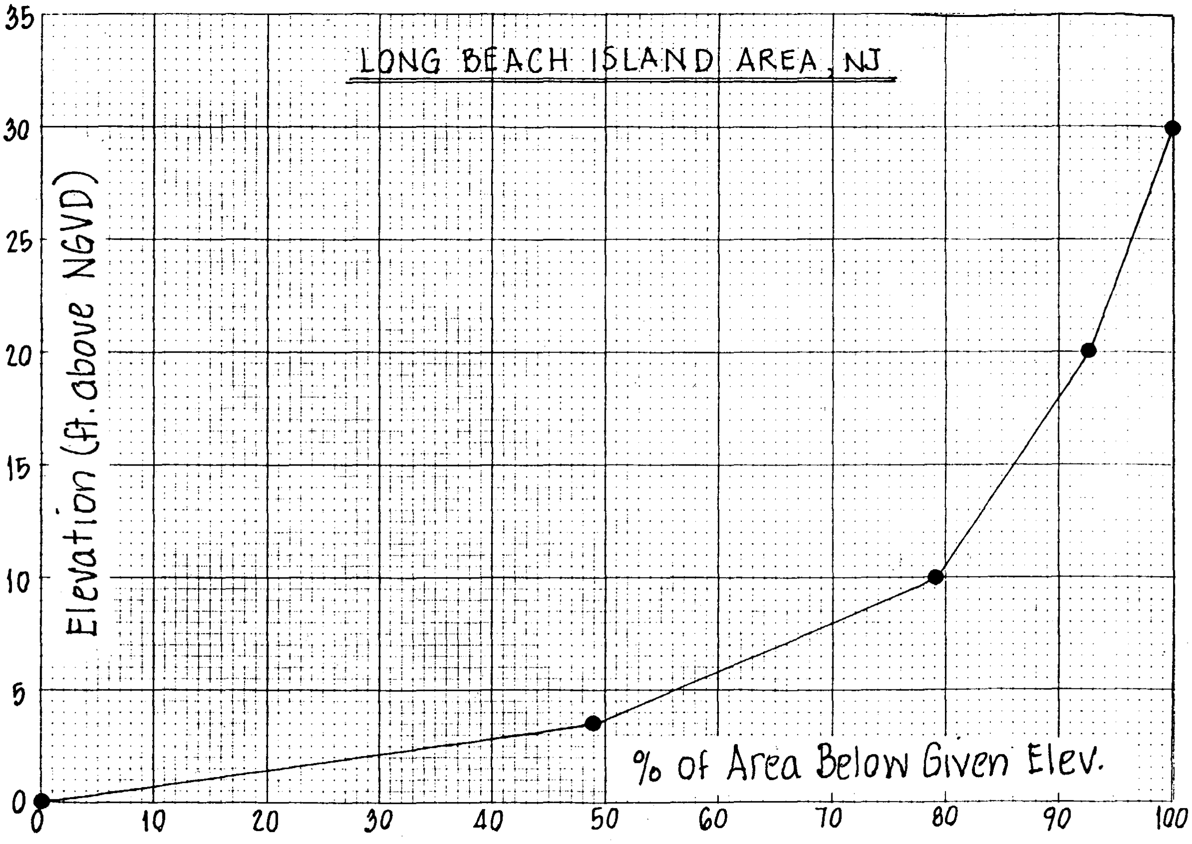


Figure 2 Distribution of Ground Elevations - Long Beach Island, NJ Area.

Table 5. Summary of Shoreline Lengths at Long Beach Island and Adjacent Mainland, New Jersey

USGS Quad	LBU Ocean Shoreline (mi)	LBI Bay Shoreline			Mainland shoreline (mi)	Wetlands shoreline (mi)
		Bulk. (mi)	Unbulk. (mi)	Total (mi)		
Barnegat Light	1.19	0.74	1.86	2.60	0	4.32
Long Beach NE	2.24	0.30	1.79	2.09	0	0.60
Ship Bottom	9.39	6.41	6.26	12.67	18.24 *	26.60
Tuckerton	3.87	2.61	4.69	7.30	14.60 *	18.17
Beach Haven	6.26	5.02	2.68	7.70	0	4.79
Total (mi)	22.95	15.08	17.28	32.36	32.84	54.48

* Boundary between wetlands and mainland.

Table 6. Summary of topographic conditions in Dividing Creek, New Jersey

USGS Quad	Area (sq mi) Between Given Elevations (ft)					Total Area	Wetlands Area
	0<Z<5	5<Z<10	10<Z<20	20<Z<30	30<Z<40		
Dividing Creek	6.66	10.56	9.57	4.47	–	31.25	6.66
Cedarville	15.43	11.95	4.70	2.29	–	34.36	15.43
Port Norris	15.69	1.88	0.42	0.02	–	18.01	15.69
Fortescue	10.41	–	–	–	–	10.41	10.41
Overall Totals							
Total	48.19	24.39	14.69	6.79	–	94.05	48.19
% of Total	51.23	25.93	15.62	7.21	–	100.00	
Cum %	51.23	77.16	92.78	100.00			

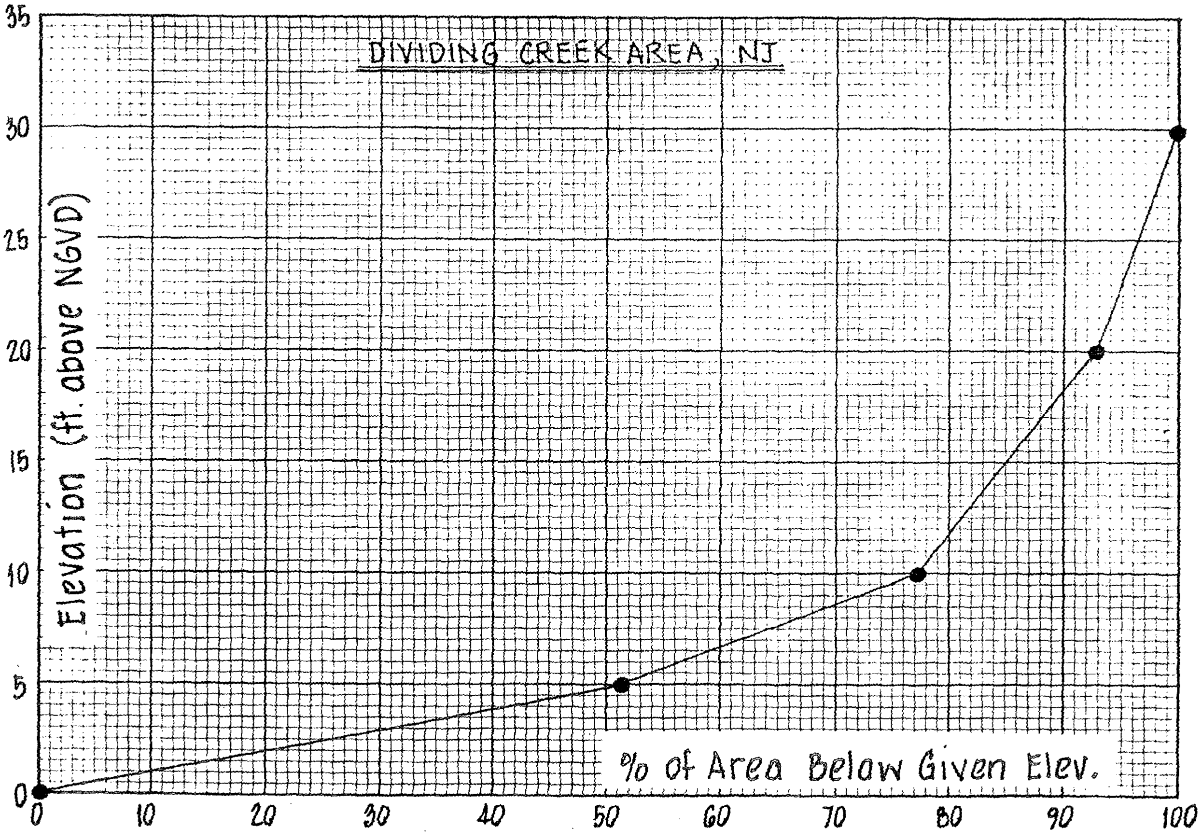


Figure 3 Distribution of Ground Elevations - Dividing Creek, NJ Area.

Table 7. Summary of Shoreline Lengths at Dividing Creek, New Jersey

USGS Quad	Delaware Bay * Shoreline (mi)
Dividing Creek	17.88
Cedarville	51.07
Port Norris	19.22
Fortescue	8.79
TOTAL (mi)	96.96

* Boundary between wetlands and Delaware Bay

Miami and Miami Beach Area, Florida

The Miami/Miami Beach, Florida, area is covered by two USGS quads: Miami and North Miami. The area is heavily developed, both commercially and residentially. Miami Beach is primarily a resort area while Miami itself is a major metropolitan area. Major municipalities include the City of Miami itself, North Miami, Miami Shores, and North Miami Beach on the mainland, and Miami Beach on the barrier island. There are also many smaller political subdivisions. The land is generally low in elevation as shown in Table 8. The distribution of land elevations is shown in Figure 4 and summarized in Table 8. While only 16% of the land is below + 5-foot NGVD elevation, 52% is between + 5 and + 10 feet so that 69% is below + N feet and 98% is below + 15 feet in elevation. There is virtually no land above the + 20-foot elevation. In addition, most of the low-lying land is heavily developed and very little of it is undeveloped wetlands. As a result of the low-lying topography, most of the shoreline has been bulkheaded. Shoreline lengths are summarized in Table 9. Of the 125 miles of shoreline on the USGS quads, more than 100 miles or 80% are bulkheaded. The shorelines in Table 9 are classified as either ocean or bay shoreline. The major bodies of water are the Atlantic Ocean fronting the barrier island, and Miami Beach and Biscayne Bay, the bay between the Miami Beach barrier island and the mainland. Numerous manmade or man-improved islands are located in Biscayne Bay. Many of them support residential development or they serve to support causeways that connect the barrier island with the mainland. Most of these small islands' shorelines are completely bulkheaded.

Corpus Christi Area, Texas

Corpus Christi, Texas, is located on the Gulf of Mexico about 150 miles north of the U.S.-Mexican border. The area is developed around the major city of Corpus Christi and several smaller municipalities such as Portland and Ingleside. The towns are located on Corpus Christi Bay and are sheltered from the Gulf of Mexico by Mustang Island and Padre Island, two undeveloped barrier islands. Portions of the undeveloped barrier islands are included in the present analysis. The area under study is covered by six USGS quads: Corpus Christi, Crane Island NW, Oso Creek NE, Oso Creek NW, Port Ingleside, and Portland. The distribution of land elevations in the Corpus Christi area is given in Figure 5 and summarized in Table 10. In general, little land is below the + 5-foot contour (only 9%), while all of it is below the 30-foot contour. The land elevation distribution at Corpus Christi is somewhat unique among the index sites, since the function is approximately linear suggesting a very steep shoreline in an average sense.

The shoreline length and its distribution among the six quads is given in Table 11. Most of the 189-mile long shoreline is unbulkheaded.

San Francisco Bay Area, California

The portion of the south San Francisco Bay Area considered in the present study is covered by the following four USGS quads: Redwood Point, Newark, Palo Alto, and Mountain View. The area covered is the shallow, southernmost portion of San Francisco Bay. The major metropolitan areas in the area are Hayward, Newark, and Fremont on the east side of the bay, and Palo Alto, Redwood City, Sunnyvale, Mountain View, and Menlo Park on the west side of the bay. Most of the residential areas associated with these towns are at sufficiently high elevation to not be significantly affected by sea level rise of the magnitude under consideration here; however, the low-lying areas surrounding the bay itself are vulnerable. Generally, terrain in the San Francisco area is quite hilly except for the low-lying areas adjacent to the San Francisco Bay. Most of the bay shoreline in this area is covered by salt evaporators: portions of the bay separated from the main bay by levees and used to commercially extract salt from bay water through natural evaporation. The bay is thus subdivided by the levees. Redwood Creek and Steinberger Slough drain into the bay in this area. The distribution of elevations is given in Figure 6 and summarized in Table 12 for that portion of the area below the + 30-foot contour. Because of the evaporators, 59% of the land lower than + 30 feet is below + S feet NGVD elevation. Shoreline lengths are summarized in Table 13. Two lengths are given in the table: the length along the outermost levees that separate the evaporators from the bay, and the shoreline length behind the evaporators, i.e., the shoreline between the evaporators and fast land. This latter shoreline nearly coincides with the + 5-foot contour.

Table 8. Summary of Topographic Conditions at Miami and Miami Beach, Florida

USGS Quad	Area (sq mi) Between Given Elevations (ft)					Total Area
	0<Z<5	5<Z<10	10<Z<15	15<Z<20	20<Z	
			Miami Beach			
North Miami	1.72	1.35	0.33	0.03	0	3.43
Miami	4.38	2.22	0.08	0.02	0	6.70
Total	6.10	3.57	0.41	0.05	0	10.13
% of Total	60.2	35.2	4.0	0.5		100.0
Cum %	60.2	95.4	99.4	100.0		
			Miami			
North Miami	12.65	36.36	13.01	0.05	0	62.08
Miami	3.85	15.95	15.32	1.79	0	36.92
Total	16.50	52.31	28.33	1.84	0	99.0
% of Total	16.7	52.8	28.6	1.9		100.0
Cum %	16.7	69.4	98.1	100.0		
			Overall Totals			
Total	22.60	55.88	28.74	1.89		109.13
% of Total	20.7	51.2	26.3	1.7		100.0
Cum %	20.7	71.9	98.2	100.0		

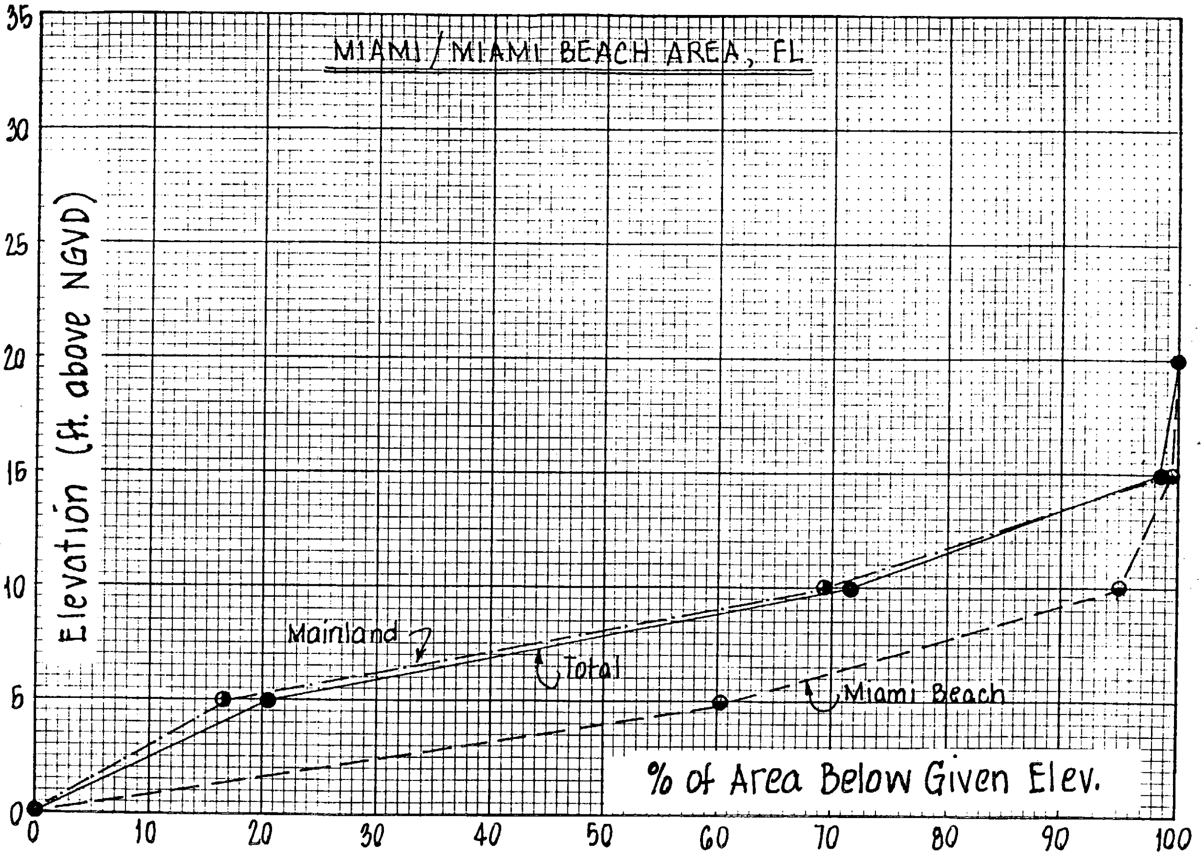


Figure 4 Distribution of Ground Elevations - Miami/Miami Beach, FL Area.

Table 9. Summary of Shoreline Lengths at Miami Beach, Florida

USGS Quad	Ocean Shoreline (mi)	Bay Shoreline *			Mainland Shoreline		
		Bulk. (mi)	Unbulk. (mi)	Total (mi)	Bulk. (mi)	Unbulk. (mi)	Total (mi)
North Miami	8.49	15.93	2.98	18.91	6.44	3.84	10.28
Miami	7.75	68.85	16.08	84.93	10.21	0.82	11.03
Total (mi)	16.24	84.78	19.06	103.83	16.65	4.66	21.31

* Includes shoreline of islands in bay between Miami and Miami Beach

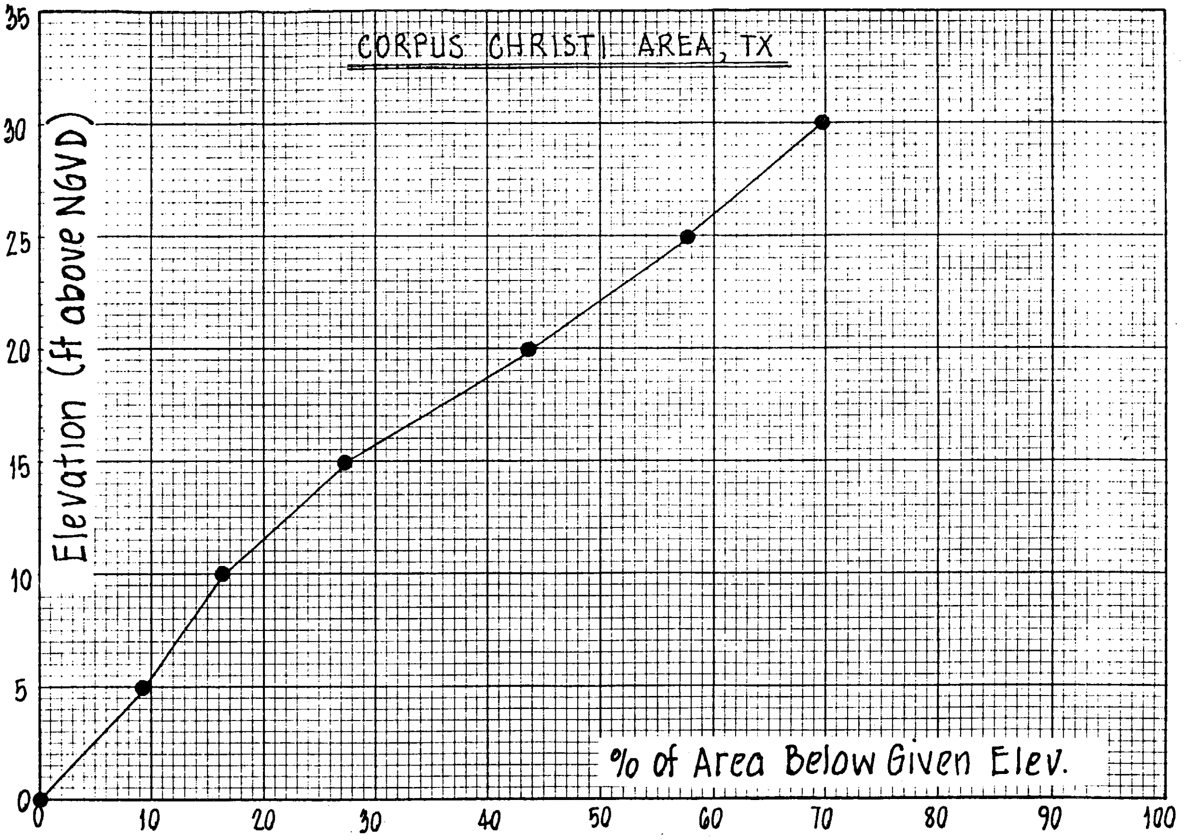


Figure 5 Distribution of Ground Elevations - Corpus Christi, TX Area.

Table 10. Summary of topographic conditions at Corpus Christi, Texas

USGS Quad	Area (sq mi) Between Given Elevations (ft)							Total Area
	0<Z<5	5<Z<10	10<Z<15	15<Z<20	20<Z<25	25<Z<30	30<Z	
Oso Creek NE								
Encinal	1.22	1.65	4.66	7.50	1.19	0.63	–	16.85
Mainland	0.59	0.09	5.03	6.92	3.29	0.01	–	16.73
Ward Is.	0.08	0.09	0.20	0.02	–	–	–	0.39
JFK Caus.	0.04	0.02	–	–	–	–	–	0.06
Total	1.93	2.66	9.89	14.14	4.48	0.64	–	34.03
% of Total	5.7	7.8	29.1	42.4	13.2	1.9		
Cum %	5.7	13.5	42.5	85.0	98.1	100.0		
Oso Creek NW								
Below HW2444 Bridge	0.90	1.07	2.67	6.79	13.60	15.07	22.05	62.15
Total	0.90	1.07	2.67	6.79	13.60	15.07	22.05	62.15
% of Total	1.4	1.7	4.3	10.9	21.9	24.2	35.5	
Cum %	1.4	3.1	7.4	18.3	40.2	64.4	100.0	
Port Ingleside								
Mainland	0.49	0.86	1.97	3.75	2.34	1.08	0.87	11.36
Undev. Is.	1.87	0.71	0.20	0.05	0.03	0.02	–	2.87
Total	2.36	1.57	2.17	3.80	2.37	1.10	0.87	14.24
% of Total	16.6	11.0	15.2	26.7	16.6	7.7	6.1	
Cum %	16.6	27.6	42.8	69.5	86.1	93.8	100.0	
Crane Islands NW								
Mustang Is	5.88	3.21	1.07	0.53	–	–	–	10.69
Mainland	0.31	0.21	0.07	0.01	–	–	–	0.60
Total	6.19	3.42	1.14	0.54				11.29
% of Total	54.8	30.3	10.1	4.8				
Cum %	54.8	85.1	95.2	100.0				
Portland	0.28	0.11	0.03	0.03	0.03	0.03	–	0.52
Corpus Christi	2.48	2.49	1.46	0.73	1.41	1.95	24.7	35.22
Total	2.76	2.60	1.49	0.76	1.44	1.98	24.7	35.74
% of Total	7.7	7.3	4.2	2.1	4.0	5.5	69.1	
Cum %	7.7	15.0	19.2	21.3	25.3	30.8	100.0	
Overall Totals								
Total	14.14	11.32	17.36	26.03	21.89	18.79	47.62	157.15
% of Total	9.0	7.2	11.0	16.6	13.9	12.0	30.3	
Cum %	9.0	16.2	27.2	43.8	57.7	69.7	100.0	

Table 11. Summary of Shoreline Lengths - Corpus Christi Area, Texas

USGS Quad	Shoreline Length		
	Bulk. (mi)	Unbulk. (mi)	Total (mi)
Corpus Christi	9.7	41.3	51.0
Crane Island NW	1.7	42.4	44.1
Oso Creek NE	7.8	36.2	44.0
Oso Creek NW	–	6.0	6.0 *
Port Ingleside	2.6	29.8	32.4
Portland	1.7	9.8	11.5
Totals	23.5	165.5	189.0

* Along Oso Creek

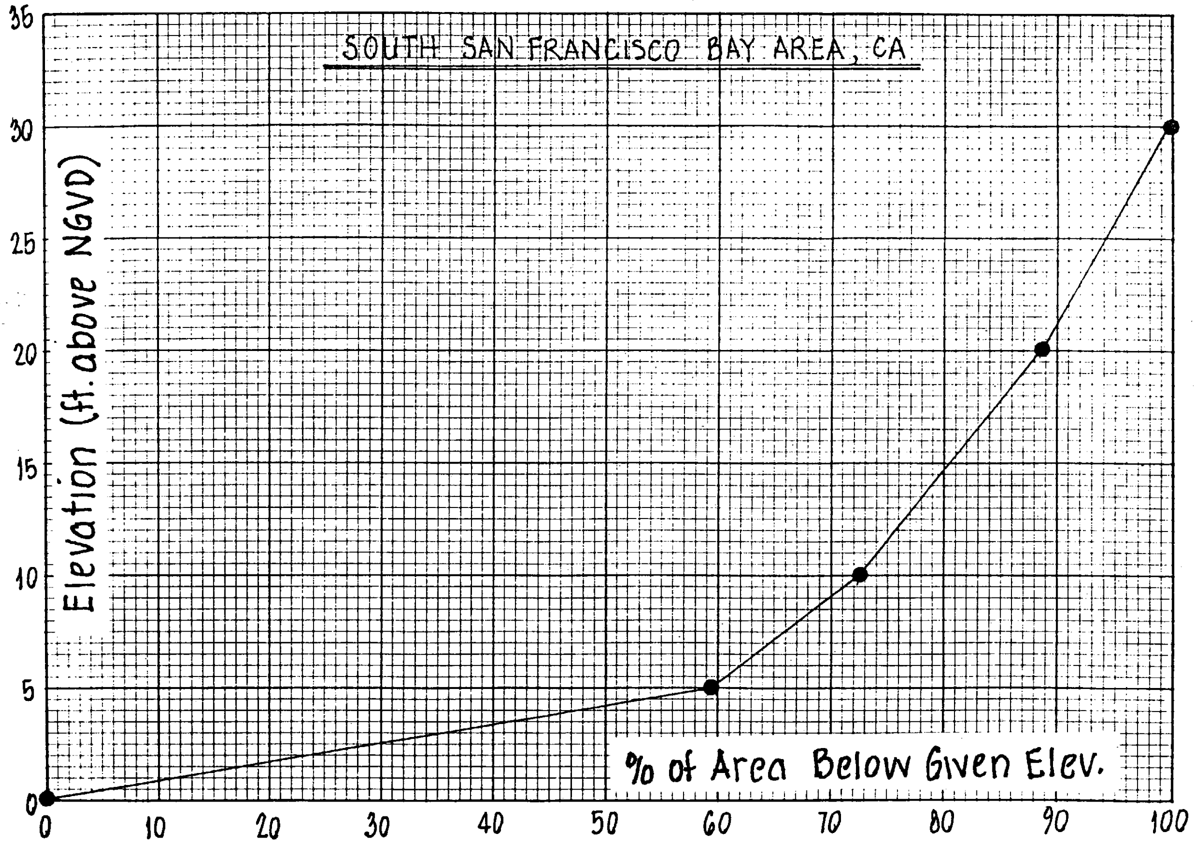


Figure 6 Distribution of Ground Elevations - South San Francisco Bay, CA Area.

Table 12. Summary of Topographic Conditions in San Francisco Area, California

USGS Quad	Area (sq mi) Between Given Elevations (ft)				Total Area	Wetlands Area
	0<Z<5	5<Z<10	10<Z<20	20<Z<30	<30	
Redwood Point	14.65	0.26	0.01	0	14.92	4.28
Newark	22.10	7.34	7.75	4.62	41.81	3.19
Palo Alto	6.33	2.70	4.25	3.75	17.03	0.40
Mountain View	14.59	2.57	3.64	2.47	23.28	2.31
Total	57.67	12.87	15.65	10.84	97.04	10.18
% of Total	59.4	13.3	16.1	11.2	100.0	
Cum %	59.4	72.7	88.8	100.0		

Table 13. Summary of Shoreline Lengths - San Francisco Area, California

USGS Quad	Inner Shoreline Length * (mi)	Outer Shoreline Length ** (mi)
Redwood Point	0.89	18.19
Newark	14.76	6.26
Palo Alto	8.35	0.89
Mountain View	13.00	17.00
Total	37.00	42.35

* Shoreline between salt evaporators and mainland (approximately) coincides with 5 foot contour.
** Shoreline between evaporators and San Francisco Bay.

CHAPTER 4

LONG BEACH ISLAND, NEW JERSEY - IN-DEPTH ANALYSIS

EVALUATION OF ALTERNATIVES

Long Beach Island, New Jersey, is a barrier island approximately 23 miles long, averaging between 1000 and 3200 feet wide. It comprises an area of about 7.4 square miles. It is bounded on the north by Barnegat Inlet and on the south by Beach Haven and Little Egg Inlets. The island shelters Little Egg Harbor and Manahawkin and Barnegat Bays from the Atlantic Ocean. The island is entirely developed with single-family houses except for the southern 3 miles, which is part of Brigantine National Wildlife Refuge. There are no high-rise condominiums and only one motel with as many as three stories. It is heavily populated by vacationers during the summer months but the population during the remainder of the year is relatively small. Access to the island is by a single bridge from Manahawkin on the mainland to the town of Ship Bottom near the middle of the island. Long Beach Island's ocean shoreline is protected by dunes along most of its entire length. The dune crests are at about + 10 feet above NGVD with a few rising to + 20 feet. The island's bay shoreline is about 32 miles long; about 15 miles of the bay shoreline is bulkheaded. See Table 5. The bay shoreline is dotted with small marinas and other boat launching and docking facilities. There is also a small amount of salt marsh along the bay shoreline comprising about 0.43 square miles or 5.7% of the island's area.

SHORELINE AND TOPOGRAPHIC CONDITIONS

Shoreline lengths along Long Beach Island and the adjacent mainland are summarized in Table 5, and topographic conditions are summarized in Table 4. These data are given for each of the USGS quad sheets analyzed. Long Beach Island is covered by five quads: Barnegat Light, Long Beach NE, Ship Bottom, Tuckerton, and Beach Haven. The Barnegat Light quad also covers the southern end of Island Beach State Park, the undeveloped barrier island just north of Long Beach Island, while the Ship Bottom and Tuckerton quads alsoc over a significant area of the mainland behind Long Beach Island. The distribution of elevations on Long Beach Island is given in Figure 7. About 6% of the island is below about 3.5 feet in elevation (NGVD); about 84% of the island is between 3.5 feet and 10 feet in elevation. Only 9% is above 10 feet, and less than 1% (a few scattered high dunes near the northern end of the island) is above 20 feet in elevation. The distribution of elevations on the mainland is significantly different. (See Figure 7 for the distribution of elevations on both the mainland and on the barrier island.) Of the mainland area below 40 feet in elevation, about 57% is below + 3.5 feet NGVD. This area is defined as coastal wetlands on the USGS quads.

LEVEL OF DEVELOPMENT

The level of development on Long Beach Island was determined from an analysis of aerial photographs obtained from the New Jersey Department of Environmental Protection, Bureau of Coastal Engineering. Two sets of photographs, dated March 23, 1982, and March 30, 1984, were used to determine the number of buildings on the island and their location relative to the prevailing high-water shoreline. These data are summarized in Table 14. The distribution of houses with respect to the shoreline is plotted in Figure 8. The cumulative number of houses summed along the entire length of the island is plotted as a function of the distance measured landward across the island from the high water shoreline. Thus if the shoreline were to erode 500 feet from the ocean side, approximately 4,700 buildings on Long Beach Island would be affected. If the shoreline were to erode 1,000 feet, 9,800 buildings would be located seaward of the new shoreline. This relationship is nearly linear, indicating an almost uniform level of development across the island from its seaward side to its bayward side. It deviates from a linear relationship only for distances exceeding 1,000 feet because of the island's variable width. Thus the cumulative number of buildings drops off for distances greater than 1,000 feet with that distance measured from the existing high-water shoreline. The linear portion of the curve can be expressed by the equation:

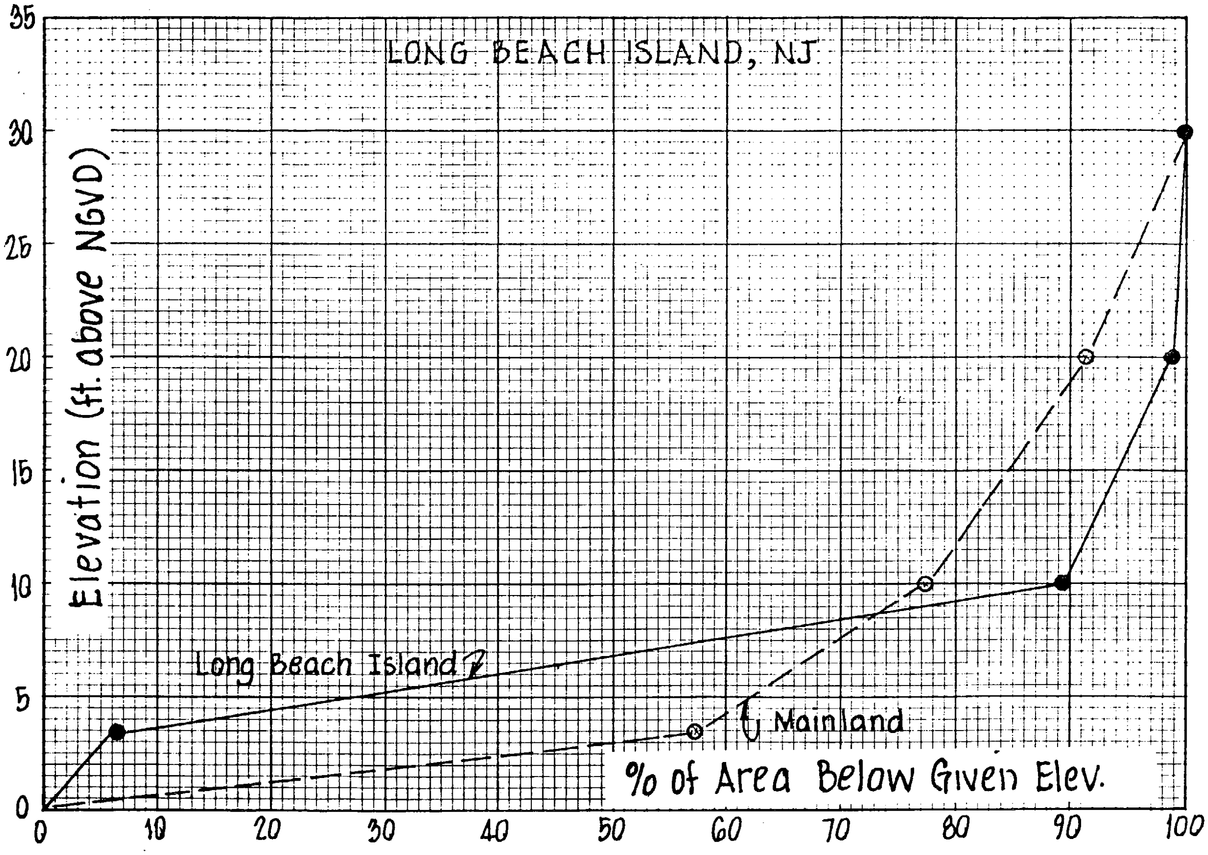


Figure 7 Distribution of Ground Elevation - Long Beach Island and Mainland and Adjacent to Long Beach Island.

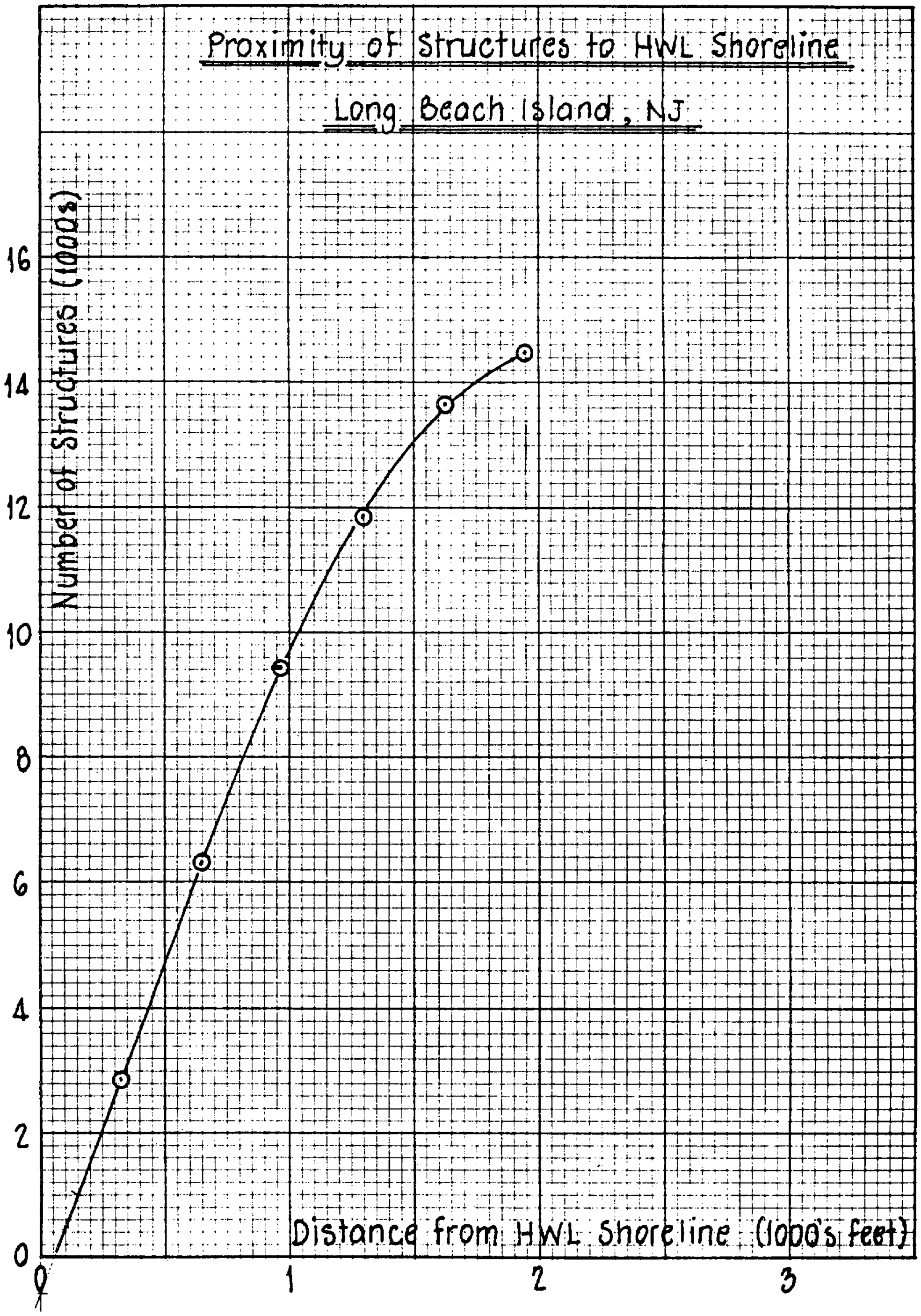


Figure 8 Proximity of Buildings to High Water Shoreline - Long Beach Island (Based on Analysis of 1984 Aerial Photographs).

Table 14. Distribution of Buildings on Long Beach Island

Distance from Ocean Shoreline (ft)	Number of Buildings	Cumulative Number	%
0 to 325	2834	2834	19.65
325 to 650	3464	6298	43.67
650 to 980	3110	9408	65.24
980 to 1300	2468	11876	82.35
1300 to 1630	1756	13632	94.52
1630 to 1960	789	14421	100.00

$$N = 10.4 X - 600 \qquad (3)$$

in which N = the number of buildings affected and X = the distance measured landward from the present high-water shoreline in feet. Equation 3 is valid for values of X between 60 feet and 1000 feet.

Development density varies along the island as shown in Figure 9. In general, building density is lower in the more northerly communities where lot cover age is lower. The area per building, averaged over the entire island, is 12,600 square feet per building or a density of 2,200 buildings per square mile. In the northerly communities of Barnegat Light and Loveladies, about 50% of the homes are of recent construction and are elevated on pilings one floor above ground level.

SEA LEVEL RISE SCENARIO

By 2100, for purposes of this study, mean sea level at Long Beach Island was assumed to be 2 meters above 1986 levels plus that portion of the historically observed sea level rise that exceeds 0.0012 meters per year, i.e., the increase in mean sea level that would occur if the observed historical rate were to prevail (Titus, this volume). At Long Beach Island, the historical rate of sea level rise has been about 0.004 meters per year. Thus, mean sea level is given by the equation,

$$Z = 0.004(YR-1986) + 0.0001424(YR-1986)^2 \qquad (4)$$

where Z is the elevation of mean sea level above the 1986 level (meters) and YR is the year. Thus by 2100, mean sea level at Long Beach Island will be 2.31 meters above the 1986 level. The first term of Equation 4 gives the historical rate, while the second term gives the rate due to the accelerated "greenhouse effect." Equation 4 is plotted in Figure 10 along with sea level curves for other historical rates, i.e., for various values of the coefficient of the first term in equation 4,

A rough estimate of the average rate of shoreline recession for Long Beach Island can be derived from the rate of sea level rise by using the Bruun rule (Bruun, 1962). For the Atlantic coast of the U.S., the profile closure depth is approximately 30 feet. At Long Beach Island, the 30-foot contour is approximately 4,000 feet from shore on average and the dune crests can be assumed to be about 10 feet high. Thus, the profile extending from dune crest to closure depth is about 40 feet high, and a one foot change in mean sea level will result in 4000/40 = 100 feet of shoreline recession. Combining this rate of erosion with the mean sea level curves results in the shoreline recession curve in Figure 11. This curve, given by,

$$X = 328.1\{0.004(YR-1986) + 0.0001434(YR-1986)^2\} \qquad (5)$$

in which X is the shoreline recession in feet. It is simply 100 times the sea level rise curve given by Equation 4.

Coupled with the building density data of Figure 8, the number of houses affected by the rise in sea level can be determined from the shoreline recession curve. Figure 12 shows the number of buildings on Long Beach Island affected by sea level rise as a function of time. The cumulative number of buildings is given by,

$$N = 13.65(YR-1986) + 0.4893(YR-1986)^2 - 600 \qquad (6)$$

for the years after 2010.

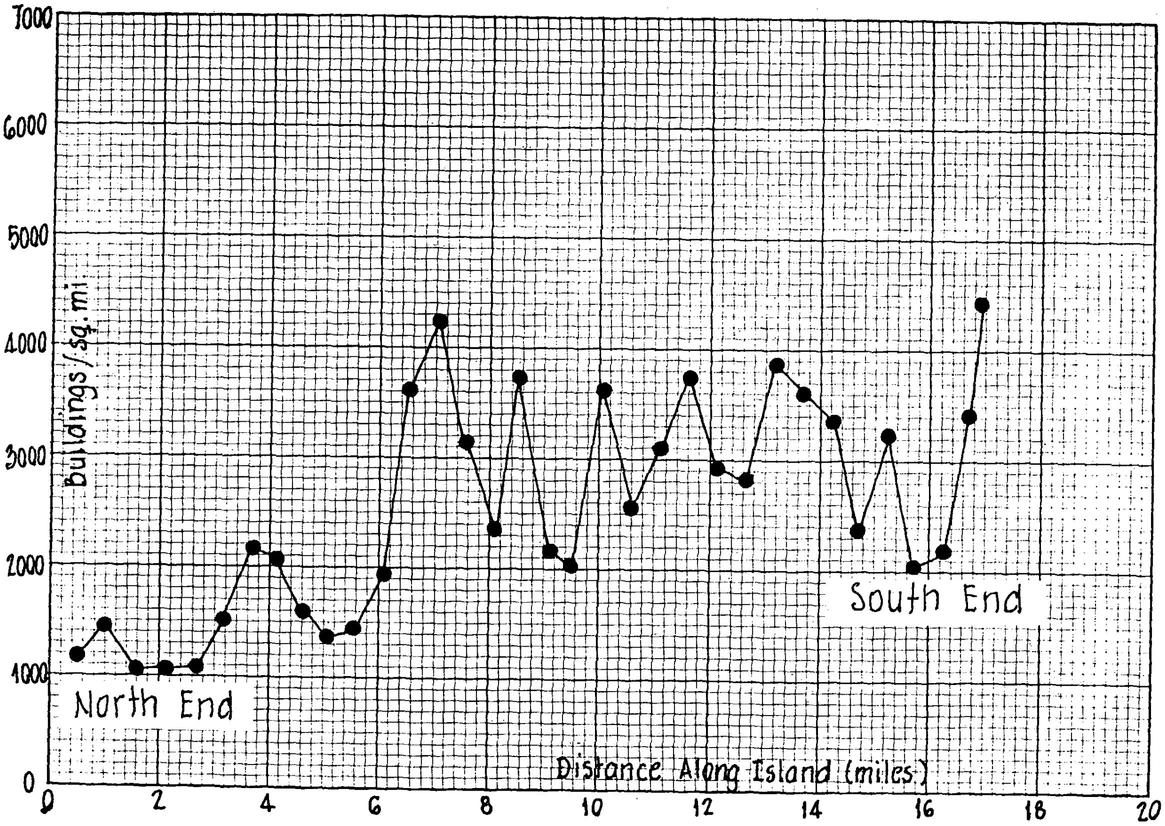


Figure 9 Distribution of Building Density along Long Beach Island (Based on Analysis of 1984 Aerial Photographs).

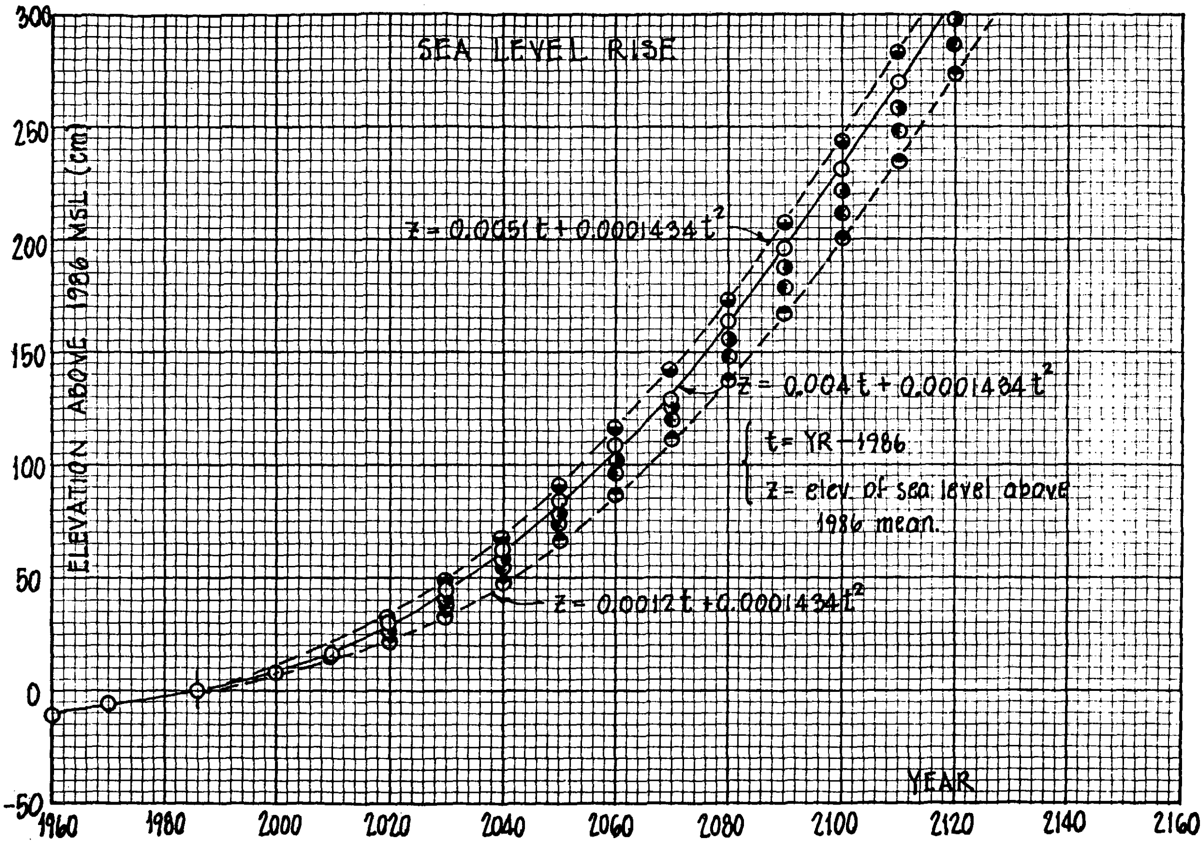


Figure 10 Sea Level as a Function of Time - Long Beach Island.

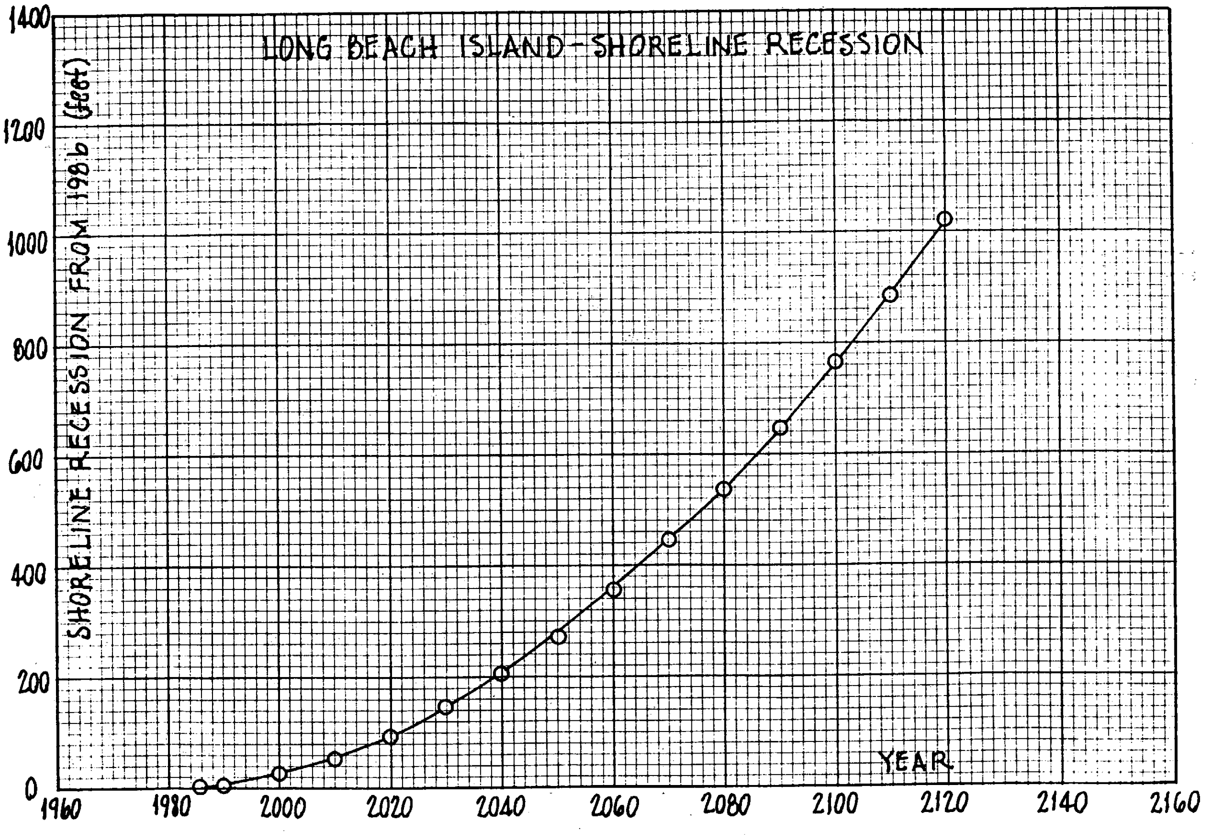


Figure 11 Shoreline Recession as a Function of Time - Long Beach Island.

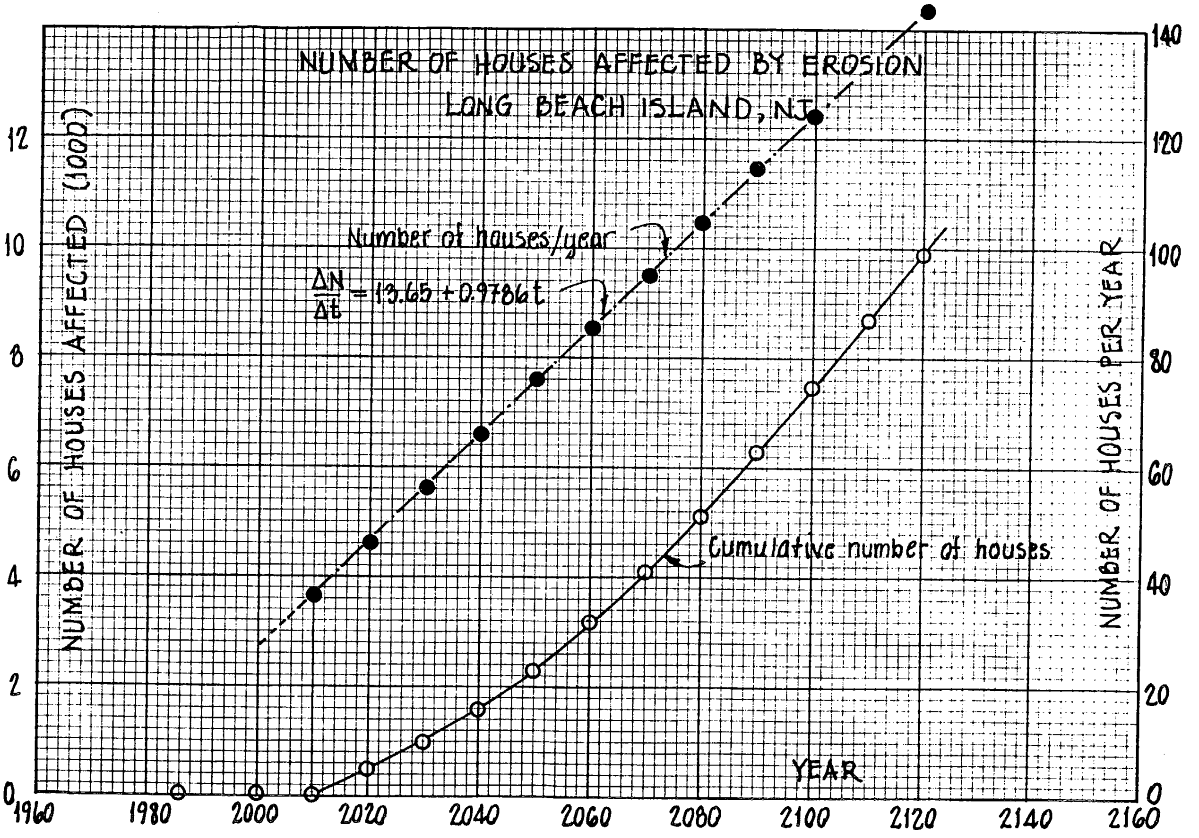


Figure 12 Number of Houses per Year and Cumulative Number of Houses Affected by Sea Level Rise as a Function of Time - Long Beach Island.

Because of the setback of existing buildings behind the dunes, the analysis shows that the buildings closest to the beach are not affected until 2010. Actually, they will feel the effect of sea level rise sometime earlier because of their vulnerability to storm damage as the dune buffer between them and the sea disappears; however, based on the given sea level rise scenario, the buildings will remain landward of the shoreline until 2010. The lower curve of Figure 12, which shows the cumulative number of buildings affected by erosion, should probably be shifted leftward to account for owners abandoning or moving buildings that experience storm damage more and more frequently as the shoreline, recedes. The annual rate at which buildings are affected by shoreline recession can be found from the slope of the cumulative number of buildings affected. The rate is given by,

$$R = 13.65 + 0.9786(YR-1986) \qquad (7)$$

in which R = the number of buildings affected per year. Since the cumulative number of buildings varies parabolically, the annual rate at which buildings are affected varies linearly with time. Approximately 37 buildings per year will be affected in 2010. By 2100, however, 125 buildings per year will come within reach of the encroaching shoreline.

RESPONSE TO SEA LEVEL RISE

Reproduce Landward Migration of Barrier Island

One possible response to a rising sea level at Long Beach Island would be to physically introduce a landward migration of the barrier island. As sea level rises and erodes the island's ocean beaches, additional land would be created on the bay side of the island by bulkheading and filling. As buildings are affected by the encroaching ocean shoreline, they would be moved to new land created on the bayward side of Long Beach Island. Initially, fill to create the new land would be obtained from the bay adjacent to the island, possibly by deepening, expanding, or moving the Atlantic Intracoastal Waterway. In later stages, however, the cumulative quantity of fill needed would, like beach nourishment, require the exploitation of offshore sand resources. (See Leatherman, this volume.)

There are three major elements contributing to the cost of this scenario. They are: a) the cost of creating new land and subsequently raising the elevation of the island as high tide levels increase; b) the cost of moving buildings; and c) the cost of replacing infrastructure as it becomes inundated or damaged by the encroaching sea. Some of these costs will be incurred even if sea level does not rise. For example, infrastructure such as roads, highways, buried utilities, etc., must be replaced as their useful lifetime runs out. Also, some buildings would be razed and replaced even without sea level rise. In some cases, a rise in sea level may only reduce the economic lifetime of a structure and hasten its replacement. The true costs attributable to sea level rise are the additional costs that would not have been otherwise incurred, i.e., the cost of replacing a road that would not otherwise require replacement or of replacing the road in S years rather than in 10 years.

On Long Beach Island, the number of buildings affected by sea level rise in each year following the year 2010 can be computed from Equation 7. The cumulative number of buildings is given by Equation 6. The average cost of moving a building of the size of those located on Long Beach Island is about $10,000 including the reconstruction of a new foundation. This is the cost to move the building a distance of less than 1/2 mile. Thus in 2010, 37 buildings would be either abandoned to the sea or moved at a cost of $10,000 each (1987 dollars).

Determining the cost of creating additional land to which buildings can be moved requires that the volume of fill needed and its unit cost be determined. The scenario investigated here assumes that fill will be required to raise the land elevation. The land will initially be raised at the same rate as sea level rises. As sea level rises further, starting in 200S, new land will be created at an elevation + 1.4 feet above spring high tides. As a first approximation, tidal ranges in the bay behind Long Beach Island were assumed to be unaffected by any increase in mean sea level. Additional land area will also be created at an elevation to keep it at least 1.4 feet above the then-prevailing spring high tides. See Figure 13. The depth of the bay close to shore immediately behind Long Beach Island averages about 4.1 feet below NGVD datum. Actually it ranges from about 1 foot deep over relatively large areas to more than 10 feet deep in some small, restricted areas -- mostly due to nearshore navigation channels and deepened small craft mooring areas. The mean tidal range at several locations behind Long Beach Island is given in Table 15. The average mean tidal range assumed for the present study was 2.2 feet. The mean spring tidal range was taken to be 3.2 feet. From Figure 7, each foot of sea level rise above + 3.5 feet would inundate about 13% of the island's area. Thus the portion of the island that would have to be raised is 13% of the island's original 1986 area. New land created after 2005 would be at an elevation exceeding + 3.5 feet NGVD to keep it at least 1.4 feet above spring high tides at the then-prevailing mean sea level.

The scenario adopted for the rate of land creation was: a) starting at present, land would be raised at a rate to keep its elevation 1.4 feet above spring high tides; and b) starting in 2005, land would be replaced on the bay side of the island each year at a rate equal to the number of buildings moved each year times an average building lot area of 12,600 square feet, i.e., 12,600 times the value of R given by Equation 7. (The year 2005 rather than 2010 was used as the start of filling in order to account for the possibility that some owners would take preventative action before their buildings were damaged.) Figure 14 shows the volume of fill required each year following 2005 along with the cumulative volume required. The annual amount of fill increases almost linearly with time so that by 2100, about 680,000 cubic yards of fill will be needed each year. A total of 41 million cubic yards of fill will be required by the year 2100!

For this scenario, 12,600 square foot building lots are re-established on the bay side of the island, and the annual volume of fill required between the present and the year 2005 is given by,

$$dV/dt = 12{,}300 + 877(YR-1986) \qquad (8)$$

where dV/dt is the rate at which sand must be used to create land in cubic yards per year. The cumulative volume used up to a given year is given by,

$$V = 12{,}300(YR-1986) + 438(YR-1986)^2 \qquad (9)$$

for the years between the present and 200S, with V in cubic yards. For the years following 2005, the annual volume and cumulative volume are given by,

$$dV/dt = 73{,}534 + 5{,}273(YR-1986) + 0.427(YR-1986)^2 \qquad (10)$$

and,

$$V = -1{,}957{,}900 + 73{,}534(YR-1986) + 2{,}636(YR-1986)^2 + 0.142(YR-1986) \qquad (11)$$

respectively.

These equations are plotted in Figure 14.

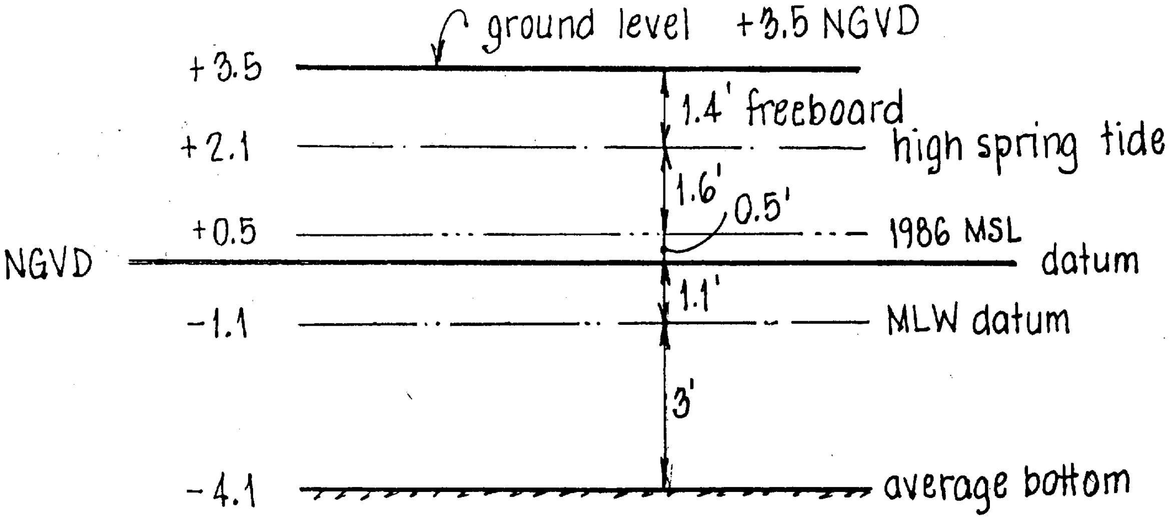


Figure 13 Datums and Tide Levels in Bay Behind Long Beach Island, NJ

Table 15. Mean Tidal Range in Bays Behind Long Beach Island

Location	Mean Range (feet)
Barnegat Light	2.3
Surf City	1.0
Ship Bottom	1.5
Spray Beach	2.2
Beach Haven	2.2
Holgate	2.4

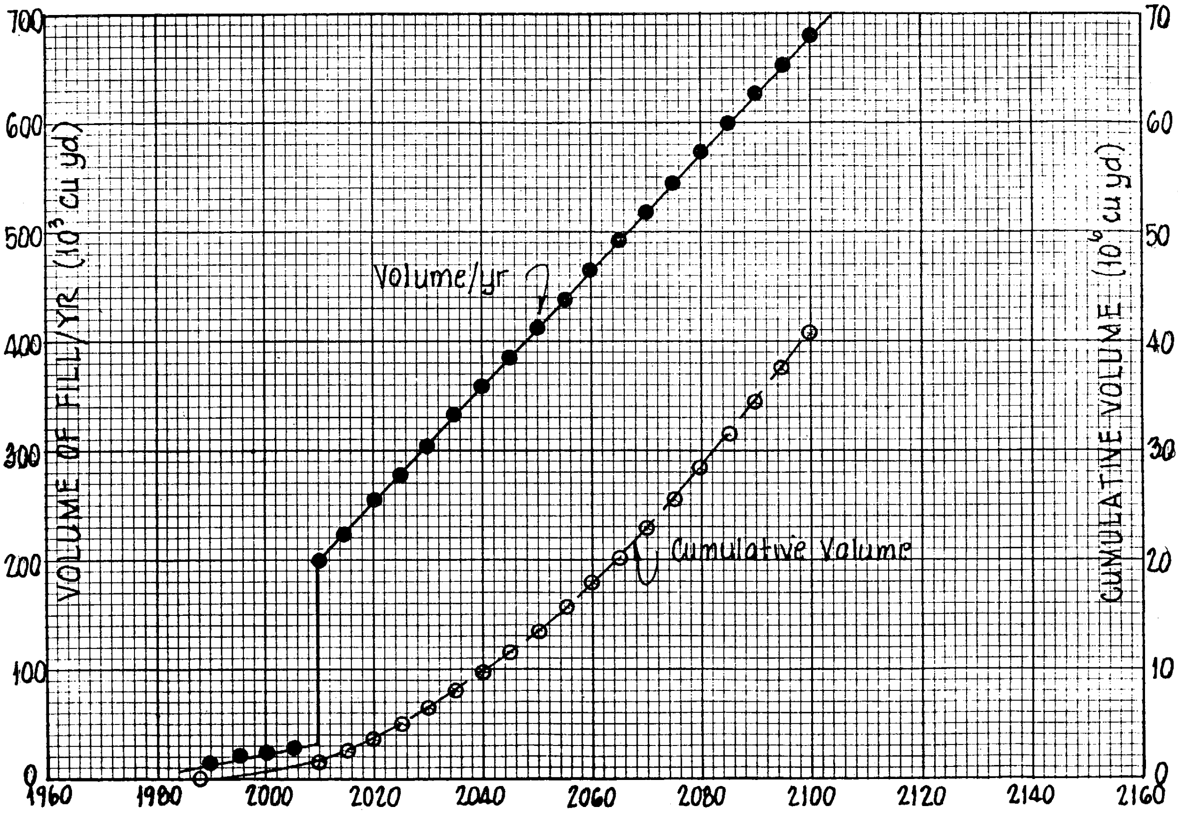


Figure 14 Volume of Fill and Cumulative Volume of Fill Required to Raise Long Beach Island, NJ as a Function of Time.

Three major elements contributing to the costs of implementing this alternative are: a) the cost of fill; b) the cost of replacing infrastructure including roadways and buried utilities (see Table 16); and c) the cost of raising and moving buildings to the landward side of the barrier island. These costs are shown in Figure 15 as a function of time.

Raise Island in Place

A second alternative, similar to the preceding one, is to simply raise the elevation of the island but without moving it landward into shallower water. Buildings would be elevated as necessary and fill placed on the island. Buildings already raised on pilings would simply have rill placed beneath them. Thus the present trend in coastal areas of constructing elevated buildings on pilings would simplify implementation of this alternative. Much of the buried infrastructure might continue to be used. For example, water, and storm and sanitary sewers would still be serviceable for several years. They would simply end up being buried deeper beneath the ground surface. Eventually, however, they would have to be replaced as increased seepage into storm and sanitary sewers becomes a problem because of the relatively higher water table. The sea water environment would also accelerate deterioration of the pipes. Roadways and sidewalks would have to be replaced at the time the island is raised. This would be the major infrastructure replacement expense under this alternative.

The amount of fill required for this scenario is slightly less than the preceding scenario; however, the difference is negligible. The amount of bulkheading is also about the same as for the preceding alternative since the island's perimeter remains the same. See Figure I.5a.

The number of houses involved under this alternative would also be somewhat less than the number involved in the preceding alternative, particularly- if houses, as they are replaced, are replaced with houses constructed on elevated piling. The cost of simply raising a building in place is also assumed to be less than the cost of both raising and moving it to another site. For this study, however, the number of houses to be raised was assumed to be that given by equation 6.

The three primary elements contributing to the cost of this alternative are: a) the cost of fill; b) the cost of replacing some infrastructure; and c) the cost of raising houses. See Figure 15a.

Dike Around Island and Provide Interior Drainage

A third response to rising sea level along a highly developed barrier island like Long Beach Island, New Jersey, would be to construct dikes and an interior drainage system. The drainage system would have to handle both the seepage under the dike resulting from an elevated sea level as well as the interior runoff resulting from precipitation. The drainage system would have to handle the storm water that might otherwise drain by gravity into the sea. In general, the requirements to handle the runoff from precipitation will initially determine the size of the storm water storage facilities and pumps needed. Since it would be uneconomical to provide pumps having the capacity to drain runoff from rare storms with long return periods, storage facilities capable of holding runoff until it can be pumped into the sea would have to be provided. For the Long Beach Island scenario, relatively small storage facilities located under the street ends along the back side of the island were assumed to provide the most economical storage alternative. Since space is generally not available to construct large storm water storage facilities on Long Beach Island, a number of small tanks capable of holding the runoff from a cross-section of the island about two blocks wide was assumed. Preliminary dimensions for the tanks were what might be reasonably constructed beneath the street ends -- tanks approximately 50 feet wide, 100 to 200 feet long, and 10 to 20 feet deep. The storage capacity of such tanks vary from a minimum of about 50,000 cubic feet to a maximum of about 200,000 cubic feet. Storm water pumping would be episodic with most of it occurring during and after major rain storms. The average annual precipitation at Long Beach Island is about 45 inches per year. This precipitation is not uniformly distributed over time; rather, it occurs during irregularly spaced storm periods. Because of Long Beach Island's relatively small area, the precipitation can be assumed to be uniformly distributed over the island.

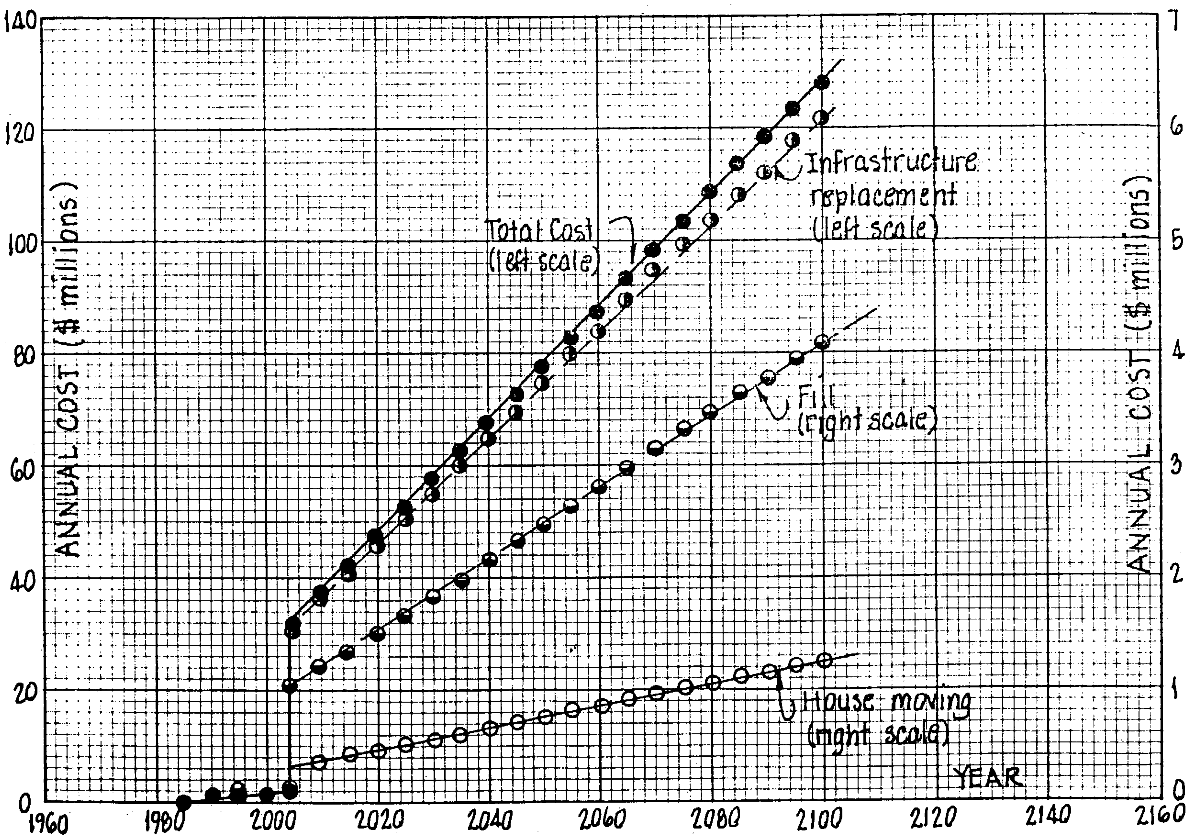


Figure 15 Annual Cost of Fill, Infrastructure Replacement, and House Moving for Long Beach Island, NJ as a Function of Time - Raise and Move Island Alternative.

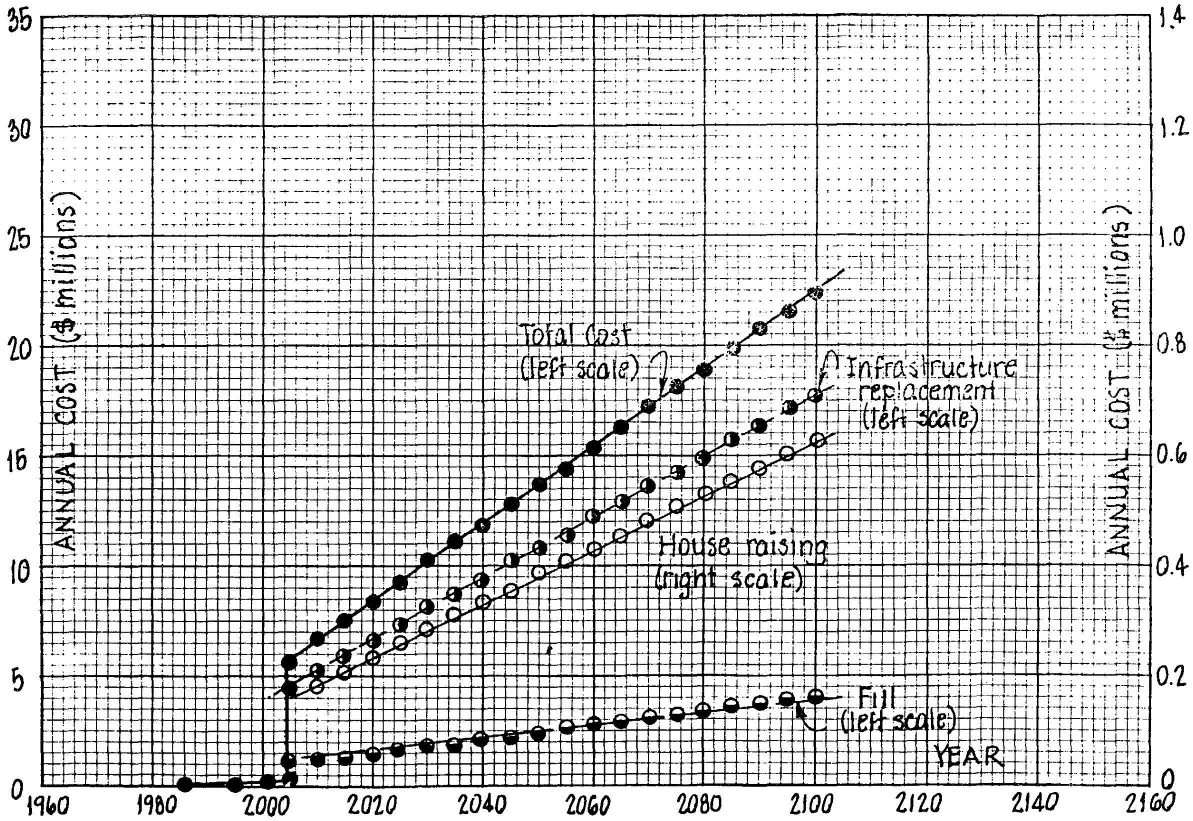


Figure 15a Annual Cost of Fill, Infrastructure Replacement, and House Raising for Long Beach Island, NJ as a Function of Time - Raise Island Alternative.

Table 16. Highways and Streets - Long Beach Island, New Jersey

Shore-Parallel Roads	
Primary N-S Road	30.14 mi.
Second Major N-S Road	6.85
Third Major N-S Road	5.21
Total Other N-S Road	10.83
Total Shore-Parallel	53.03
Shore-Normal Roads	
Total E-W Roads	70.79
Total Shore-Normal	70.79
TOTAL	123.82

A hydrologic analysis of Long Beach Island was performed to determine the amount of storm runoff that might be expected. This was used to size the storage and pumping facilities needed to handle the runoff. Rainstorms with return periods ranging from 10 to 50 years were investigated and routed through the proposed street-end storage tanks to determine how much interior flooding might result during periods of high runoff when the tank storage capacity is exceeded. Runoff values were calculated using Soil Conservation Service (SCS) methods outlined in "Urban Hydf ology for Small Watersheds," Technical Release 55 (SCS TR-55). This method relates the runoff per inch of rainfall to the watershed area, slope, land use, and the condition of the land cover. Rainfall values were obtained from the National Weather Service's Rainfall Frequency Atlas of the United States, Technical Paper No. 40. Storms having return periods ranging from 10 to 50 years with durations ranging from 30 minutes to 24 hours were analyzed. Peak discharges were developed for drainage areas of about 24 acres, the contributing area assumed for each of the individual storage tanks. Peak discharges are given in Table 17 for rainfalls of 24 hours' duration. For a storage tank capacity of 150,000 cubic feet, a pumping capacity of 30 cubic feet per second is required to minimize flooding the interior of the island during major rainstorms. If each individual drainage system drains about 24 acres, about 200 such systems are needed to serve Long Beach Island.

In addition to interior runoff, seawater seepage beneath the dikes will occur, at first only during high tides, but later, as sea level rises and the difference in elevation between mean sea level and the interior land increases, seepage will occur during much of the tidal cycle. As time passes and sea level rises, the amount of seepage will increase. Eventually, it might be necessary to pump almost continuously, albeit at a relatively low rate when compared to stormwater drainage pumping requirements. To control seepage, an interior drainage system of buried drain pipes was investigated. These drains would intercept seepage and convey it to the storage tanks beneath the street ends. During periods of little or no storm runoff, the drainage system would continue to intercept and hold the seepage until the water reached a given level in the tank, at which time a pump would turn on and drain the tank.

Dikes to hold back the sea have long been constructed in Holland where much of the land is beneath the present sea level. Because of its high population density, land reclamation has been economically justified in Holland. It has been a matter of survival. The question remains whether it is economical to protect areas such as Long Beach Island, New Jersey, from a rising sea level. At first, it would be economical since it would only require replacing existing bulkheads with higher, more substantial structures. Bulkheads similar to those now in existence along much of Long Beach Island's bay shoreline would be adequate to protect the land during periods of high spring tides. As existing bulkheads deteriorate, higher bulkheads that also penetrate deeper into the soil would take their place. The cost attributable to sea level rise is only the added cost of building higher, more substantial bulkheads. However, if the rate of sea level rise is so rapid that the bulkheads must be raised or replaced before they reach the end of their useful life, the cost of sea level rise is the value of protection for the remaining lifetime of the bulkhead, which is now no longer adequate to provide protection, plus the added cost of building a new, more substantial bulkhead to replace it. For the present drainage scenario, a substantial concrete sheet pile bulkhead backed by an earth embankment was designed. See Figure 16. The estimated cost per foot of the bulkhead is $500. A sheet pile bulkhead was selected because it can be designed to provide sufficient soil penetration to limit the rate of seepage beneath it. The earth embankment provides lateral stability, and the rubble toe protection prevents scour.

The amount of seepage beneath the sheet pile bulkhead was investigated using a computer program that determines flow patterns beneath a bulkhead and calculates flow rates per unit length of bulkhead into a system of drains on the interior side of the bulkhead. The number and pattern of drains can be selected. Several patterns were investigated. In addition, several depths of penetration for the sheet pile bulkhead were investigated with the computer model. The computed seepage patterns are shown in Figures 17 through 23. Figures 17 and 18 show seepage patterns under a vertical bulkhead for two different depths of soil penetration. Penetration depth is 6 feet in Figure 17 and 10 feet in Figure 18. For a soil permeability of 0.0005 feet per second (typical for sands), the amount of seepage under the wall penetrating 6 feet (Figure 17) is 0.002 cubic feet per second per foot (cfs/ft) of bulkhead. For 10 feet of penetration, the seepage rate is 0.0017 cfs/ft. Figures 19 and 20 show the effect of providing a single drain 4 feet below the ground surface and 4 feet behind the bulkhead, for 6 feet and 10 feet of pile penetration, respectively. The amount of seepage into the drain is 0.00105 cfs/ft, while the total seepage rate under the wall is 0.00363 cfs/ft. Only about 29% of the seepage is intercepted by the drain. Figure 23 shows the configuration finally adopted as typical for a drainage system for Long Beach Island.

Table 17. Summary of Rainfall Frequency Analysis - 24 Hour Rainfall

Recurrence Interval (yrs)	Rainfall Depth (in)	Runoff Depth (in)	Peak * Discharge (cfs)
1	2.8	1.1	7
5	4.5	2.2	33
10	5.5	2.9	44
25	6.0	3.5	53
50	6.6	4.0	60

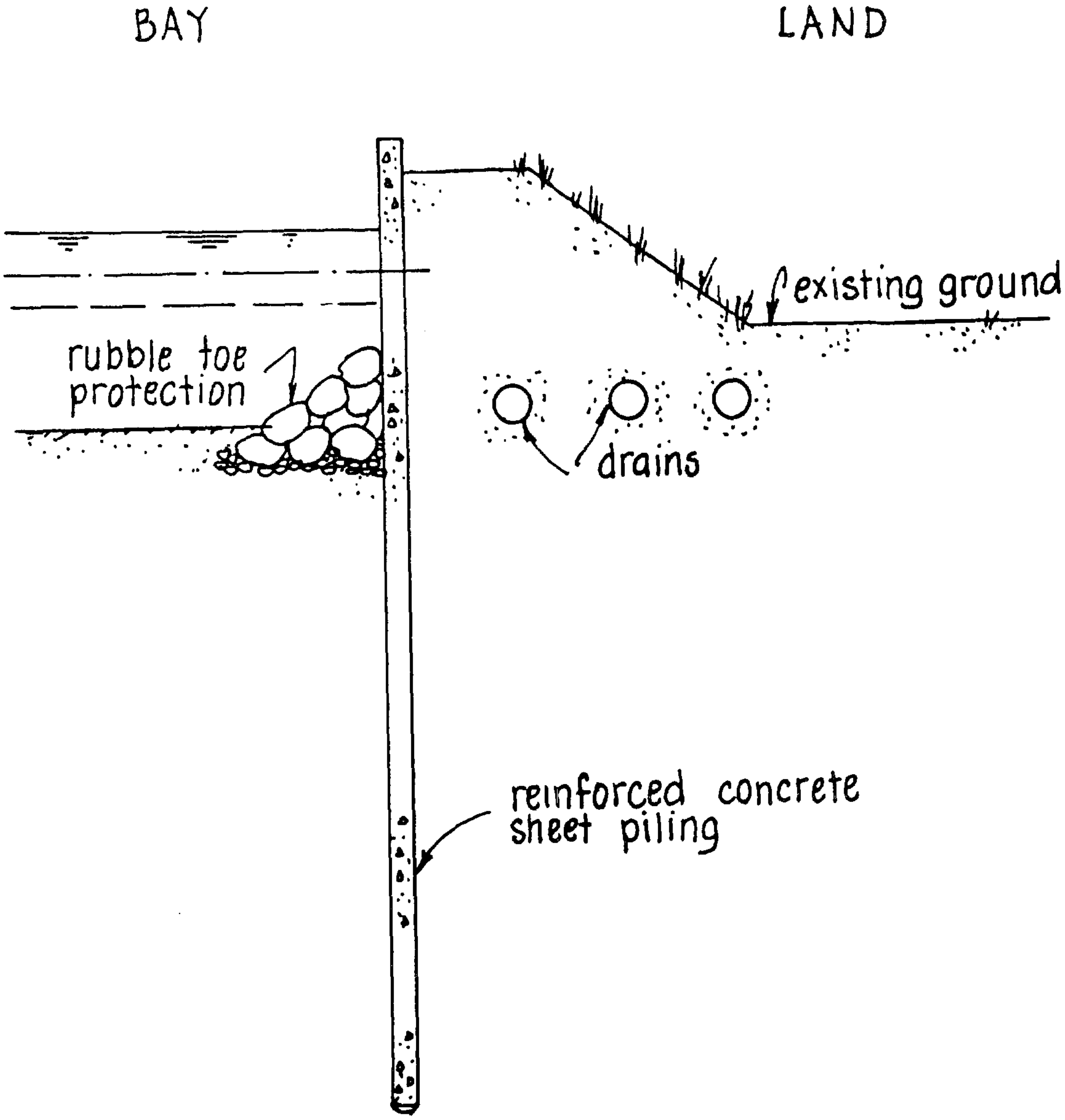
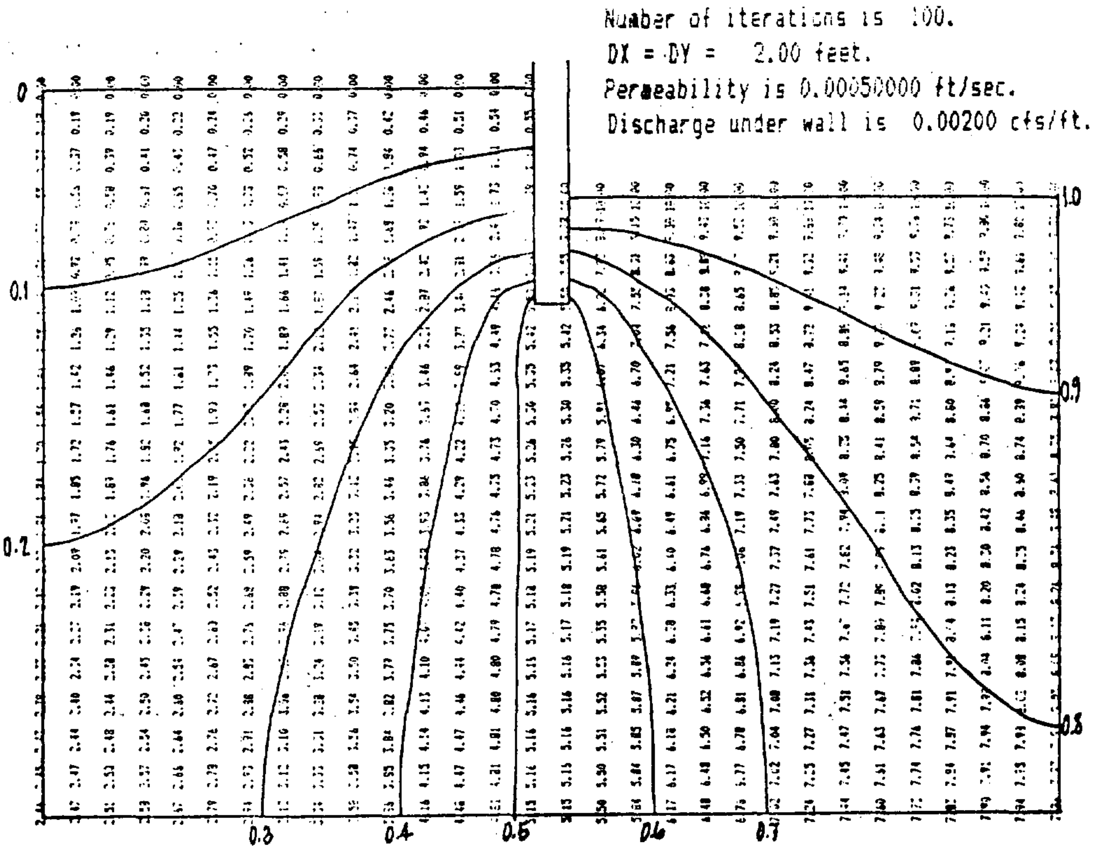
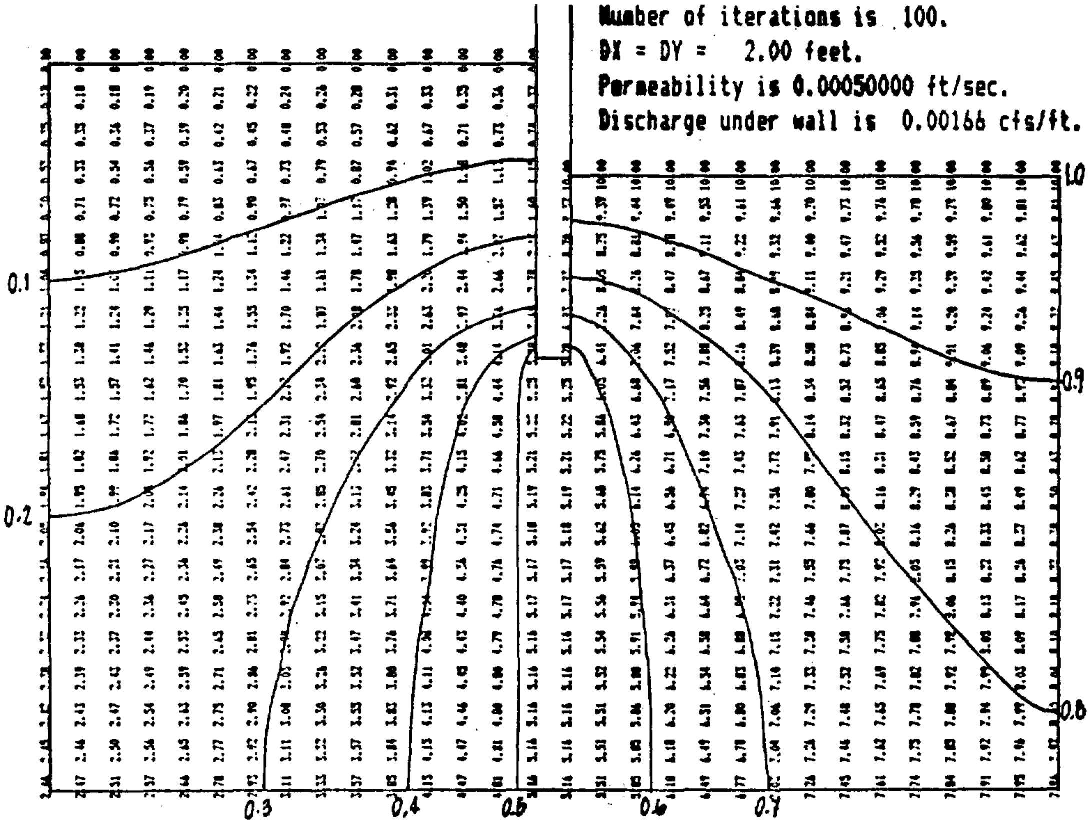


Figure 16 Typical Cross-Section for Concrete Sheet Pile Bulkhead/Dike.



```
Number of iterations is 100.
DX = DY =   2.00 feet.
Permeability is 0.00050000 ft/sec.
Discharge under wall is  0.00200 cfs/ft.
```

Figure 17 Seepage Under Sheet Pile Cutoff Wall - 6 foot Penetration, No Drains.



```
Number of iterations is 100.
DX = DY =   2.00 feet.
Permeability is 0.00050000 ft/sec.
Discharge under wall is  0.00166 cfs/ft.
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Figure 18 Seepage Under Sheet Pile Cutoff Wall - 10 foot Penetration, No Drains.

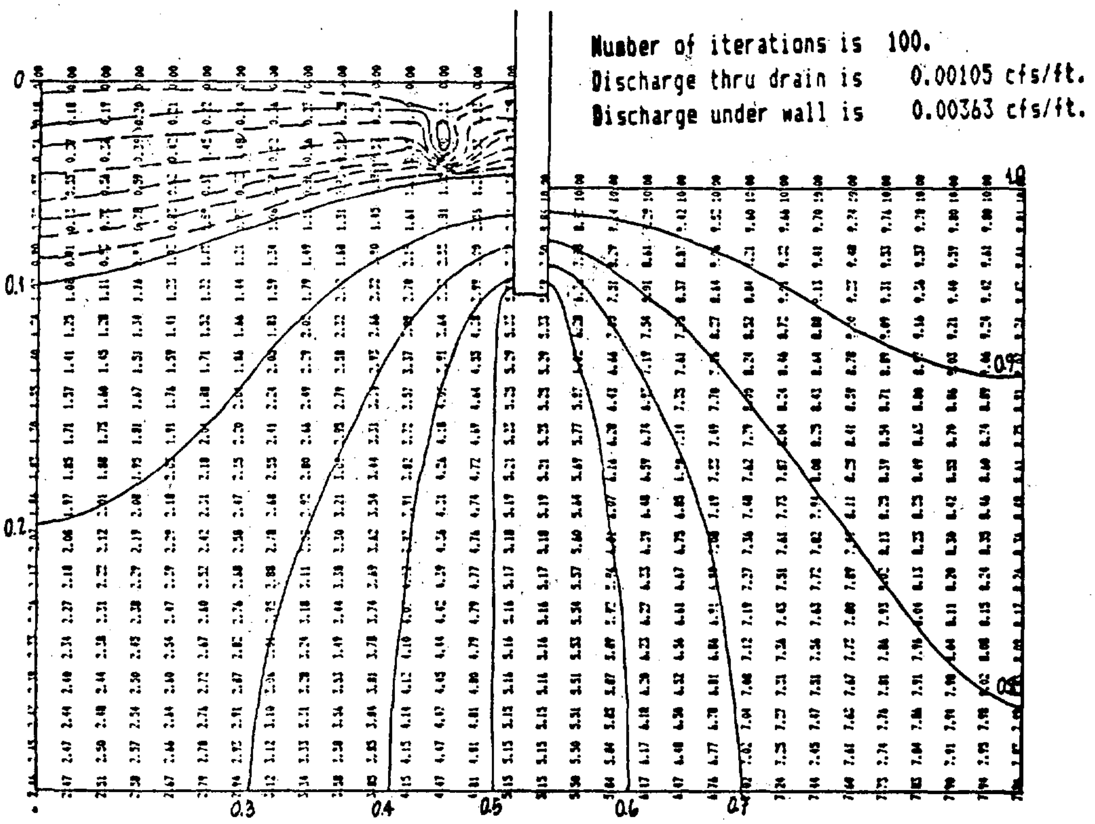


Figure 19 Seepage Under Sheet Pile Cutoff Wall - 6 foot Penetration, One Drain.

Number of iterations is 100.
Discharge thru drain is 0.00072 cfs/ft.
Discharge under wall is 0.00297 cfs/ft.

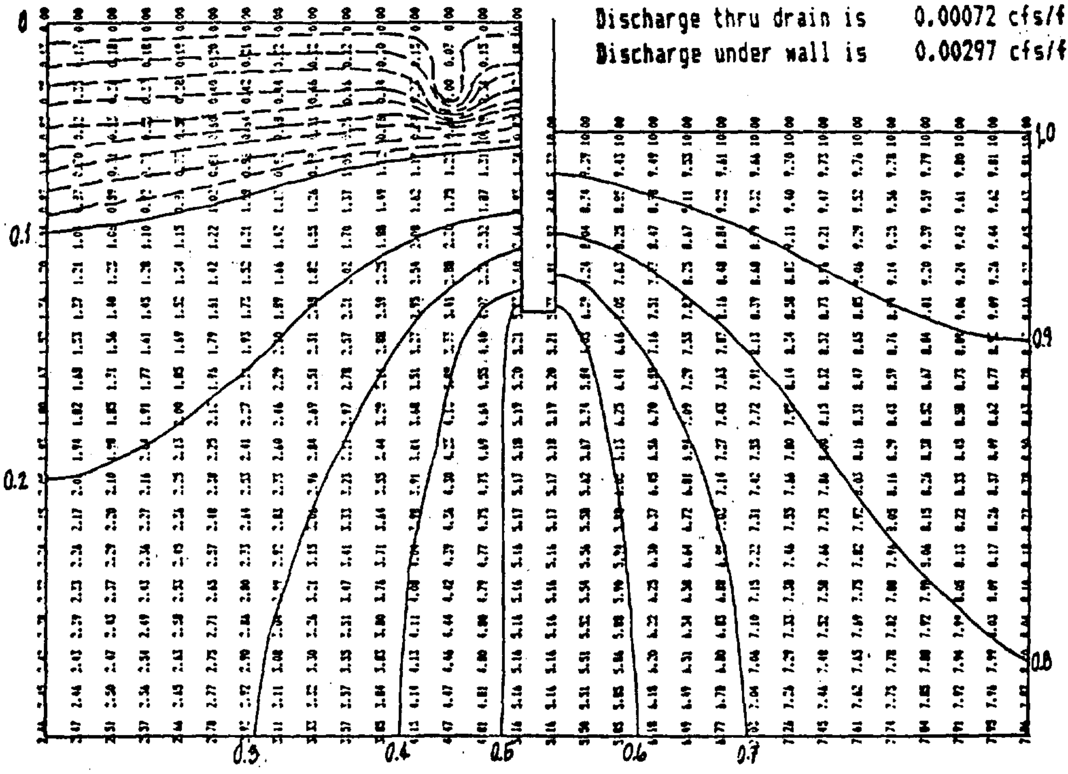
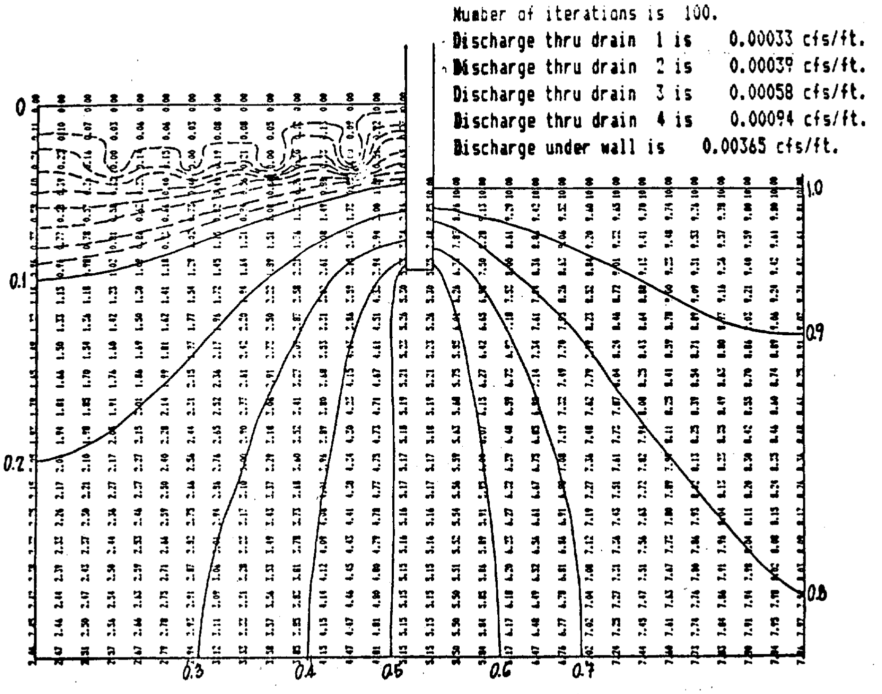
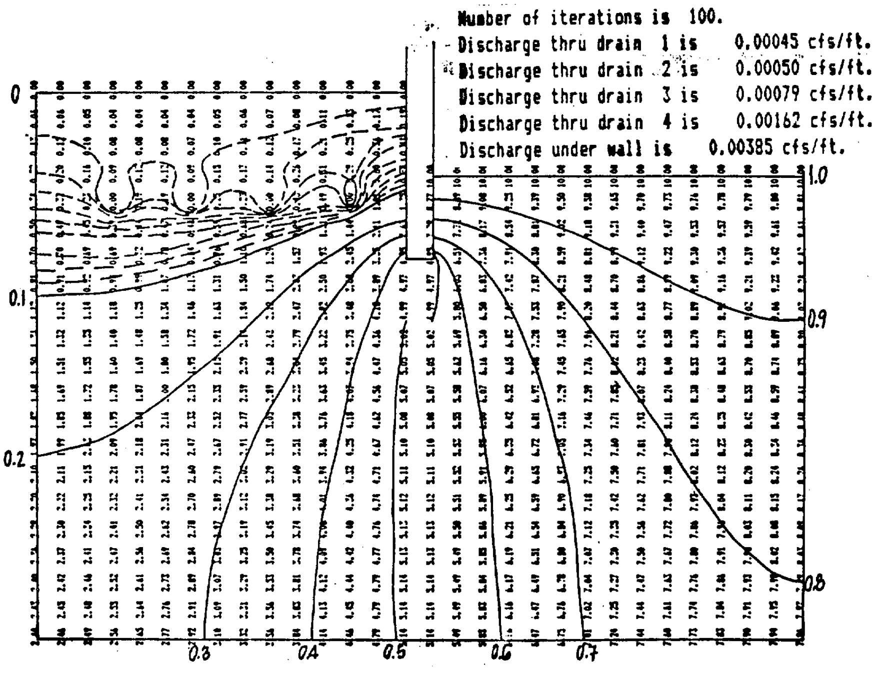


Figure 20 Seepage Under Sheet Pile Cutoff Wall - 10 foot Penetration, One Drain.



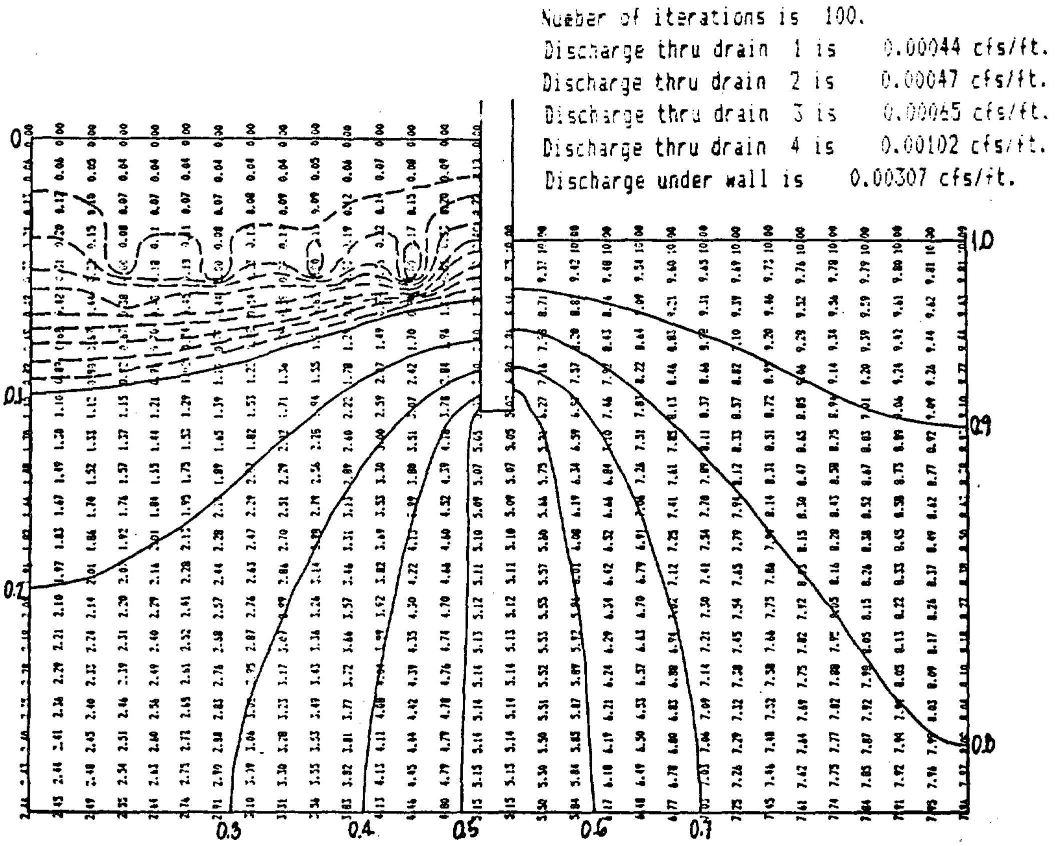
Number of iterations is 100.
Discharge thru drain 1 is 0.00033 cfs/ft.
Discharge thru drain 2 is 0.00039 cfs/ft.
Discharge thru drain 3 is 0.00058 cfs/ft.
Discharge thru drain 4 is 0.00094 cfs/ft.
Discharge under wall is 0.00365 cfs/ft.

Figure 21 Seepage Under Sheet Pile Cutoff Wall - 6 foot Penetration, Four Drains 4 feet Below Ground.



Number of iterations is 100.
Discharge thru drain 1 is 0.00045 cfs/ft.
Discharge thru drain 2 is 0.00050 cfs/ft.
Discharge thru drain 3 is 0.00079 cfs/ft.
Discharge thru drain 4 is 0.00162 cfs/ft.
Discharge under wall is 0.00385 cfs/ft.

Figure 22 Seepage Under Sheet Pile Cutoff Wall - 6 foot Penetration, Four Drains 8 feet Below Ground.



```
Number of iterations is 100.
Discharge thru drain  1 is    0.00044 cfs/ft.
Discharge thru drain  2 is    0.00047 cfs/ft.
Discharge thru drain  3 is    0.00065 cfs/ft.
Discharge thru drain  4 is    0.00102 cfs/ft.
Discharge under wall is    0.00307 cfs/ft.
```

Figure 23 Seepage Under Sheet Pile Cutoff Wall - 10 foot Penetration, Four Drains 8 feet Below Ground.

Drains are located 8 feet below the ground surface, spaced 6 feet apart, with the closest drain about 4 feet behind the bulkhead. The total discharge under the wall is 0.0031 cfs/ft, while the drains intercept a total of 84% of the flow beneath the bulkhead. (Note that the total seepage intercepted by the drains is not 100% because of simplifying assumptions made in the program.) The results of the seepage analysis are summarized in Table 18.

Elements contributing to the cost of implementing this alternative are: a) the construction of new bulkheads along the portion of the shoreline not now bulkheaded; b) the cost of constructing raised bulkheads; c) the cost of the interior drainage system; d) the cost of the storm water detention tanks; e) the cost of the pumps and pumping stations; and f) the cost of electrical power to operate the pumping system.

SUMMARY OF COSTS OF ALTERNATIVES AT LONG BEACH ISLAND

The cost of each of the three assumed alternative actions at Long Beach Island was evaluated. The unit costs assumed in the analysis along with the lifetime of each element are given in Table 19. Fill was assumed to cost about $6.00 per cubic yard. This is an average cost for hydraulically dredged rill obtained from the bay areas and later from offshore sources as nearshore sources are depleted. The drainage system involves Figure costs for the storage facilities, pumps, street and sidewalk replacement, and the drainage pipes. Major elements of the system such as the storage facility were assumed to have a lifetime of 50 years. Other elements, such as the pumps, were assumed to have shorter lifetimes. The $300,000 cost reflects the shorter lifetime of those elements such as pumps, etc., and assumes their replacement over the SO-year lifetime of the entire system.

The costs of the three alternatives investigated for Long Beach Island are summarized in Table 20.

Raising the island in place is estimated to cost $1.36 billion. Most of this cost is associated with replacing roadways, sidewalks, and other above-ground utilities as the island is raised. The cost of fill is estimated at $247 million, and the cost of raising buildings is estimated at $37 million.

Moving the island landward and raising it in response to sea level rise is estimated to cost $7.67 billion. The major cost, that of replacing the infrastructure, is $7.35 billion. This includes replacing all of the buried utilities, a major factor in establishing the higher cost of this alternative when compared with the preceding alternative. The cost of raising and moving houses under this alternative is $74 million. The cost of raising and moving a house is assumed to be twice the cost of simply raising a house. Also, with the replacement of houses by houses elevated on piling over the years, there will probably be fewer houses that will have to be raised at the time the island is raised.

The third alternative, that of providing a dike around the island and providing an interior drainage system, appears to be the least expensive alternative with a total overall cost of $542 million. Most of this cost, $285 million, is associated with the construction of a dike system, assumed to occur in the year 2028. Construction of the interior drainage system and its operation contributes $137 million to the cost. Power was assumed to be available at $0.12 per kWh and the drainage system was assumed to operate for about 1000 hours per year. Each of the nearly 200 storage/pumping systems was assumed to have an overall efficiency of 50% and to pump at the rate of 30 cubic feet per second against a head of 20 feet for the 1000 hours.

Constructing new bulkheads and raising existing bulkheads contributes about $20 million to the cost of this alternative. These costs are incurred between the present and the year 2028, when the bulkheads would be abandoned in favor of a major dike system. The cost of raising bulkheads is discussed below. In general, the only cost included here is the added cost of replacing existing or new bulkheads with higher bulkheads at the end of their useful lifetime.

Table 18. Summary of Seepage Analysis Between Sheet Pile Bulkheads

Case	No. of Drains	Depth of Penetration (ft)	Discharge Under Wall (cfs/ft)	Discharge to Drains (cfs/ft)	Percent Interception
I (Figure 17)	0	6	0.0020	0	0
II (Figure 18)	0	10	0.0017	0	0
III (Figure 19)	1	6	0.0036	0.0011	29
IV (Figure 20)	1	10	0.0030	0.0007	24
V (Figure 21)	4	6	0.0037	0.0022	62
VI (Figure 22)	4	6	0.0039	0.0034	87
VII (Figure 23)	4	10	0.0031	0.0026	84

Table 19. Assumed Unit Costs

Item	Lifetime	Unit Cost
Bulkheads	10 yr	$ 130.00/ft
Fill	–	$ 6.00 cu yd
Dike System	50 yr	$ 500.00/ft
Raising Houses	–	$ 5,000 ea
Raising and Moving Houses	–	$ 10,000 ea
Drainage System (storage tanks, pumps, and drainage pipes)	50 yr	$ 300,000 ea
Infrastructure		
Roadway 2-lane		$ 150.00/ft
Roadway 4-lane		$ 290.00/ft
Sanitary sewer		$ 180.00/ft
Storm sewer		$ 110.00/ft
Water		$ 20.00/ft
Gas		$ 20.00/ft
TOTAL	2-lane	$ 480.00/ft
	4-lane	$ 620.00/ft

Table 20. Summary of Costs of Three Long Beach Island Alternatives

Alternative (Cost Item)	Average Annual Cost *	Cumulative Cost **
Raise Island in Place		
Fill	$ 2.2 million	$ 247 million
Infrastructure (roads only)	9.4 million	1072 million
Raise buildings	0.3 million	37 million
Totals	$ 11.9 million	$1356 million
Raise and Move Island Landward		
Fill	$ 2.2 million	$ 247 million
Infrastructure (roads and buried utilities)	64.5 million	7352 million
Raise and move buildings	0.6 million	74 million
Totals		
Dike Island and Provide Interior Drainage System		
New Bulkheads	0.1 million	12 million
Raise Bulkheads (added cost between the years 1986 and 2028)	0.1 million	8 million
Dike System (constructed in 2028)	2.5 million	285 million
Drainage System	0.5 million	57 million
(system operation)	1.6 million	180 million
Totals	4.8 million	542 million

* Cumulative total cost divided by 114 years. Note, however, that all costs may not extend over the entire 114 year period.

** Total costs incurred between the years 1986 and 2100.

CHAPTER 5

SUMMARY OF ACTIONS AND THE COST OF RESPONDING TO SEA LEVEL RISE AT INDEX SITES

The USGS quads for each of the index sites was studied, and a strategy for responding to a rising sea level was determined for the site. Specifically, the elevation of developed areas was considered, and those areas below + 10 feet NGVD were considered for protection. If a reasonable level of development was present, a dike system to surround the development or to tie it in with high ground was proposed as the. response. The length of the dike required was determined from the map. The unit cost of constructing a dike was assumed to be about $500 per linear foot of dike. If the diked area was isolated, and connected to surrounding high land by roads at a low elevation, the cost of raising the elevation. of the roadway and/or replacing it was included in the cost of responding to sea level rise. In general, a two-lane highway was considered as the connecting link and its cost determined. The unit cost of replacing a two-lane highway was assumed to be $480 per lineal foot. The cost of replacing a four-lane highway was $620 per foot. These figures include the cost of replacing utilities buried beneath the roadway, lighting, and drainage. If the shoreline is already protected by existing bulkheads, the length of the existing bulkhead was determined and consideration given to raising and/or replacing it as sea level rises. The total cost of replacing the bulkhead was, not attributed to sea level rise, but rather an analysis of the cost of replacing the bulkhead with A higher bulkhead was made., That portion of the cost of raising bulkheads attributable to an increase in the mean sea level is made up of two components: the added cost, over and above the bulkhead's replacement cost, of having to build a higher bulkhead at the end of its useful lifetime, and the cost of replacing the bulkhead early because it does not provide sufficient protection against a rising sea level. For the present study, only the former costs are considered, i.e., the bulkhead's design is assumed to adequately consider the projected increase in sea level so that a rise in sea level does not require its early replacement, but rather, deterioration of the materials or some other mode of failure is the cause for its replacement.

The cost of raising bulkheads depends on the initial cost per lineal foot of the bulkhead, its initial height, its useful lifetime (how often it needs to be replaced), and the increase in bulkhead height whenever it needs to be replaced. The required increase in bulkhead height will vary with time, since the rate at which sea level is projected to rise varies with time. Bulkhead costs vary approximately with the LS power of the height. Thus, a cost increase factor was calculated based on the increase in sea level during the bulkhead's lifetime. For example, for a bulkhead with a lifetime of 20 years,. the increase in sea level over 20 years was used to compute the increase in bulkhead height necessary. Obviously, the increase in height depends on what point in time the bulkhead is replaced, since the rate at which sea level is rising is projected to increase. The cost increase factor was defined as the increased bulkhead height divided by its original height raised to the 1.5 power. The cost increase factor multiplied by the initial bulkhead cost (1986 dollars) gives the new bulkhead cost (1986 dollars). The length of bulkhead to be replaced each year was taken to be the total bulkhead length divided by the bulkhead's lifetime.

Assuming an initial bulkhead height of 5 feet, replacement every 10 years, and an initial cost of $130.00 per foot, the added cost per foot of bulkhead per year averaged over the 114-year period between 1986 and 2100 is about $1.60. This will be lower during the early years of the 114-year period but will be higher toward the end of the next century. The total cost for the time period extending to the year 2100 will be the total bulkhead length requif ed times the increased cost per foot per year times 114 years. For 1 mile of bulkhead, this amounts to expending more than $1.2 million just to replace existing bulkheads at the end of their lifetime with the required higher bulkheads.

For areas that are presently unbulkheaded, consideration- was given to the need for new, additional bulkheading to protect vulnerable, low-lying areas. New bulkheading was assumed to cost $130 per lineal foot. This represents the present (1988) cost of aluminum sheet piling about 13 feet long with a concrete cap and anchors.

For buildings located in sparsely developed areas where construction of a dike system would not be economical, consideration was given to moving individual structures to higher ground. Again, not all structures would be moved under such circumstances. The decision to move a structure would depend on its value, its condition, its movability, and the availability of high land within a reasonable distance to which the structure could be moved. It was assumed that about one-half of the buildings identified on the USGS quads would be moved. That is, half of the isolated buildings were considered to be candidates for moving; however, the number of buildings shown on the undeveloped (unshaded) areas of the USGS quads may not be representative of the actual number of buildings present because of development that may have occurred since the time the quads were last corrected. Therefore, the number of buildings on the quads was used to estimate the cost of moving structures. The unit cost of moving a structure was assumed to be about $10,000 based on recent costs to move a 1000.square foot house a distance of about 1/2 mile. This figure includes the cost of preparing a new, simple foundation system (simple footings or concrete slab). Obviously, larger structures and moves of more than 1/2 mile would increase this cost.

The summary of actions that might be taken at each of the index sites is given in Table 21.

COST OF RESPONDING TO SEA LEVEL RISE AT INDEX SITES

The costs of responding to sea level rise at the six index sites are given in Table 22. The costs in the table are the total costs that would be incurred during the 114-year period between 1986 and 2100, which are attributable just to the increase in sea level. Structure replacement costs that would be incurred if sea level remained at its present level have been subtracted. Where bulkheads are already present or are needed to respond to higher sea levels,. the cost of replacing them with higher bulkheads at the end of their useful lifetime overshadows most of the other costs considered. The cost for the New York index site is $275 million, with $205 million of that attributable to raising the existing and proposed bulkheads. Where bulkheading is not considered to be practical because of low levels of economic development, the costs are significantly less. For example, at Dividing Creek, New Jersey, only 6.1 miles of new bulkheading appear justified and the cost is only $5.8 million, most of it associated with raising 7.2 miles of highway. The Long Beach Island area cost figures on Table 22 are given for both the mainland behind the barrier island and for the island and mainland combined. Note that the cost of raising the roads on Long Beach Island are not included.

USGS TOPOGRAPHIC DATA ANALYSIS - INDEX SITES

In order to extrapolate the results from the six index sites to a sub-set of the sites investigated by Park et al. (this volume), the topographic and economic development conditions at the six index sites were compared with the conditions at Park's sites. These comparisons were subsequently used to determine the cost of responding to sea level rise at Park's sites. Topography digitized from USGS quads (Park et al., this volume) was used to determine the distribution of land elevations and shoreline lengths at the six index sites. For most of the sites, a spatial matrix of ground elevations averaged over a 500- by 500-meter pixel was available. For the New York and Corpus Christi areas, elevations were averaged over a 250- by 250-meter pixel. A histogram of the distribution of elevations was determined by summing the number of pixels having an elevation within a given elevation interval. For the land elevation histograms, 10 intervals of 1 foot each between elevations 0 and 10 feet NGVD were selected for the analysis. In addition, the number of pixels with elevations above the 10-foot elevation and the total number of pixels with elevation above 0 feet NGVD were determined. In addition, a simple algorithm was developed to estimate the shoreline lengths for each of the index sites. The length of the shoreline was determined using an algorithm that sweeps the elevation matrix two columns at a time and two rows at a time and assigns a shoreline length to the resulting four-pixel pattern, depending on the number of pixels with elevations above zero. If all four pixels are above 0 or below 0, no shoreline length is assigned. It one or three pixels are at 0 or below, the shoreline length assigned is 1.414 times the length of the side of a pixel. If two pixels are at 0 elevation or below, the length of shoreline assigned is either 1.0 times the length of a side or 2.828 times the length of side, depending on the pattern of land and water pixels. If the land pixels are diagonally opposed, the shoreline length factor is 2.828, while if the land pixels are adjacent to one another, the shoreline length factor is 1.0. Because of the coarse size of the pixels (500 meters x 500 meters), in most cases, the algorithm underestimates the length of the actual shoreline, since small variations in the actual shoreline are replaced by straight line segments. For engineering purposes, the estimate is probably sufficient since erosion/flood control structures such as bulkheads are constructed in straight-line segments to minimize their length rather than along the lines of a tortuous shoreline. A correlation between shoreline lengths determined from the digitized data and shoreline lengths found from planimetering the USGS quads is shown in Figure 24. The index site corresponding to each point is indicated on the figure. The data are scattered about the 45 degree line of equality.

Table 21. Summary of Actions Required as Sea Level Rises at Index Sites

Index Site and USGS Quad	New Bulk. (mi)	Raise Exist. Bulkhead (mi)	Buildings to Move (#)	Highway to Raise (mi)
New York, NY Area				
Weehawken	29.50	21.32	21	2.89
Arthur Kill	5.93	4.03	27	–
Brooklyn	2.28	14.91	–	–
The Narrows	6.69	3.50	–	–
Jersey City	11.25	58.89	–	–
Elizabeth	9.92	–	–	–
Central Park	17.52	30.19	–	–
Subtotal	83.09	132.84	48	2.89
Long Beach Island, NJ Area				
Ship Bottom *	0.67	–	139	1.49
Tuckerton *	3.73	–	135	–
Long Beach NE *	–	–	–	–
Beach Haven *	–	–	–	–
Subtotal	4.40	–	274	1.49
* Excludes Long Beach itself.				
Miami, FL Area				
North Miami	12.83	22.37	–	2.54
Miami	2.83	79.06	27	–
Subtotal	15.66	101.43	27	2.54
Corpus Christi, TX Area				
Oso Creek NE	15.86	9.10	82 **	5.97
Portland	–	–	8	3.73
Crane Island NW	–	2.39	83	2.24
Port Ingleside	–	2.98	111	4.18
Subtotal	15.86	14.47	284	16.12
** Includes trailer park structures				
San Francisco, CA Area				
Redwood Point	0.89	–	83	1.49
Newark	0.60	6.56	28	2.53
Palo Alto	0.89	6.41	8	1.34
Mountain View	1.49	3.43	84	0.75
Subtotal	3.87	16.40	203	6.11
Totals	113.32	265.14	1287	36.31

Table 22. Costs Associated With Sea Level Rise at Index Sites.

New York Area, NY & NJ			
New Bulkheads	83.1 mi		$ 57.0 million
Raise Bulkheads	215.9 mi		205.3 million
Move Buildings	48		0.5 million
Raise Highways	2.9 mi		9.5 million
		Total	$ 272.3 million
Long Beach Island Area, NJ (Mainland only)			
New Bulkheads	4.4 mi		$ 3.0 million
Raise Bulkheads	4.4 mi		4.2 million
Move Buildings	270		2.7 million
Raise Highways	1.5 mi		3.8 million
		Total	$ 13.7 million
Long Beach Island Area, NJ (Mainland and bulkheading on back side of island)			
New Bulkheads	17.2 mi		$ 11.9 million
Raise Bulkheads	36.7 mi		35.0 million
Move Buildings	270		2.7 million
Raise Highways	1.5 mi		3.8 million
		Total	$ 53.4 million
Dividing Creek Area, NJ			
New Bulkheads	6.1 mi		$ 4.2 million
Raise Bulkheads	6.1 mi		5.8 million
Move Buildings	478		4.8 million
Raise Highways	7.2 mi		18.2 million
		Total	$ 33.0 million
Miami and Miami Beach Area, FL			
New Bulkheads	15.7 mi		$10.8 million
Raise Bulkheads	117.1 mi		111.3 million
Move Buildings	27		0.3 million
Raise Highways	2.5 mi		8.3 million
		Total	$ 130.7 million
Corpus Christi Area, TX			
New Bulkheads	15.9 mi		$ 10.9 million
Raise Bulkheads	30.3 mi		28.8 million
Move Buildings	284		2.8 million
Raise Highways	16.1 mi		40.9 million
		Total	$ 83.4 million
San Francisco Bay Area, CA			
New Bulkheads	3.9 mi		$ 2.7 million
Raise Bulkheads	20.3 mi		19.3 million
Move Buildings	203		2.0 million
Raise Highways	6.1 mi		20.0 million
		Total	$ 44.0 million

Table 23 provides topographic information on the six index sites where the overall distribution of ground level elevations is given. These data were determined by planimetering the USGS quads. Table 24 provides topographic, shoreline length, and the slope of the land below given elevations as determined from the quads, while Table 25 provides similar data as determined from the digitized topographic data. Shoreline lengths obtained from the digitized topographic data analysis are given in Table 26 for the six index sites as well as for 18 additional coastal locations around the U.S.

Table 23. Summary of Index Site Topographic Conditions
(Based on Total Land Area)

Elevation (ft)	Z<5	Z<10	Z<15	Z<20	Z<25	Z<30	Z<35	Z<40	Total
Long Beach Island, NJ Area									
USGS Area Below Elevation	22.5	36.5	–	42.6	–	45.9	45.9	45.9	45.9
USGS % Below Elevation	49.1	79.4	–	92.8	–	100.0	100.0	100.0	100.0
Digitized USGS % Below Elevation	51.0	61.6	76.8	77.1	78.4	78.7	78.7	78.7	100.0
Dividing Creek, NJ Area									
USGS Area Below Elevation	48.2	72.6	–	87.3	–	94.1	94.1	94.1	94.1
USGS % Below Elevation	55.2	83.2	–	92.8	–	100.0	100.0	100.0	100.0
Digitized USGS % Below Elevation	35.6	49.3	98.7	99.0	99.4	99.6	99.7	99.8	100.0
Miami, FL Area									
USGS Area Below Elevation	22.6	78.5	107.2	109.1	109.1	109.1	109.1	109.1	109.1
USGS % Below Elevation	20.7	71.9	98.3	100.0	100.0	100.0	100.0	100.0	100.0
Digitized USGS % Below Elevation	29.7	67.9	99.7	100.0	100.0	100.0	100.0	100.0	100.0
Corpus Christi Area, TX									
USGS Area Below Elevation	14.1	25.5	42.8	68.9	90.7	109.5	157.2	157.2	157.2
USGS % Below Elevation	20.5	37.0	62.1	100.0	100.0	100.0	100.0	100.0	100.0
Digitized USGS % Below Elevation	33.1	44.0	89.7	94.6	97.0	97.1	97.4	97.4	100.0
New York, NY Area									
USGS Area Below Elevation	–	78.1	–	122.7	–	148.8	148.8	148.8	178.5
USGS % Below Elevation	–	52.5	–	82.5	–	100.0	100.0	100.0	100.0
Digitized USGS % Below Elevation	23.0	31.4	87.8	89.1	90.1	90.2	90.5	90.5	100.0
San Francisco, CA Area									
USGS Area Below Elevation	57.7	68.1	–	83.6	–	94.4	–	–	94.4
USGS % Below Elevation	61.1	72.1	–	88.5	–	100.0	100.0	100.0	100.0
Digitized USGS % Below Elevation	20.7	25.1	85.7	86.3	86.6	86.8	87.0	87.1	100.0

Table 24. Average Ground Slope Near Shoreline
(Based on data obtained from USGS quads)

Index Site	Area Below Given Elevation (sq mi)		Shoreline length (mi)	Slope of Land Below Given Elevation	
	<5 ft	<10 ft		<5 ft	<10 ft
New York	–	78.14	220.7	–	0.0054
Long Beach Island	22.55	36.46	109.8	0.0046	0.0057
Dividing Creek	48.19	72.58	97.0	0.0019	0.0025
Miami	22.60	78.48	141.4	0.0059	0.0034
Corpus Christi	14.14	25.46	189.0	0.0127	0.0141
San Francisco	57.67	70.54	42.4	0.0007	0.0011

Table 24. Average Ground Slope Near Shoreline
(Based on digitized USGS topo data)

Index Site	Area Below Given Elevation (sq mi)		Shoreline length (mi)	Slope of Land Below Given Elevation	
	<5 ft	<10 ft		<5 ft	<10 ft
New York	43.04	58.70	333.4	0.0073	0.0108
Long Beach Island	18.73	22.59	77.4	0.0039	0.0065
Dividing Creek	46.80	64.81	122.3	0.0025	0.0036
Miami	32.91	75.24	119.4	0.0034	0.0030
Corpus Christi	26.18	34.83	130.1	0.0047	0.0071
San Francisco	17.32	20.98	175.1	0.0096	0.0158

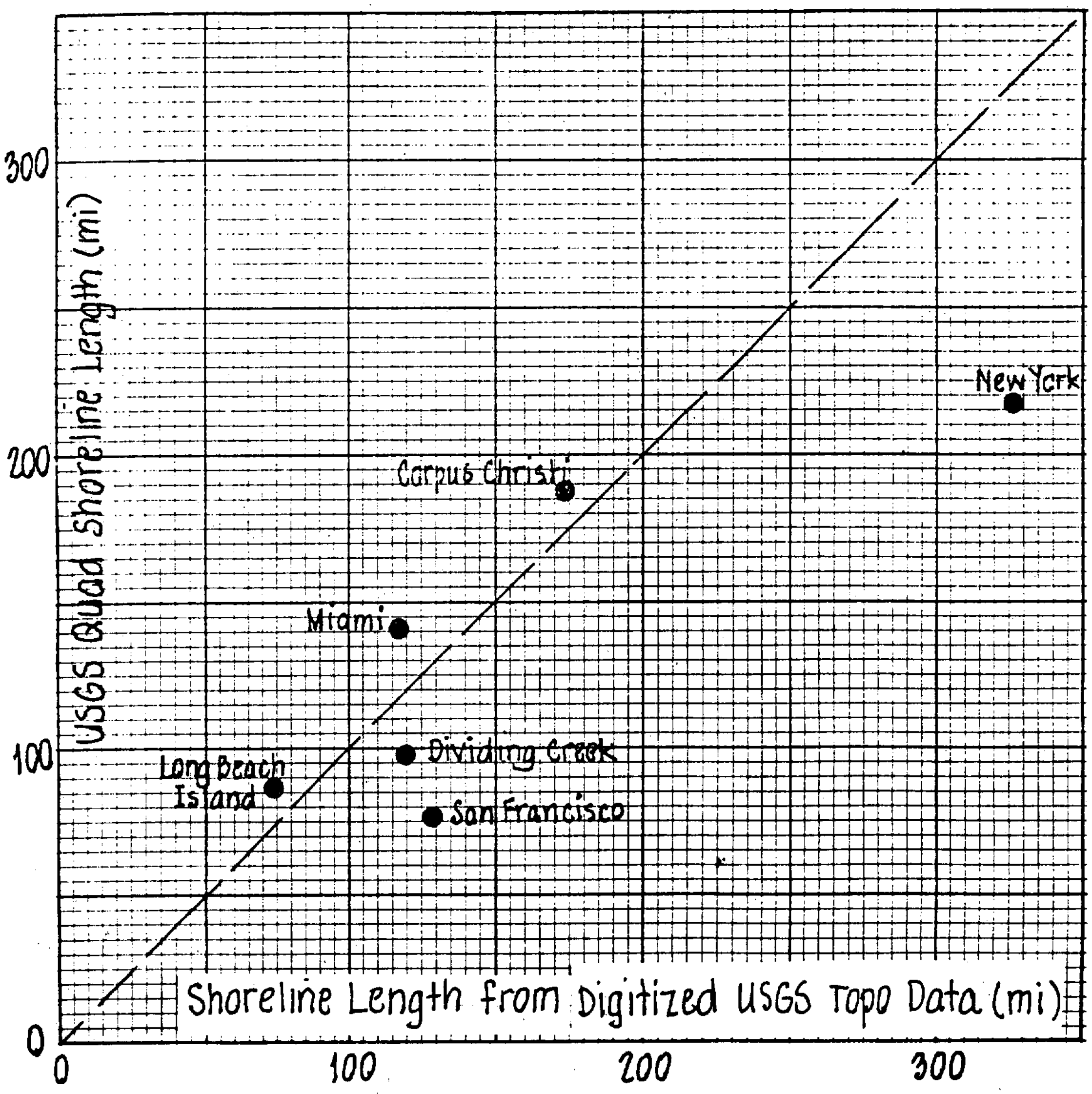


Figure 24 Correlation Between Shoreline Lengths Measured from USGS Quads and Shoreline Lengths Obtained from Digitized USGS Topographic Data.

Table 28. Summary of Coastal Site Shoreline Lengths and Areas

Site Abbrev.	Shoreline Length (mi)	Area (sq mi)		Devel.
		<5 ft	<10 ft	
MEFREEPO	141.9	22.1	24.1	1.0
MEROCKLA	75.2	10.5	12.2	0.6
MEJONESP	183.2	38.1	39.6	0.4
MAMARBLE	57.2	4.1	22.3	1.5
MAWESTPO	121.2	15.8	22.3	1.5
MAORLEAN	144.4	37.9	42.8	24.8
RIWATCHH	106.9	12.2	17.8	1.6
CNBRIDGE	66.8	12.7	23.4	12.4
* NYBROOKL	333.4	43.0	58.7	52.0
NYNARROW	252.0	15.0	41.5	15.0
NYPATCHO	85.3	12.6	17.0	5.1
NYSOUTHA	184.6	11.0	20.5	2.0
* NJDIVIDC	122.3	46.9	64.9	3.0
NJLONGBE	77.4	18.7	22.6	2.3
DEREHOBA	99.1	11.0	18.9	1.2
MDEASTON	73.2	11.0	20.8	0.5
MDCOVEPT	9.6	0.2	0.2	0.0
MDELKTON	53.2	4.5	6.3	0.1
MDMIDDLE	108.1	4.9	10.2	0.2
VACOLBEA	252.0	15.2	41.8	–
VABLOXOM	81.5	28.9	33.4	0.0
VANEWPOR	143.0	27.7	49.2	9.3
VAWILTON	170.4	24.8	50.2	1.6
NCENGELH	85.1	169.4	190.1	1.1
NCWILMIN	150.1	32.0	44.0	27.3
NCLONGBA	159.1	66.1	95.8	2.2
NCCAMPLE	115.7	23.2	30.0	1.4
SCHILTON	233.8	83.4	103.6	9.9

Site Abbrev.	Shoreline Length (mi)	Area (sq mi)		Devel.
		<5 ft	<10 ft	
SCCHARLE	164.5	74.3	109.2	12.2
SCBROOKG	87.2	63.6	72.4	1.6
GASEAISL	145.8	49.2	55.9	1.1
FLLOSTMA	182.5	187.1	184.1	0.0
FLCARDSO	93.9	84.8	85.5	0.1
FLFTGADS	130.4	99.5	141.5	0.7
FLAPALAC	96.7	21.9	34.0	1.9
* FLMIAMI	119.4	32.9	75.2	46.3
FLVENICE	50.2	4.2	10.1	1.9
FLSTAUGU	91.9	26.0	41.9	5.9
FLEVERGL	215.9	204.2	204.2	1.0
FLCAPECA	159.1	36.8	70.2	54.4
FLSNIPEI	51.5	37.5	72.3	0.0
FLKEYWES	** 33.6	3.4	5.0	0.0
FLHOLLEY	114.6	19.4	28.1	0.6
FLFORTMY	63.1	31.6	75.1	12.3
FLPORTRI	0.1	0.0	0.0	0.0
FLSTJOSE	89.6	12.3	27.6	0.0
ALGRANDI	60.3	24.3	35.0	0.6
MSPASSCH	62.0	10.2	13.4	1.0
MSGULFPO	29.6	6.6	11.4	1.6
LALULING	186.7	160.4	176.4	20.0
LABARATA	236.7	141.0	141.1	1.5
LAGOLDME	279.6	201.1	201.1	2.2
LABELLEC	354.3	174.6	177.3	7.9
LACAMERO	262.8	116.1	122.3	2.1
LAPONCHA	70.9	86.1	92.4	2.9
LASULPHU	99.4	92.6	139.4	5.3
LALMISER	120.7	–	212.6	2.1
LAGRANDC	202.5	170.1	170.6	1.2
LAPELICA	202.4	66.5	66.5	0.1
LAMAINPA	229.0	50.8	50.8	0.0
TXALLIGA	186.2	148.3	194.1	0.2
TXGREENI	114.4	80.1	89.4	0.0

	Site Abbrev.		Shoreline Length (mi)	Area (sq mi)		Devel.
				<5 ft	<10 ft	
*	TXPORTLA		175.1	26.2	34.8	6.0
	TXPALACI		141.8	38.9	66.2	0.5
	TXRIVER		112.0	33.5	77.2	0.0
	TXSMITHP		109.6	46.0	55.6	1.3
	TXTIVOLI		137.4	42.7	77.5	1.4
	CABENICI	**	358.7	52.2	56.8	6.3
	CAANONUE		57.3	3.8	4.0	0.0
	CASANQUE	**	130.1	17.3	21.0	9.0
	CAOCEANS	**	28.9	0.8	1.6	0.1
	CAPTSAL	**	27.1	0.6	0.6	0.0
*	CAPALOAL		133.6	84.6	98.7	17.8
	CAALBION		34.2	0.0	0.0	0.0
	CAFERNDA		85.9	12.5	40.0	0.8
	CATIJUAN		72.6	150.1	157.9	68.9
	CAPTMUGU		64.0	39.8	60.3	0.0
	ORPORTOR		51.0	1.5	1.93	0.3
	ORYAQUIN		109.6	0.3	0.6	0.1
	WAANACOR		105.9	6.5	7.0	0.4
	WAGARDNI		90.1	2.4	3.0	0.3
	WANEMAH		158.8	51.4	54.5	4.1
	WAPORTGA		83.8	6.6	7.6	1.7
	WATACOMA		115.7	2.5	4.0	0.7

* Denotes Site Index
** Denotes Fine Grid Data (250 m x 250 m)

CHAPTER 6

EXTRAPOLATION OF COSTS TO INCLUDE THE SHELTERED SHORELINES OF THE U.S.

A regression analysis was made using the costs of responding to sea level rise at the six index sites in order to determine the costs at 78 other coastal sites for which digitized topographic data were available (Park et al., this volume). These 84 sites comprise about 13.6% of the U.S. shoreline. The regression analysis developed equations for the amount of new bulkheading required, the amount of bulkheading that will be needed to respond to sea level rise in the years between the present and the year 2100, the number of buildings to be moved, and the number of miles of highway that would have to be raised to provide access to nearshore areas. These variables were related to topographic and development variables such as the percentage of the land below the + 5-foot NGVD contour that is economically developed, and the average slope of the land below the + 5- foot contour.

The percentage of the shoreline's length that is bulkheaded correlated with the percentage of the land below the + 5-foot contour that is economically developed and with the average land slope below the + 5-foot contour (see Figure 25). For steep land slopes (SQ, the slope of the line on the figure (Sl) is lower. For flatter nearshore slopes (lower SQ, S1 is greater. (The slope of the land is defined here as,,the +5-foot elevation divided by the average distance between the + 5-foot contour and the shoreline. The average distance of the + S-foot contour from the shoreline is equal to the land area below + 5 feet divided by the shoreline length.) Similarly, the length of bulkheading to be raised in response to sea level rise was also related to the percentage of land below + 5 feet that is economically developed and the average land slope (see Figure 26). Again, the slopes of the lines on the figure (S2) were found to be a function of the land slope below the + 5-foot contour (SL). The relationship between the slopes of the lines on Figures 25 and 26 and the nearshore land slope is shown.in Figure 27. The slopes of the lines on the figures vary almost linearly with SL. The equation is,

$$B\% = S1\ (\%AD5) \qquad (12)$$

in which B% is the percentage of the shoreline that is presently bulkheaded, S1 is the slope of the line in Figure 25 and %AD5 is the percentage of land below the + S foot contour that is economically developed. Similarly,

$$R\% = S2\ (\%AD5) \qquad (13)$$

in which R% is the percentage of the shoreline length that will be bulkheaded by the year 2100 due to sea level rise, i.e., the amount of bulkheading that will have to be raised in order to provide continued protection because of rising sea level. S2 is the slope of the lines in Figure 26. The slopes S1 and S2 are related to the land slope near shore by the relationships,

$$S1 = -146.8\ SL + 1.85 \qquad (14)$$

and

$$S2 = -167.6\ SL + 2.20 \qquad (15)$$

See Figure 27. The length of new bulkheading that will be needed is simply the amount that will eventually be needed (the amount that would have to be raised), R%, minus the amount that is presently there, B%.

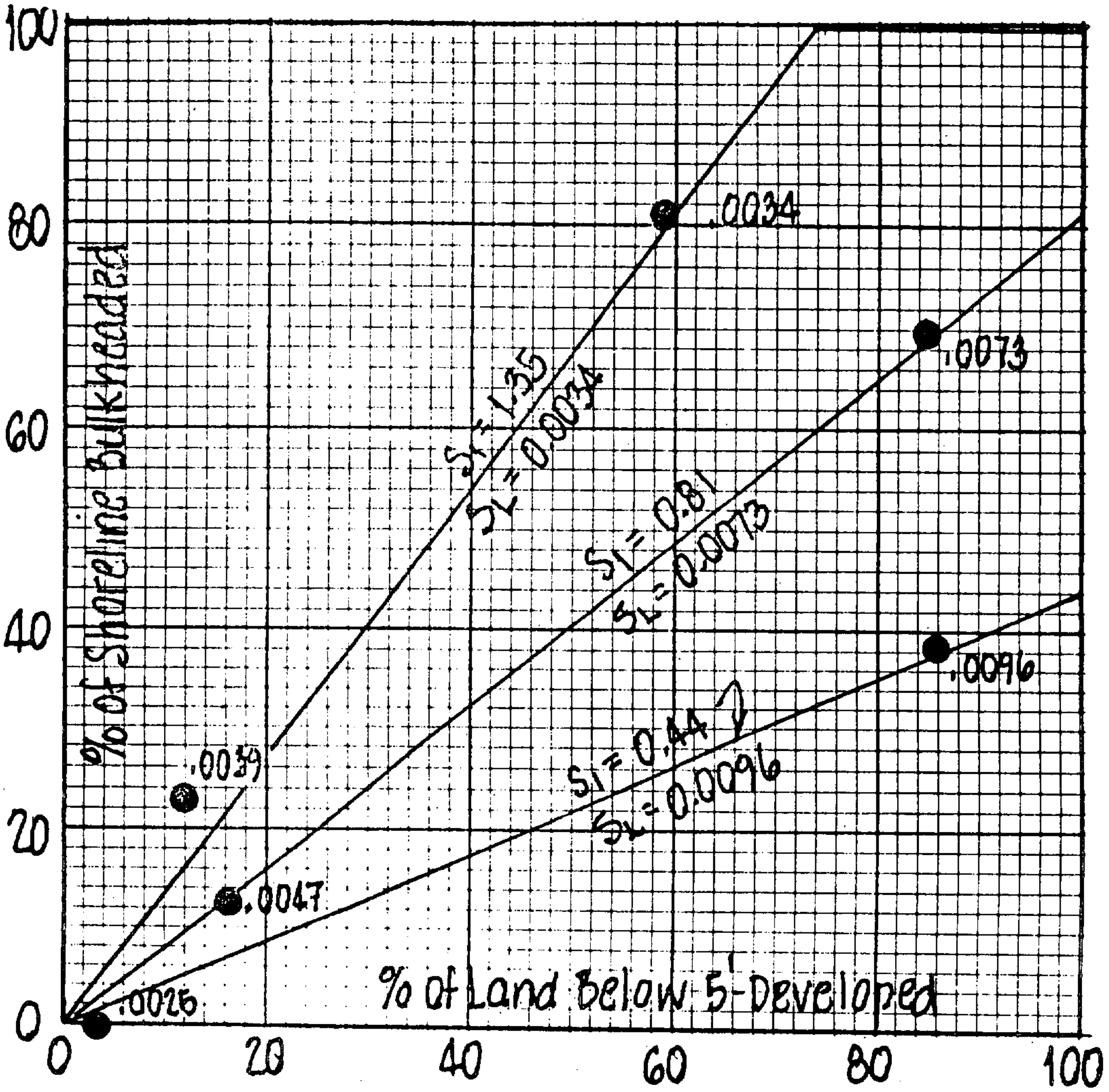


Figure 25 Correlation Between % of Shoreline Bulkheaded and % of Land Below +5 feet that is Developed and Slope of Land Near Shore.

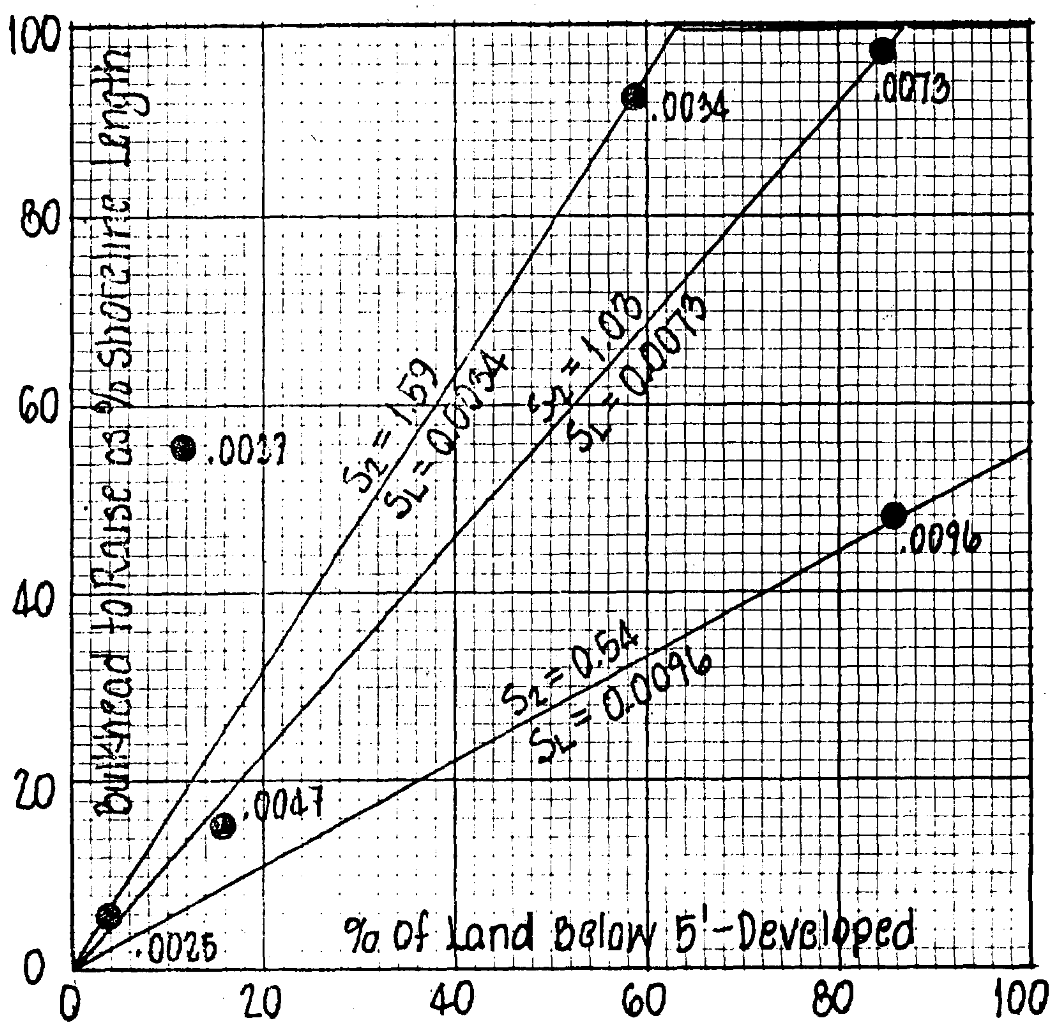


Figure 26 Correlation Between Amount of Bulkheading to be Raised as a % of Shoreline Length and % of Land Below +5 feet that is Developed and Slope of Land Near Shore.

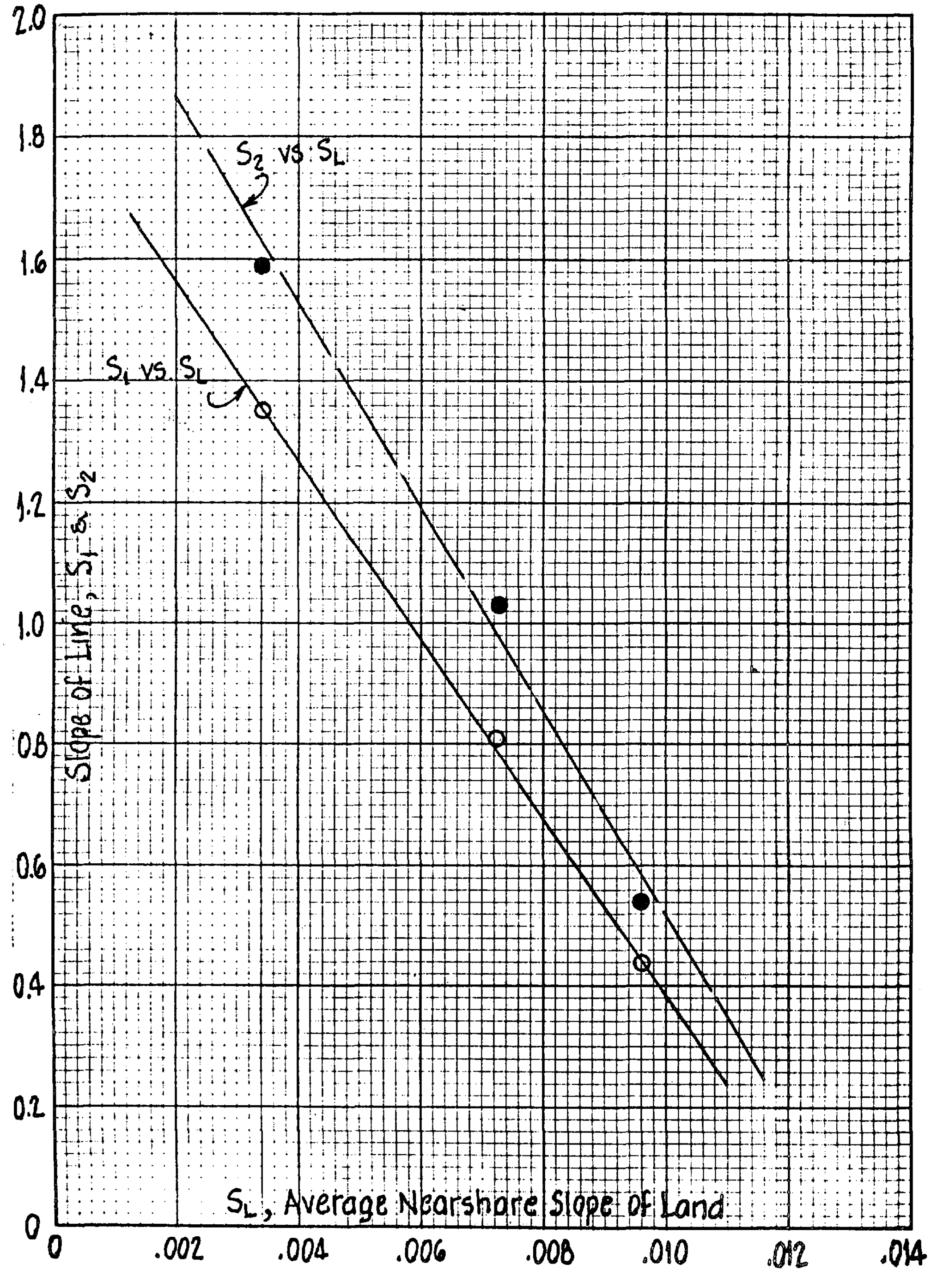


Figure 27 Relationships for Slopes of Regression Lines for Bulkheading Variables and Slope of Land Near Shore.

The number of houses that are candidates for moving was related to the percent of the shoreline that is presently bulkheaded by the relationship shown in Figure 28. The number of houses is given by,

$$N = 0.04762\ B\%^2 - 9.762\ B\% + 500 \qquad (16)$$

N can be determined by first determining B% from equation 12 and then using equation 16.

No satisfactory expression could be established to determine the number of miles of highways that would have to be raised or relocated. To estimate the costs of highway relocation, the number of miles was simply expressed as a fraction of the developed land area below + 5 feet in elevation. Thus,

$$LH = 0.45\ AD5 \qquad (17)$$

in which LH is the length, in miles, of highways that have to be replaced and ADS is the area, in square miles, of developed land below + 5 feet +in elevation.

Costs were estimated for constructing new bulkheads, for periodically raising the existing and new bulkheads, for moving houses, and for raising/relocating highways in low-lying areas. Costs were estimated in the same way as they were estimated for the index sites. The results of the analysis are given in Table 27.

The numbers in parentheses in Table 27 are the numbers of miles of new and total bulkheading, the number of buildings to be moved, and the number of miles of highways to be raised or relocated, respectively. For the 84 sites for which shoreline lengths and developed areas were determined, the total cost of responding to sea level rise is about $3.36 billion. This is the low estimate with the cost of bulkheading/diking at $130.00 per foot. If this cost is increased to $500.00 per foot, the cost of responding to sea level rise increases to $10.8 billion (see Table 28). Since these 84 sites represent 13.6 of the U.S. sheltered shorelines, the low estimate for the entire U.S. shoreline is $24.6 billion, while the high estimate is $80.2 billion. These figures are obviously biased because of the@ characteristics of the 84 coastal sites on which the extrapolation is based. The sites favor the rural, little-developed southeastern U.S. coastal regions while ignoring the heavily developed Northeastern States and the Pacific Northwest. While several heavily developed areas such as the New York metropolitan area, the Miami/Miami Beach area, and the San Francisco Bay area have been included in the present analysis, a more representative sample of coastal sites would probably provide significantly higher cost estimates. The costs are summarized by coastal region in Table 29.

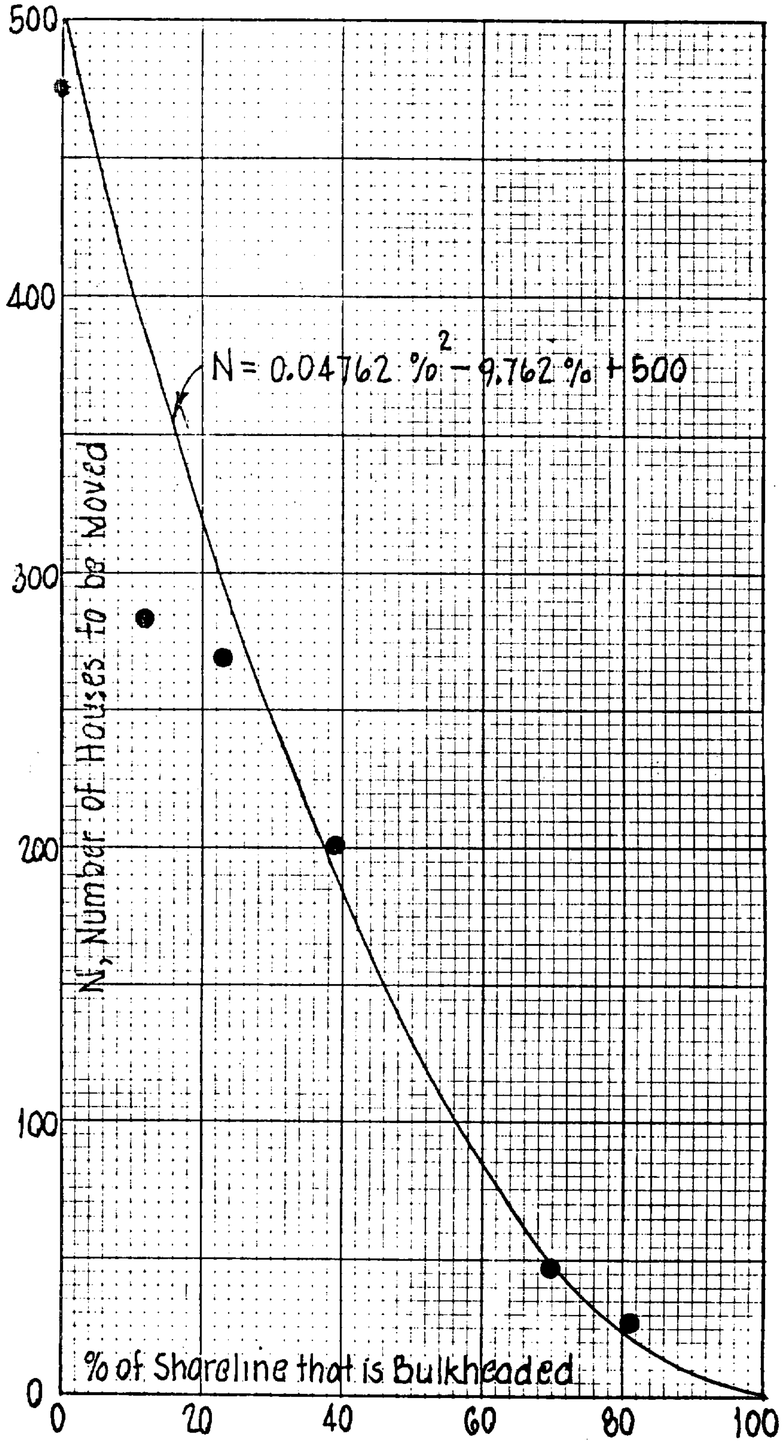


Figure 28 Relationship for Number of Houses to be Moved as a Function of the % of Shoreline that is Bulkheaded.

Table 27. The Cost of Sea Level Rise at 84 Sites Along the U.S. Coastline - Low Estimate

Site	Cost of New Bulkheads	Cost to Raise Bulkheads	Cost to Move Buildings	Cost to Replace Highways	Total Cost
MEFREEPO	$ 4.09 (5.96 mi)	$ 6.99 (7.36 mi)	$ 4.60 (460)	$ 1.11 (0.44 mi)	$ 16.79
MEROCKLA	$ 2.44 (3.55 mi)	$ 4.20 (4.42 mi)	$ 4.55 (455)	$ 0.66 (0.26 mi)	$ 11.85
MEJONESP	$ 1.60 (2.33 mi)	$ 2.69 (2.83 mi)	$ 4.88 (488)	$ 0.47 (0.18 mi)	$ 9.64
MAMARBLE	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 2.20 (0.87 mi)	$ 7.20
MAWESTPO	$ 5.99 (8.72 mi)	$ 10.40 (10.93 mi)	$ 4.32 (432)	$ 1.65 (0.65 mi)	$ 22.36
MAORLEAN	$ 85.61 (124.72 mi)	$ 137.26 (144.35 mi)	$ 0.12 (12)	$ 28.30 (11.16 mi)	$ 251.28
RIWATCHH	$ 6.22 (9.06 mi)	$ 11.04 (11.61 mi)	$ 4.21 (421)	$ 1.87 (0.74 mi)	$ 23.33
CNBRIDGE	$ 45.88 (66.84 mi)	$ 63.56 (66.84 mi)	$ 0.00 (0)	$ 14.10 (5.56 mi)	$ 123.53
NYBROOKL	$ 156.07 (227.38 mi)	$ 271.45 (285.47 mi)	$ 0.56 (56)	$ 43.32 (17.09 mi)	$ 471.39
NYNARROW	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 17.08 (6.74 mi)	$ 22.08
NYPATCHO	$ 21.54 (31.38 mi)	$ 36.95 (38.86 mi)	$ 2.05 (205)	$ 5.82 (2.29 mi)	$ 66.36
NYSOUTHA	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 2.32 (0.91 mi)	$ 7.32
NJDIVIDC	$ 4.39 (6.40 mi)	$ 7.31 (7.69 mi)	$ 4.50 (450)	$ 1.88 (0.74 mi)	$ 18.08
NJLONGBE	$ 8.04 (11.71 mi)	$ 13.48 (14.18 mi)	$ 3.63 (363)	$ 2.53 (1.00 mi)	$ 27.68
DEREHOBA	$ 4.29 (6.25 mi)	$ 7.66 (8.05 mi)	$ 4.40 (440)	$ 1.32 (0.52 mi)	$ 17.67
MDEASTON	$ 2.03 (2.95 mi)	$ 3.47 (3.65 mi)	$ 4.61 (461)	$ 0.55 (0.22 mi)	$ 10.66
MDCOVEPT	$ 0.00 (0.00mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
MDELKTON	$ 0.18 (0.26 mi)	$ 0.38 (0.40 mi)	$ 4.95 (495)	$ 0.11 (0.05 mi)	$ 5.63
MDMIDDLE	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.22 (0.09 mi)	$ 5.22
VACOLBEA	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.78 (0.31 mi)	$ 5.78
VABLOXOM	$ 0.00 (0.00 mi)	$ 0.00 (0.00 0mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00

Site	Cost of New Bulkheads	Cost to Raise Bulkheads	Cost to Move Buildings	Cost to Replace Highways	Total Cost
VANEWPOR	$ 37.15 (54.13 mi)	$ 62.75 (66.00 mi)	$ 1.99 (199)	$ 10.56 (4.17 mi)	$ 112.46
VAWILTON	$ 6.54 (9.53 mi)	$ 11.24 (11.82 mi)	$ 4.47 (447)	$ 1.77 (0.70 mi)	$ 24.01
NCENGELH	$ 0.42 (0.61 mi)	$ 0.69 (0.72 mi)	$ 4.93 (493)	$ 0.78 (0.31 mi)	$ 6.81
NCWILMIN	$ 75.52 (110.02mi)	$ 127.11 (133.68 mi)	$ 0.40 (40)	$ 22.33 (8.81 mi)	$ 225.36
NCLONGBA	$3.15 (4.60mi)	$ 5.24 (5.51 mi)	$ 4.72 (472)	$ 1.44 (0.57mi)	$ 14.56
NCCAMPLE	$ 3.05 (4.44 mi)	$ 5.14 (5.41 mi)	$ 4.72 (472)	$ 1.44 (0.57 mi)	$ 14.56
SCHILTON	$ 24.70 (35.98 mi)	$ 41.12 (43.25 mi)	$ 3.61 (361)	$ 10.02 (3.96 mi)	$ 79.46
SCCHARLE	$ 21.96 (31.99 mi)	$ 36.47 (38.35 mi)	$ 3.28 (328)	$ 10.69 (4.22 mi)	$ 72.39
SCBROOKG	$ 2.56 (3.73 mi)	$ 4.24 (4.46 mi)	$ 4.59 (459)	$ 1.87 (0.74mi)	$ 13.26
GASEAISL	$ 2.84 (4.13 mi)	$ 4.73 (4.97 mi)	$ 4.73 (473)	$ 1.11 (0.44 mi)	$ 13.40
FLLOSTMA	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
FLCARDSO	$ 0.13 (0.19 mi)	$ 0.21 (0.22 mi)	$ 4.98 (498)	$ 0.11 (0.05 mi)	$ 5.44
FLFTGADS	$ 0.74 (1.07 mi)	$ 1.22 (1.28 mi)	$ 4.92 (492)	$ 0.56 (0.22 mi)	$ 7.43
FLAPALAC	$ 2.88 (4.20 mi)	$ 4.85 (5.10 mi)	$ 4.58 (458)	$ 0.88 (0.35 mi)	$ 13.19
FLMIAMI	$ 65.02 (94.73 mi)	$ 108.72 (114.34 mi)	$ 0.25 (25)	$ 22.13 (8.73 mi)	$ 196.12
FLVENICE	$ 1.21 (1.76 mi)	$ 2.69 (2.82 mi)	$ 4.66 (466)	$ 0.89 (0.35mi)	$ 9.45
FLSTAUGU	$ 11.14 (16.23 mi)	$ 18.62 (19.58 mi)	$ 3.42 (342)	$ 3.85 (1.52 mi)	$ 37.04
FLEVERGL	$ 1.20 (1.75 mi)	$ 1.98 (2.08 mi)	$ 4.92 (492)	$ 1.11 (0.44 mi)	$ 9.21
FLCAPECA	$ 93.40 (136.08 mi)	$ 151.28 (159.10 mi)	$ 0.13 (13)	$ 28.74 (11.34 mi)	$ 273.56
FLSNIPEI	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
FLKEYWES	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
FLHOLLEY	$ 2.42 (3.52 mi)	$ 4.11 (4.33 mi)	$ 4.70 (470)	$ 0.66 (0.26mi)	$ 11.90

Site	Cost of New Bulkheads	Cost to Raise Bulkheads	Cost to Move Buildings	Cost to Replace Highways	Total Cost
FLFORTMY	$ 26.44 (38.52 mi)	$ 46.86 (46.13 mi)	$ 0.81 (81)	$ 13.98 (5.52 mi)	$ 85.10
FLPORTRI	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
FLSTJOSE	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
ALGRANDI	$ 1.51 (2.20 mi)	$ 2.51 (2.64 mi)	$ 4.65 (465)	$ 0.67 (0.27 mi)	$ 9.35
MSPASSCH	$ 2.01 (2.93 mi)	$ 3.43 (3.60 mi)	$ 4.55 (455)	$ 0.55 (0.22 mi)	$ 10.54
MSGULFPO	$ 2.95 (4.29 mi)	$ 4.95 (5.21 mi)	$ 3.69 (369)	$ 0.89 (0.35 mi)	$ 12.47
LALULING	$ 19.53 (28.45 mi)	$ 32.30 (33.97 mi)	$ 3.62 (362)	$ 16.51 (6.52mi)	$ 71.96
LABARATA	$ 2.87 (4.18mi)	$ 4.75 (5.00 mi)	$ 4.83 (483)	$ 1.76 (0.69 mi)	$ 14.21
LAGOLDME	$ 3.51 (5.11 mi)	$ 5.81 (6.11 mi)	$ 4.82 (482)	$ 2.53 (1.00 mi)	$ 16.67
LAGRANDC	$ 1.60 (2.33 mi)	$ 2.64 (2.78 mi)	$ 4.89 (489)	$ 1.32 (0.52 mi)	$ 10.45
LAPELICA	$ 0.30 (0.43 mi)	$ 0.50 (0.52mi)	$ 4.98 (498)	$ 0.11 (0.05 mi)	$ 5.89
LAMAINPA	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
LABELLEC	$ 17.29 (25.20 mi)	$ 28.70 (30.18 mi)	$ 4.33 (433)	$ 9.03 (3.56 mi)	$ 59.35
LACAMERO	$ 5.51 (8.03 mi)	$ 9.15 (9.62 mi)	$ 4.71 (471)	$ 2.63 (1.04mi)	$ 22.00
LAPONCHA	$ 2.85 (4.15mi)	$ 4.70 (4.94 mi)	$ 4.45 (445)	$ 3.31 (1.31mi)	$ 15.30
LASULPHU	$ 6.67 (9.71 mi)	$11.02 (11.59 mi)	$ 4.09 (409)	$ 6.07 (2.39 mi)	$ 27.85
LALMISER	$ 1.80 (2.62 mi)	$ 2.97 (3.12 mi)	$ 4.79 (479)	$ 2.43 (0.96 mi)	$ 11.98
TXALLIGA	$ 0.14 (0.21 mi)	$ 0.24 (0.25mi)	$ 4.99 (499)	$ 0.11 (0.05 mi)	$ 5.49
TXGREENI	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
TXPORTLA	$ 18.33 (26.71 mi)	$ 31.42 (33.05 mi)	$ 3.62 (362)	$ 4.95 (1.95 mi)	$ 58.33
TXPALACI	$ 1.65 (2.40 mi)	$ 2.75 (2.90 mi)	$ 4.84 (484)	$ 0.56 (0.22 mi)	$ 9.80
TXRIVER	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00

Site	Cost of New Bulkheads	Cost to Raise Bulkheads	Cost to Move Buildings	Cost to Replace Highways	Total Cost
TXSMITHP	$ 3.13 (4.56 mi)	$ 5.20 (5.47 mi)	$ 4.60 (460)	$ 1.44 (0.57 mi)	$ 14.37
TXTIVOLI	$ 4.22 (6.14 mi)	$ 7.03 (7.40 mi)	$ 4.57 (457)	$ 1.55 (0.61 mi)	$ 17.37
CABENICI	$ 22.70 (33.08 mi)	$ 39.00 (41.01mi)	$ 4.14 (414)	$ 6.14 (2.42 mi)	$ 71.98
CAANONUE	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
CASANQUE	$ 31.73 (46.23 mi)	$ 54.98 (57.83 mi)	$ 2.13 (213)	$ 8.71 (3.44 mi)	$ 97.56
CAOCEANS	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.08 (0.03 mi)	$ 5.08
CAPTSAL	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
CAPALOAL	$ 26.46 (38.55 mi)	$ 43.82 (46.08 mi)	$ 2.58 (258)	$ 17.07 (6.74 mi)	$ 89.93
CAALBION	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
CAFERNDA	$ 3.25 (4.73 mi)	$ 5.58 (5.87 mi)	$ 4.48 (448)	$ 0.88 (0.35 mi)	$ 14.19
CATIJUAN	$ 40.81 (59.46 mi)	$ 67.34 (70.82 mi)	$ 0.20 (20)	$ 78.60 (31.01 mi)	$ 186.95
CAPTMAGU	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
ORPORTOR	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.33 (0.13 mi)	$ 5.33
ORYAQUIN	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.11 (0.05 mi)	$ 5.11
WAANACOR	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.44 (0.18 mi)	$ 5.44
WAGARDNI	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.33 (0.13 mi)	$ 5.33
WANEMAH	$ 12.19 (17.77 mi)	$ 20.33 (21.38 mi)	$ 3.97 (397)	$ 4.62 (1.82 mi)	$ 41.11
WAPORTGA	$ 1.12 (1.63 mi)	$ 3.63 (3.82 mi)	$ 4.81 (481)	$ 1.98 (0.78 mi)	$ 11.54
WATACOMA	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.78 (0.31 mi)	$ 5.78

Table 28. The Cost of Sea Level Rise at 84 Sites Along the U.S. Coastline - High Estimate

Site	Cost of New Bulkheads	Cost to Raise Bulkheads	Cost to Move Buildings	Cost to Replace Highways	Total Cost
MEFREEPO	$ 15.74 (5.96 mi)	$ 26.90 (7.36 mi)	$ 4.60 (460)	$ 1.48 (0.44 mi)	$ 48.71
MEROCKLA	$ 9.37 (3.55 mi)	$ 16.15 (4.42 mi)	$ 4.55 (455)	$ 0.88 (0.26 mi)	$ 30.96
MEJONESP	$ 6.15 (2.33 mi)	$ 10.36 (2.83 mi)	$ 4.88 (488)	$ 0.62 (0.18 mi)	$ 22.01
MAMARBLE	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 2.20 (0.87 mi)	$ 69.54
MAWESTPO	$ 23.03 (8.72 mi)	$ 39.99 (10.93 mi)	$ 4.32 (432)	$ 1.65 (0.65 mi)	$ 22.36
MAORLEAN	$ 329.27 (124.72 mi)	$ 527.91 (144.35 mi)	$ 0.12 (12)	$ 37.73 (11.16 mi)	$ 895.02
RIWATCHH	$ 23.91 (9.06 mi)	$ 42.44 (11.61 mi)	$ 4.21 (421)	$ 2.49 (0.74 mi)	$ 73.05
CNBRIDGE	$ 176.46 (66.84 mi)	$ 244.44 (66.84 mi)	$ 0.00 (0)	$ 18.80 (5.56 mi)	$ 439.70
NYBROOKL	$ 600.28 (227.38 mi)	$ 1044.02 (285.47 mi)	$ 0.56 (56)	$ 57.75 (17.09 mi)	$ 1702.61
NYNARROW	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 22.78 (6.74 mi)	$ 27.78
NYPATCHO	$ 82.85 (31.38 mi)	$ 142.11 (38.86 mi)	$ 2.05 (205)	$ 7.76 (2.29 mi)	$ 234.77
NYSOUTHA	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 3.09 (0.91 mi)	$ 8.09
NJDIVIDC	$ 16.90 (6.40 mi)	$ 28.11 (7.69 mi)	$ 4.50 (450)	$ 2.51 (0.74 mi)	$ 52.01
NJLONGBE	$ 30.92 (11.71 mi)	$ 51.85 (14.18 mi)	$ 3.63 (363)	$ 3.38 (1.00 mi)	$ 89.78
DEREHOBA	$ 16.49 (6.25 mi)	$ 29.44 (8.05 mi)	$ 4.40 (440)	$1.76 (0.52 mi)	$ 52.11
MDEASTON	$ 7.80 (2.95 mi)	$ 13.36 (3.65 mi)	$ 4.61 (461)	$ 0.73 (0.22 mi)	$ 26.50
MDCOVEPT	$ 0.00 (0.00mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
MDELKTON	$ 0.69 (0.26 mi)	$ 1.46 (0.40 mi)	$ 4.95 (495)	$ 0.15 (0.05 mi)	$ 7.25
MDMIDDLE	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.29 (0.09 mi)	$ 5.29
VACOLBEA	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 1.03 (0.31 mi)	$ 6.03
VABLOXOM	$ 0.00 (0.00 mi)	$ 0.00 (0.00 0mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00

Site	Cost of New Bulkheads	Cost to Raise Bulkheads	Cost to Move Buildings	Cost to Replace Highways	Total Cost
VANEWPOR	$ 142.90 (54.13 mi)	$ 241.36 (66.00 mi)	$ 1.99 (199)	$ 14.08 (4.17 mi)	$ 400.33
VAWILTON	$ 25.16 (9.53 mi)	$ 43.21 (11.82 mi)	$ 4.47 (447)	$ 2.36 (0.70 mi)	$ 75.20
NCENGELH	$ 1.61 (0.61 mi)	$ 2.65 (0.72 mi)	$ 4.93 (493)	$ 1.03 (0.31 mi)	$ 10.22
NCWILMIN	$ 290.46 (110.02mi)	$ 448.89 (133.68 mi)	$ 0.40 (40)	$ 29.77 (8.81 mi)	$ 809.52
NCLONGBA	$ 12.13 (4.60mi)	$ 20.16 (5.51 mi)	$ 4.72 (472)	$ 1.92 (0.57mi)	$ 38.93
NCCAMPLE	$ 11.73 (4.44 mi)	$ 19.78 (5.41 mi)	$ 4.63 (472)	$ 1.17 (0.57 mi)	$ 37.31
SCHILTON	$ 95.00 (35.98 mi)	$ 158.16 (43.25 mi)	$ 3.61 (361)	$ 13.37 (3.96 mi)	$ 270.14
SCCHARLE	$ 84.46 (31.99 mi)	$ 140.25 (38.35 mi)	$ 3.28 (328)	$ 14.25 (4.22 mi)	$ 242.24
SCBROOKG	$ 9.85 (3.73 mi)	$ 16.30 (4.46 mi)	$ 4.59 (459)	$ 2.49 (0.74 mi)	$ 33.23
GASEAISL	$ 10.91 (4.13 mi)	$ 18.18 (4.97 mi)	$ 4.73 (473)	$ 1.48 (0.44 mi)	$ 35.30
FLCARDSO	$ 0.13 (0.19 mi)	$ 0.82 (0.22 mi)	$ 4.98 (498)	$ 0.15 (0.05 mi)	$ 6.45
FLLOSTMA	$ 0.00 (0.00i)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
FLFTGADS	$ 2.83 (1.07 mi)	$ 4.68 (1.28 mi)	$ 4.92 (492)	$ 0.75 (0.22 mi)	$ 13.17
FLAPALAC	$ 11.10 (4.20 mi)	$ 18.64 (5.10 mi)	$ 4.58 (458)	$ 1.17 (0.35 mi)	$ 35.49
FLMIAMI	$ 250.09 (94.73 mi)	$ 418.16 (114.34 mi)	$ 0.25 (25)	$ 29.50 (8.73 mi)	$ 698.00
FLVENICE	$ 4.64 (1.76 mi)	$ 10.33 (2.82 mi)	$ 4.66 (466)	$ 1.19 (0.35mi)	$ 20.82
FLSTAUGU	$ 42.85 (16.23 mi)	$ 71.61 (19.58 mi)	$ 3.42 (342)	$ 5.14 (1.52 mi)	$ 123.03
FLEVERGL	$ 4.61 (1.75 mi)	$ 7.62 (2.08 mi)	$ 4.92 (492)	$ 1.48 (0.44 mi)	$ 18.63
FLCAPECA	$ 359.24 (136.08 mi)	$ 581.85 (159.10 mi)	$ 0.13 (13)	$ 38.32 (11.34 mi)	$ 979.54
FLSNIPEI	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
FLKEYWES	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
FLHOLLEY	$ 9.31 (3.52 mi)	$ 15.85 (4.33 mi)	$ 4.70 (470)	$ 0.88 (0.26mi)	$ 30.71

Site	Cost of New Bulkheads	Cost to Raise Bulkheads	Cost to Move Buildings	Cost to Replace Highways	Total Cost
FLFORTMY	$ 101.69 (38.52 mi)	$ 168.71 (46.13 mi)	$ 0.81 (81)	$ 18.64 (5.52 mi)	$ 289.85
FLPORTRI	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
FLSTJOSE	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
ALGRANDI	$ 5.81 (2.20 mi)	$ 9.66 (2.64 mi)	$ 4.65 (465)	$ 0.90 (0.27 mi)	$ 21.03
MSPASSCH	$ 7.74 (2.93 mi)	$ 13.18 (3.60 mi)	$ 4.55 (455)	$ 0.73 (0.22 mi)	$ 26.20
MSGULFPO	$ 11.33 (4.29 mi)	$ 19.04 (5.21 mi)	$ 3.69 (369)	$ 1.19 (0.35 mi)	$ 35.24
LALULING	$ 75.12 (28.45 mi)	$ 124.22 (33.97 mi)	$ 3.62 (362)	$ 22.02 (6.52mi)	$ 224.98
LABARATA	$ 11.03 (4.18mi)	$ 18.28 (5.00 mi)	$ 4.83 (483)	$ 2.34 (0.69 mi)	$ 36.49
LAGOLDME	$ 13.50 (5.11 mi)	$ 22.34 (6.11 mi)	$ 4.82 (482)	$ 3.38 (1.00 mi)	$ 44.04
LAGRANDC	$ 6.14 (2.33 mi)	$ 10.16 (2.78 mi)	$ 4.89 (489)	$ 1.76 (0.52 mi)	$ 22.95
LAPELICA	$ 1.15 (0.43 mi)	$ 1.91 (0.52mi)	$ 4.98 (498)	$ 0.15 (0.05 mi)	$ 8.19
LAMAINPA	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
LABELLEC	$ 66.52 (25.20 mi)	$ 110.37 (30.18 mi)	$ 4.33 (433)	$ 12.04 (3.56 mi)	$ 193.26
LACAMERO	$ 21.19 (8.03 mi)	$ 35.19 (9.62 mi)	$ 4.71 (471)	$ 3.51 (1.04 mi)	$ 64.60
LAPONCHA	$ 10.94 (4.15mi)	$ 18.08 (4.94 mi)	$ 4.45 (445)	$ 4.41 (1.31mi)	$ 37.88
LASULPHU	$ 25.64 (9.71 mi)	$ 42.39 (11.59 mi)	$ 4.09 (409)	$ 8.09 (2.39 mi)	$ 80.21
LALMISER	$ 6.91 (2.62 mi)	$ 11.41 (3.12 mi)	$ 4.79 (479)	$ 3.24 (0.96 mi)	$ 26.34
TXALLIGA	$ 0.56 (0.21 mi)	$ 0.92 (0.25mi)	$ 4.99 (499)	$ 0.15 (0.05 mi)	$ 6.62
TXGREENI	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
TXPORTLA	$ 70.52 (26.71 mi)	$ 120.85 (33.05 mi)	$ 3.62 (362)	$ 6.60 (1.95 mi)	$ 201.59
TXPALACI	$ 6.33 (2.40 mi)	$ 10.59 (2.90 mi)	$ 4.84 (484)	$ 0.75 (0.22 mi)	$ 22.51
TXRIVER	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00

Site	Cost of New Bulkheads	Cost to Raise Bulkheads	Cost to Move Buildings	Cost to Replace Highways	Total Cost
TXSMITHP	$ 12.03 (4.56 mi)	$ 19.99 (5.47 mi)	$ 4.60 (460)	$ 1.92 (0.57 mi)	$ 38.54
TXTIVOLI	$ 16.21 (6.14 mi)	$ 27.05 (7.40 mi)	$ 4.57 (457)	$ 2.07 (0.61 mi)	$ 49.91
CABENICI	$ 87.33 (33.08 mi)	$ 149.99 (41.01mi)	$ 4.14 (414)	$ 8.18 (2.42 mi)	$ 249.64
CAANONUE	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
CASANQUE	$ 122.04 (46.23 mi)	$ 211.47 (57.83 mi)	$ 2.13 (213)	$ 11.62 (3.44 mi)	$ 347.26
CAOCEANS	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.11 (0.03 mi)	$ 5.11
CAPTSAL	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
CAPALOAL	$ 101.76 (38.55 mi)	$ 168.54 (46.08 mi)	$ 2.58 (258)	$ 22.76 (6.74 mi)	$ 295.64
CAALBION	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
CAFERNDA	$ 12.49 (4.73 mi)	$ 21.47 (5.87 mi)	$ 4.48 (448)	$ 1.17 (0.35 mi)	$ 39.61
CATIJUAN	$ 156.97 (59.46 mi)	$ 258.98 (70.82 mi)	$ 0.20 (20)	$ 104.80 (31.01 mi)	$ 520.96
CAPTMAGU	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.00 (0.00 mi)	$ 5.00
ORPORTOR	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.44 (0.13 mi)	$ 5.44
ORYAQUIN	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.15 (0.05 mi)	$ 5.15
WAANACOR	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.59 (0.18 mi)	$ 5.59
WAGARDNI	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 0.44 (0.13 mi)	$ 5.44
WANEMAH	$ 46.90 (17.77 mi)	$ 78.19 (21.38 mi)	$ 3.97 (397)	$ 6.16 (1.82 mi)	$ 135.22
WAPORTGA	$ 4.30 (1.63 mi)	$ 13.95 (3.82 mi)	$ 4.81 (481)	$ 2.65 (0.78 mi)	$ 25.72
WATACOMA	$ 0.00 (0.00 mi)	$ 0.00 (0.00 mi)	$ 5.00 (500)	$ 1.03 (0.31 mi)	$ 6.03

Table 29. Nationwide Estimate ($ millions)

	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

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