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POTENTIAL IMPACTS OF SEA LEVEL RISE
ON THE BEACH AT OCEAN CITY, MARYLAND

by

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SUMMARY

Recent reports by the National Academy of Sciences and others have concluded that increasing atmospheric concentrations of carbon dioxide and other gases can be expected to cause a global warming that could raise sea level a few feet in the next century. Unfortunately, it is not yet possible to accurately predict future sea level. Estimates for the year 2025 range from five to twenty-one inches above current sea level, while estimates of the rise by 2100 range from two to eleven feet.

Several issues must be resolved for society to rationally address the possibility of a significant rise in sea level. Officials in coastal areas making decisions about near-term projects with long lifetimes must determine whether the risk of sea level rise justifies a shift to strategies that can more successfully accommodate a rise in sea level. The research community needs to decide whether to accelerate studies to more accurately project future sea level. These decisions require assessments of the adequacy of existing forecasts, prospects for improving the estimates, and the level of resources that can be saved if more definitive estimates become available.

These decisions also require an understanding of the consequences of sea level rise. To further this understanding, EPA has initiated studies of the impacts of sea level rise on Charleston, South Carolina; Galveston, Texas; coastal wetlands; municipal drainage facilities; and salinity of surface and ground water.

This study examines the potential implications of sea level rise for efforts to control erosion of the beach at Ocean City, Maryland, a typical Atlantic Coast resort. Because current trends in sea level and other factors are already causing significant erosion at Ocean City and other ocean beach resorts, strategies for addressing coastal erosion constitute a class of near-term decisions that may depend on sea level rise. Because land and improvements are often worth well over one million dollars per acre in these areas, and erosion increases the likelihood of storm damage and federal disaster payments, the success of erosion control measures has great economic importance to the nation. We hope that this report will promote a reasoned consideration of the long-term consequences of sea level rise, and thereby enhance the eventual success of erosion control strategies at Ocean City and other coastal communities.

In this report, three independent teams of coastal process scientists estimate the erosion that will take place at Ocean City for three scenarios of future sea level rise: (1) current trends of I foot per century along the Atlantic coast; (2) the National Academy of Sciences estimate of a 2-1/3 foot global rise in the next century with an 11 inch rise by 2025; and (3) the EPA mid-high scenario of a global rise of 4-1/2 feet in the next century and 15 inches by 2025. The quantity of sand necessary to maintain the current shoreline is also estimated for each of the scenarios. Using these estimates and previous studies by the Corps of Engineers and others, the potential costs of erosion control are also examined.

CONCLUSIONS

1. Sea level rise could double the rate of erosion at Ocean City in the next forty years. If no additional erosion control measures are taken, the shore will erode 85-153 feet by 2025 assuming current sea level trends. An 11-inch global rise in sea level would increase expected erosion to between 180 and 238 feet, if no additional measures are taken; a 15-inch rise would increase expected erosion to between 216 and 273 feet.

2. The projected rise in sea level would increase the quantity of sand necessary to maintain the current shoreline for the next forty years from 5-10 million cubic yards if current trends continue, to 11-15 million cubic yards for the two scenarios of accelerated sea level rise.

3. Projected sea level rise would increase the priority of erosion control-measures under current policies of the Corps of Engineers. Current policies place a greater emphasis an flood protection than recreational benefits provided by proposed projects. Because of the substantial erosion that could occur from a rise in sea level, the need for flood protection will be greater if sea level rises.

4. A significant rise in sea level would require a change in the technology used to control erosion at Ocean City. The current plan to construct groins was designed to curtail erosion caused by sand moving along the shore. However, groins do not prevent erosion caused by sea level rise. Placement of additional sand onto the beach would offset erosion caused by both sea level rise and alongshore transport.

5. The cost of controlling erosion caused by sea level rise does not threaten the economic viability of Ocean City in the next forty years. Even the most pessimistic estimate of future erosion control implies a cost of less than fifty cents for every visitor that comes to Ocean City each year. Protecting the shore at Ocean City will continue to be economically justified.

6. Understanding the likely impact of sea level rise on Ocean City in the next century will require identification of the most cost-effective and environmentally acceptable sources for up to fifty million cubic yards of sand to be placed on the beach.

7. Better estimates of future sea level rise would enable decision makers to more adequately determine the most prudent strategy for controlling erosion at Ocean City.

8. Although improved procedures for estimating erosion are desirable, current methods are sufficient to yield first-order estimates for use in long-term planning.

ACKNOWLEDGMENTS

We wish to express our appreciation for the numerous people who provided helpful contributions and encouraged us to publish this report. Torrey Brown and Sarah Taylor of the Maryland Department of Natural Resources initially requested that EPA use the Ocean City situation as a case study of sea level rise impacts. Sandy Coyman of Ocean City's Department of Planning and Community Development provided numerous editorial contributions to make the report more readable. Ed Fulford and Suzette May of the Army Corps of Engineers provided several important insights concerning erosion processes along the Maryland coast.

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Dennis Tirpak and John S. Hoffman of EPA's Office of Policy Analysis made important organizational contributions to Chapter 1. William Hoffman and Marria O'Malley of EPA's Region III reviewed the report from the perspective of wetland and marine policy. Susan MacMillan of ICF Incorporated and Joan O'Callaghan of EPA provided detailed editorial contributions. Finally, Margo Brown prepared the manuscript.

Without the contributions of these and other people who encouraged us along the way, this report would not have been possible.

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CHAPTER I:

SEA LEVEL RISE AND THE MARYLAND COAST

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INTRODUCTION

In the last few decades, Americans have increasingly used the resources offered by our coastal areas. The popularity of beaches now accounts for a multibillion dollar industry. Recreational hunting and fishing, while less significant nationwide, are major attractions in coastal wetlands and estuaries, such as Louisiana's marshes and swamps, Chesapeake Bay, and Narragansett Bay.' Recreational boating has also become more widespread in coastal areas.[2]

To accommodate increasing numbers of visitors, modern high-rise hotels and condominiums, houses, and marinas have replaced the small cottages and vacant land that once characterized ocean beach resorts and barrier islands. High land values have sometimes encouraged people to create land by filling marshes and shallow bays. Many mainland areas within a short commute to the beach are also being developed extensively.

Increasing development has entailed certain economic and environmental risks. Buildings in many coastal areas are vulnerable to severe storms which generally occur every thirty to fifty years (Kunreuther 1978). In many areas, the beaches are eroding, which gradually removes an important recreational asset and increases the vulnerability of shorefront property to storms. The filling of coastal marshes has sometimes destroyed fish and wildlife habitats and impaired water quality in coastal areas (Office of Technology Assessment 1984). Bulkheads that eliminate natural bay beaches can threaten the food supply of shore birds.

Congress has enacted several policies to address these risks. In 1968 it found that "many factors have made it uneconomic for the private insurance industry alone to make flood insurance available."[3] As a result, it enacted the National Flood Insurance Act which requires property owners with federally insured mortgages in coastal hazard areas to obtain flood insurance, and requires participating communities to take measures to ensure that newly constructed buildings will not be destroyed by a major storm. In 1972 Congress declared that it is national policy to "preserve, protect, develop, and where possible to restore or enhance, the resources of the nation's coastal zones for this and succeeding generations"[4] and passed the Coastal Zone Management Act, which encourages states to develop coastal policies to ensure that new development is safe and provides for the conservation of wetlands and other natural environments. The Coastal Barrier Resources Act forbids federal subsidies to designated undeveloped barrier islands. Section 404 of the Clean Water Act requires anyone wishing to build on a coastal marsh to obtain a permit from the Army Corps of Engineers with approval by the Environmental Protection Agency. Finally, the National Environmental Policy Act requires an environmental impact statement informing the public of potential environmental risks for any major federal action, including a permit under Section 404.

These programs are generally administered by state and local governments. Over seventeen thousand communities participate in the National Flood Insurance Program, which requires them to enact zoning and building codes to prevent excessively hazardous construction. States develop coastal zone management plans subject to approval by the federal government. Provided that the necessary assessments and permits are filed, the decision whether to fill a marsh is primarily a local land use decision. Many states and localities have gone beyond federal requirements and effectively prohibited the construction of bulkheads or filling of coastal marshes.[5] These and other federal, state, and local policies have reduced the economic and environmental risks of developing coastal areas.

Recent scientific findings, however, suggest that current policies may be overlooking an environmental impact that could exacerbate the other risks: a rise in the level of the oceans. Increasing atmospheric concentrations of carbon dioxide and other gases are expected to warm our planet a few degrees centigrade in the next century by a mechanism known as the "greenhouse effect." Such a global warming would probably cause sea level to rise more rapidly than it is currently. Although estimates of the rise expected in the next one hundred years range from 38 to 211 centimeters (15 inches to 8 feet), a precise forecast will not be possible in the foreseeable future.

Even a thirty-centimeter (one-foot) rise in sea level would have important environmental impacts and would change the consequences of decisions made today. Along the open coast, beaches could erode 20 to 80 meters (60 to 250 feet), and buildings would be more vulnerable to storms (Bruun 1962). Along the shores of coastal estuaries, existing marshes would drown and homeowners in some areas would have to build levees and bulkheads to prevent new marshes from taking over their properties (Kana, Baca, and Williams 1985).

With a rise of one meter, most coastal communities would have to choose between several undesirable alternatives: investing substantial resources to maintain beaches and wetlands in their current locations; building seawalls and bulkheads to protect property while allowing beaches and marshes to erode away; or allowing beaches and marshes to encroach inland onto previously developed land. Fortunately, many of the potential costs can be avoided or reduced if timely measures are taken in anticipation of sea level rise (Barth and Titus 1984).

This report examines the erosion that sea level rise could cause the resort community of Ocean City, Maryland, over the next ninety years. Like many resorts, Ocean City has an erosion problem. Although city and state agencies are undertaking measures to reduce erosion, their strategies do not yet consider the impacts of rising sea level. We hope that this report will help promote a reasoned consideration of the long-term consequences of sea level rise, and thereby enhance the eventual success of erosion control strategies at Ocean City.* We also encourage other coastal communities with erosion problems to consider the implications of a rising sea.

In the following chapters, three coastal research teams describe their independent assessments of beach erosion from sea level rise and other factors. In Chapter 2, Leatherman presents "Geomorphic Effects of Accelerated Sea Level Rise on Ocean City, Maryland," with an appendix by Bresee. In Chapter 3, Everts presents "Effect of Sea Level Rise and Net Sand Volume Changes on Shoreline Position at Ocean City, Maryland." Finally, in Chapter 4, Kriebel and Dean present "Estimates of Erosion and Mitigation Requirements under Various Scenarios of Sea Level Rise and Storm Frequency for Ocean City, Maryland."

In this introductory chapter, written for the general reader, we summarize the results of those studies and other relevant information. We describe the basis for expecting a significant rise in sea level in the future; provide an overview of the possible impacts on Maryland and other coastal areas; summarize the three studies presented in Chapters 2 through 4; and briefly discuss the implications of these studies and additional steps that could help Ocean City and similar communities prepare for the consequences of future sea level rise. Because this study focuses primarily on erosion and beach nourishment, a more thorough assessment of the long-term economic and policy implications should be undertaken using the technical data this report provides.

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* This report does not consider options for reducing the rise in sea level due to the greenhouse effect. See Lovins et al. (1981) and Seidel and Keyes (1983) for discussions of this issue.

THE BASIS FOR EXPECTING A RISE IN SEA LEVEL

Past Trends in Sea Level

Throughout geologic history, sea level has risen and fallen by over three hundred meters (one thousand feet) due to changes in (1) the shape and size of ocean basins, (2) the amount of water in the oceans, and (3) the average density of seawater. The emergence and submergence of land has also changed sea level relative to particular land masses. The first three factors influence "global sea level"; the latter affects "relative sea level."

In the last 100 million years, changes in the size and shape of ocean basins have caused the greatest changes in global sea level (Hays and Pitman 1973). However, in the last several thousand years, these processes have usually been relatively slow and are not likely to accelerate in the near future.6

Sea level has risen and fallen with past changes in world climate. During the ice ages, the average global temperature has been 50C colder than today (Hansen et al. 1984). With glaciers covering much of the northern hemisphere, there has been less water in the oceans and the sea level has been one hundred to one hundred fifty meters (three hundred to five hundred feet) lower than today (Donn, Farrand, and Ewing 1962). During previous interglacial (warm) periods, on the other hand, global temperatures have been 1-20C warmer than today and sea level has been about six meters (twenty feet) higher (Hollin 1972).

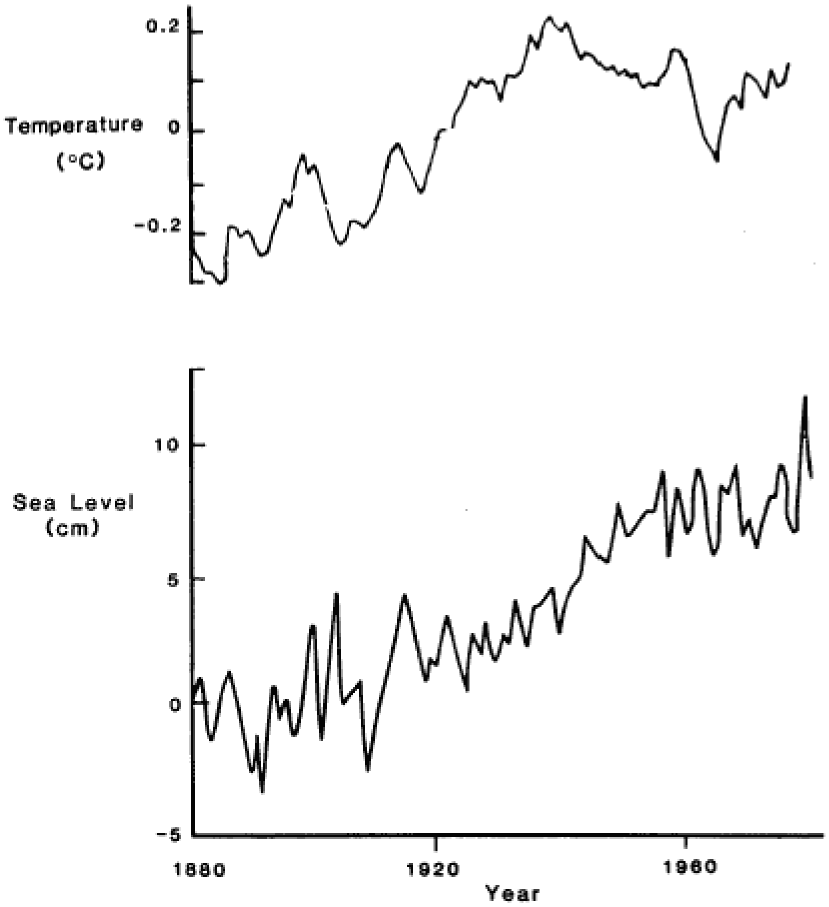
Although the glaciers that covered much of the northern hemisphere during the last ice age have melted, polar glaciers in Greenland and Antarctica contain enough water to raise sea level more than seventy meters (over two hundred feet) (Untersteiner 1975). A complete melting of these glaciers has not occurred in the last two million years, and would take tens of thousands of years even if the earth warmed substantially. However, unlike the other glaciers which rest on land, the west Antarctic ice sheet is marine-based and more vulnerable to temperature increases. Warmer ocean water would be more effective than warmer air at melting glaciers, causing West Antarctica to melt. Mercer (1970) suggests that the west Antarctic ice sheet completely disappeared during the last interglacial period, raising sea level five to seven meters (about twenty feet) above its present level.

Over relatively short periods of time, climate can influence sea level by heating and thereby expanding (or cooling and contracting) sea water. In the last century, tidal gauges have been available to measure relative sea level in particular locations. Along the Atlantic Coast, sea level has risen about 30 centimeters (one foot) in the last century (Hicks, Debaugh, and Hickman 1983). Studies combining all the measurements have concluded that average worldwide sea level has risen ten to fifteen centimeters (four to six inches) in the last one hundred years (Barnett 1983; Gornitz, Lebedeff, and Hansen 1982). At least part of this rise can be explained by the thermal expansion of the upper layers of the oceans resulting from the observed warming of 0.40C in the last century (Gornitz, Lebedeff, and Hansen 1982). Meltwater from mountain glaciers has also contributed to sea level rise (Meier 1984). Figure 1 shows that global temperature and sea level have been rising in the last century. Nevertheless, questions remain over the magnitude and causes of sea level rise in the last century.

The Greenhouse Effect

Concern about a possible acceleration in the rate of sea level rise arises from measurements that concentrations of carbon dioxide (CO_2), methane, chlorofluorocarbons, and other gases released by human activities are increasing. Because these gases absorb infrared radiation (heat), scientists generally expect the earth to warm substantially. Although some people have suggested that unknown or unpredictable factors could offset this warming, the National Academy of Sciences (NAS) has twice reviewed all the evidence and concluded that the warming will take place. In 1979, the Academy concluded: "We have tried but have been unable to find any overlooked physical effect that could reduce the currently estimated global warming to negligible proportions" (Charney 1979). In 1982, NAS confirmed the 1979 assessment (Smagorinsky 1982).

Figure 1. Global Temperatures and Sea Level Have Risen in the Last Century.



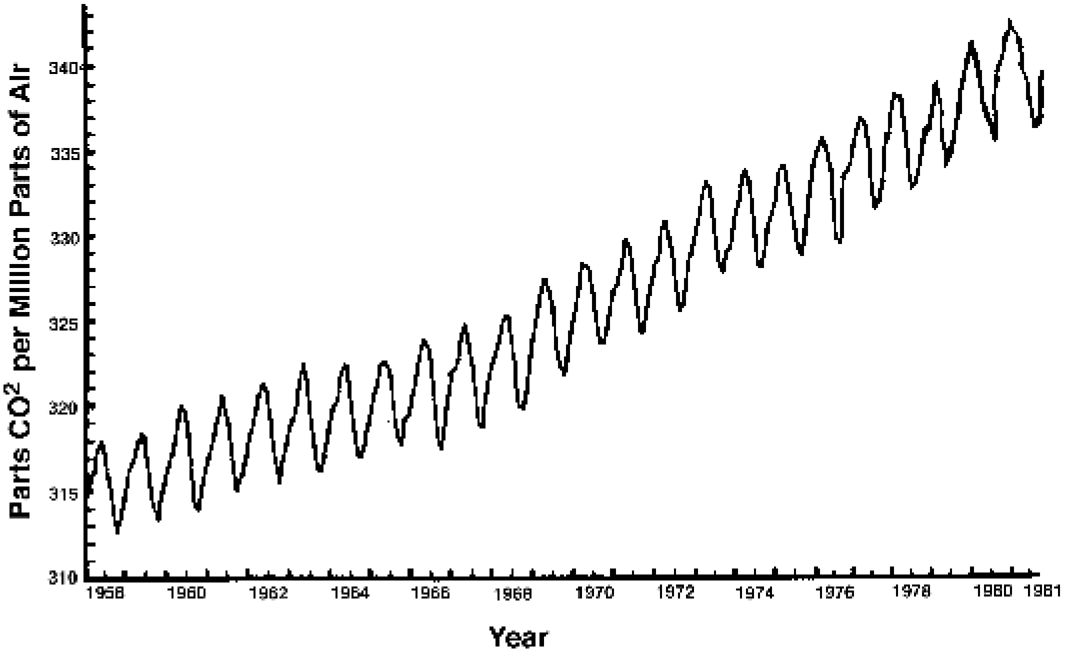
Sources: Temperature curve from: J.E. Hansen et al., "Climate Impact of Increasing Atmospheric Carbon Dioxide," Science, 1981, p. 957-966. Sea level curve adapted from: V. Gornitz, S. Lebedeff, and J. Hansen, "Global Sea Level Trend in the Past Century," Science, 1982, p. 1611-1614.

A planet's temperature is determined primarily by the amount of sunlight it receives, the amount of sunlight it reflects, and the extent to which its atmosphere retains heat. When sunlight strikes the earth, it warms the surface, which then reradiates the heat as infrared radiation. However, water vapor, C0$_2$, and other gases in the atmosphere absorb some of the energy rather than allowing it to pass undeterred through the atmosphere to space. Because the atmosphere traps heat and warms the earth in a manner somewhat analogous to the glass panels of a greenhouse, this phenomenon is generally known as the[11] greenhouse affect." Without the greenhouse affect of the gases that occur in the atmosphere naturally, the earth would be approximately 33^{o}C (60^{o}F) colder than it is currently (Hansen et al. 1984). Thus, the greenhouse effect per se is not something that will happen; it is a natural characteristic of the atmosphere.

In recent decades, the concentrations of these "greenhouse gases" have been increasing. Since the industrial revolution, the combustion of fossil fuels, deforestation, and cement manufacture have released enough C0$_2$ into the atmosphere to raise the atmospheric concentration of carbon dioxide by 20 percent (Keeling, Bacast6w, and Whorf 1982). As Figure 2 shows, the concentration has increased 8 percent since 1958. Recently, the concentrations of methane, nitrous oxide chlorofluorocarbons and some other trace gases that also absorb infrared radiation have also been increasing (Lacis et al. 1981; Ramanathan et al. 1985).

Although there is no doubt that the concentration of greenhouse gases is increasing, the future rate of that increase is uncertain. A recent report by the National Academy of Sciences (NAS) examined numerous uncertainties regarding future energy use patterns, economic growth, and the extent to which C0$_2$ emissions remain in the atmosphere (Nordhaus and Yohe 1983). The Academy estimated a 98 percent probability that C0$_2$ concentrations will be at least 450 parts per million (1.5 times the preindustrial level) by 2050 and a 55 percent chance that the concentration will be 550 parts per million. The Academy estimated that the probability of a doubling of C0$_2$ concentrations by 2100 is 75 percent.

Figure 2. Measurements of Atmospheric Carbon-Dioxide Abundance Over Time: 1958 to 1981.



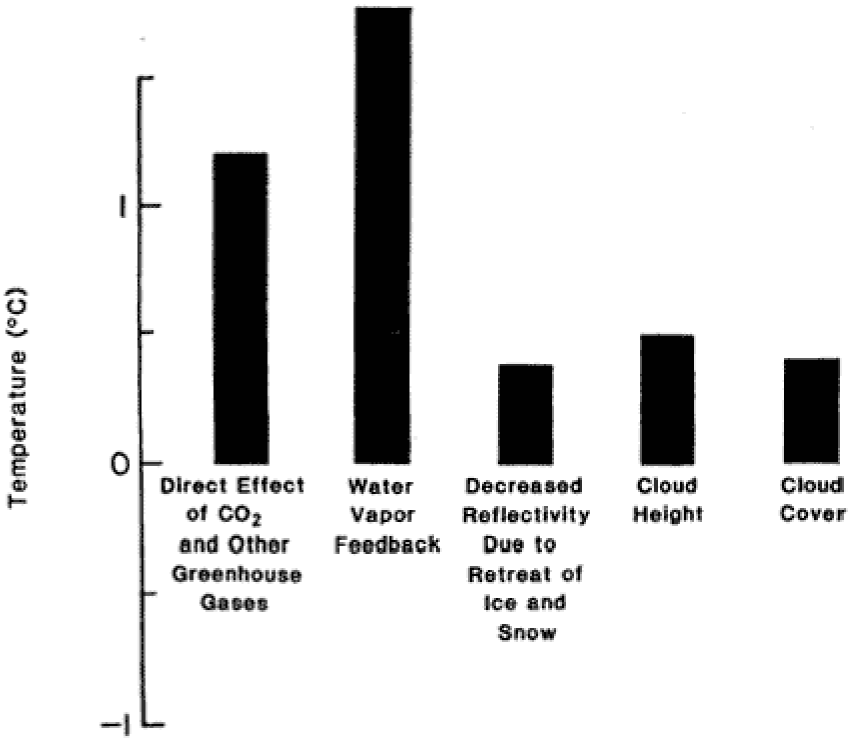
Sources: Mauna Loa Observatory, Hawaii, NOAA, U.S. Department of Commerce.

If the impact of the trace gases continues to be equal to the impact of C02, NAS analysis implies that the effective doubling of all greenhouse gases[7] has a 98 percent chance of occurring by 2050. However, uncertainties regarding the emissions of trace gases are greater than those for C02. Although the sources of chlorofluorocarbon emissions are well documented, regulatory uncertainties related to their possible impact on stratospheric ozone depletion make their growth rate -- currently about 5 percent -- impossible to forecast. The current sources of methane, nitrous oxide, and other trace gases have not yet been fully catalogued.

Considerable uncertainty also exists regarding the impact of a doubling of greenhouse gases. Physicists and climatologists generally accept the estimate by Hansen et al. (1984) that a doubling would directly raise the earth's average temperature 1.20C if nothing else changed. However, if the earth warmed 1.20C, many other aspects of climate would be likely to change, probably amplifying the direct affect of the greenhouse gases. These indirect impacts are known as "climatic feedbacks."

Figure 3 shows estimates by Hansen et al. (1984) of the most important known feedbacks. A warmer atmosphere would retain more water vapor, which is also a greenhouse gas, warming the earth more. Snow and floating ice would melt, decreasing the amount of sunlight reflected to space, causing additional warming. Although the estimates of other researchers differ slightly from those of Hansen et al., climatologists agree that these two feedbacks would amplify the global warming from the greenhouse effect. However, the impact of clouds is far less certain. Although recent investigations have estimated that changes in cloud height and cloud cover would add to the warming, the possibility that changes in cloud cover would offset part of the warming cannot be ruled out. After evaluating the evidence, two panels of the National Academy of Sciences concluded that the eventual warming from a doubling of greenhouse gases would be between 1.50 and 4.50C (30-80F).

Figure 3. Estimated Global Warming Due To A Doubling of Greenhouse Gases: Direct Effects and Climatic Feedbacks.



Although Hansen et al. estimate a positive feedback from the clouds, a negative feedback cannot be ruled out.

Sources: Adapted from: J.E. Hansen et al., "Climate Sensitivity to Increasing Greenhouse Gases," in Greenhouse Effect and Sea Level Rise: A Challenge for This Generation, edited by M.C. Barth and J.G. Titus. New York: Van Nostrand Reinhold, 1984, p. 62.

A global warming of a few degrees could be expected to raise sea level in the future, as it has in the past. The best understood mechanism is the warming and resulting expansion of sea water, which could raise sea level one-half meter in the next century (Hoffman, Keyes, and Titus 1983). Mountain glaciers could malt and release enough water to raise sea level twelve centimeters (five inches) (Revelle 1983). Revelle estimates that a 3*C warming could cause Greenland's glaciers to melt enough water to raise the sea another twelve centimeters in the next century. Antarctica could contribute to sea level rise either by meltwater running off or by glaciers sliding into the oceans.

Recent analysis by the Polar Research Board of the National Academy of Sciences indicates that glaciers in Greenland and East Antarctica, as well as those in West Antarctica, could eventually release enough ice into the oceans to raise sea level two or three centimeters (about one inch) per year.[8] However, current thinking holds that such a rapid rise is at least one hundred years away. Moreover, a complete disintegration of the West Antarctic Ice Sheet would take several centuries (Bentley 1983; Hughes 1983). It is possible that snowfall accumulation could partially offset the rise in sea level.[9]

In 1983, two independent reports estimated future sea level rise. In the National Academy of Sciences report Changing Climate, Revelle estimated that the combined impacts of thermal expansion, Greenland and mountain glaciers could raise sea level seventy centimeters (two and one-third feet) in the next century (Revelle 1983). Although he also stated that Antarctica could contribute two meters per century to sea level starting around 2050, Revelle did not add this contribution to his estimate.

In a report by the Environmental Protection Agency entitled Projecting Future Sea Level Rise, Hoffman, Keyes, and Titus (1983) stated that the uncertainties regarding the factors that could influence sea level are so numerous that a single estimate of future sea level rise is not practical. Instead, they consulted the literature to specify high, medium, and low estimates for all the major uncertainties, including fossil fuel use; the absorption of carbon dioxide through natural processes; future emissions of trace gases; the global warming that would result from a doubling of greenhouse gases (the NAS estimate of 1.50-4.50C); the diffusion of heat into the oceans; and the impact of ice and snow. They estimated that if all of the low assumptions prove to be correct, the sea will rise 13 cm (5 in) by 2025 and 38 cm (15 in) by 2075 over the 1980 level. If all of the high assumptions are correct, the sea will rise 55 cm (2 ft) by 2025 and 211 cm (7 ft) by 2075. However, because it is very unlikely that either all the high or all the low assumptions will prove to be correct, the authors concluded that the rise in sea level is likely to be between two mid-range scenarios of 26 to 39 cm (11 to 15 in) by 2025 and 91 to 136 cm (3 to 4-1/2 ft) by 2075. Figure 4 and Table 1 illustrate the EPA and NAS estimates. Although neither of these studies examined options to limit. the rise in sea level by curtailing emissions, Seidel and Keyes (1983) estimated that even a ban on coal, shale oil, and synfuels would only delay the rise in sea level expected through 2050 by twelve years.

The East Coast of the United States is slowly sinking (Hoffman, Keyes, and Titus 1983). Thus relative sea level rise at Ocean City, Maryland, will be fifteen to twenty centimeters (six to eight inches) greater than global sea level rise per century. Table 2 displays the projected rise at Ocean City for the EPA mid-range scenarios and current trends.

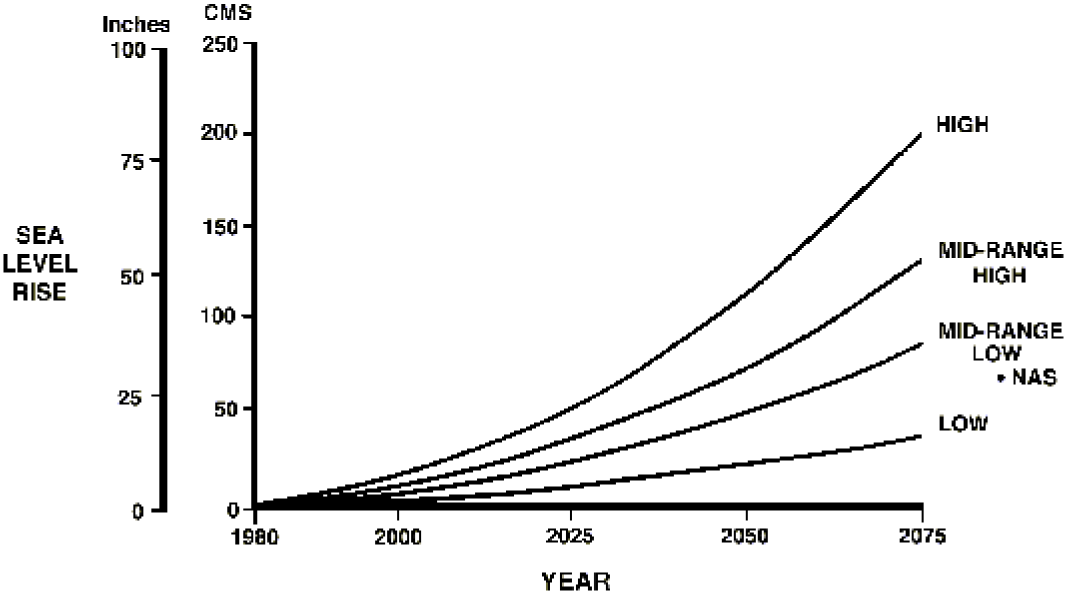


Figure 4. Global Sea Level Rise Scenarios: Low, Mid-Range Low, Mid-range High, and High.

Sources: J. Hoffman, D. Keyes, and J. Titus, Projecting Future Sea Level Rise, Washington, D.C.: Government Printing Office, 1983; Changing Climate, Washington, D.C.: NAS Press, 1983 (does not include Antarctica).

Table 1. Scenarios Of Worldwide Sea Level Rise (centimeters)

	2000	2025	2050	2075	2080	2100
Current Trends	2.0-3.0	4.5-6.8	7.0-10.5	9.5-14.3	10-15	12.0-18.0
EPA Scenarios						
High	17.1	54.9	116.7	211.5	-	345.0
Mid-range high	13.2	39.3	78.9	136.8	-	216.6
Mid-range low	8.8	26.2	52.6	91.2	-	144.4
Low	4.8	13.0	23.0	38.0	-	56.2
NAS Estimate (excluding Antarctic Contribution)	-	-	-	-	70.0	-

Table 2. Relative Sea Level Rise Scenarios For Ocean City, Maryland (absolute rise over 1980 level in centimeters (feet)

Year	Current Trend	Mid-Range Low Rise	Mid-Range High Rise
2000	7 (0.24)	12.4 (0.40)	16.8 (0.55)
2025	16 (0.53)	34.3 (1.13)	47.4 (1.55)
2050	25 (0.83)	65.2 (2.14)	91.5 (3.00)
2075	34 (1.13)	108.3 (3.55)	153.9 (5.05)

Source: J. Hoffman, D. Keyes, and J. Titus, Projecting Future Sea Level Rise, Washington, D.C.: Government Printing Office, 1983, R. Revelle, ""Probable Future Changes in Sea Level Resulting From Increased Atmospheric Carbon Dioxide, ""Changing Climate, 1983. S. Hicks, H. Debaugh, and L. Hickman, Sea Level Variations for the United States 1855-1980, Rockville, MD: U.S. Department of Commerce, NOAA-NOA, January 1983.

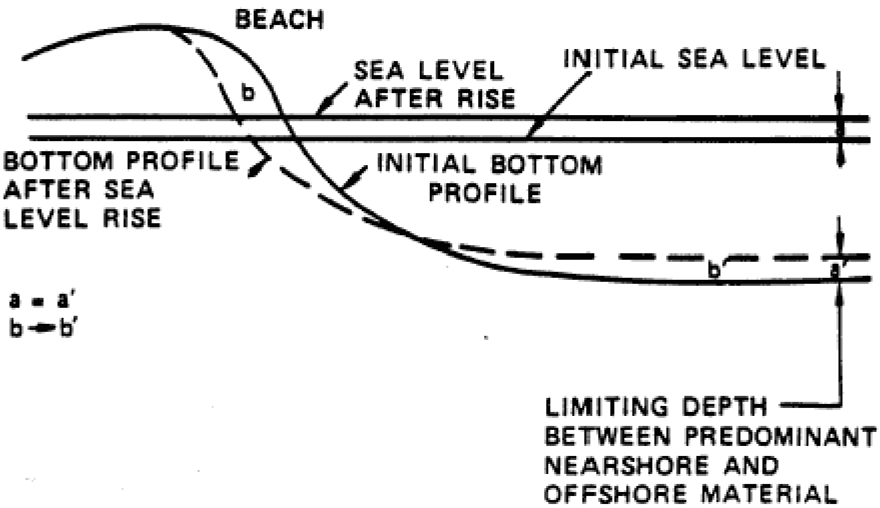
IMPACTS OF SEA LEVEL RISE

The physical impacts of sea level rise can be divided into five categories: (1) inundation of low-lying area; (2) erosion of beaches, particularly along the open coast; (3) increased flooding and storm damage; (4) increased salinity of surface and ground water; and (5) higher water tables. Most of the land low enough to be inundated in the next century consists of wetlands, such as the salt marshes along the Chesapeake Bay, and various coastal estuaries, such as Sinepuxent and Chincoteague Bays near Ocean City. At the rate of sea level rise of thirty centimeters (one foot) per century as has occurred in the last century, most salt marshes can keep pace with the rising sea through sedimentation and growth of vegetation (Orson, Panageotou, and Leatherman 1985). However, they probably could not keep pace if the sea rose much more rapidly. In fact, a report by the U.S. Fish and Wildlife Service cites sea level rise as a cause of marsh loss at Blackwater Refuge on the Eastern Shore (Pendleton and Stevenson 1983).

Although existing marsh would drown, new marsh could form inland. For example, Kana, Baca, and Williams (1985) estimate that Charleston, South Carolina would only lose 50 percent of its marshes with a one-meter rise, as long as people did not prevent new marsh from forming. However, development may prevent a I.andward migration of marshes and force these ecosystems to be lost. Decision makers might prefer to delay consideration of this issue until there is more certainty about future sea level rise. However, this strategy could make it impossible to avoid a future large-scale loss of coastal wetlands and property. Decisions being made today largely determine whether or not development will prevent marshes from forming inland. Most building codes, master plans, and zoning codes assume that once an area just inland of the marsh is developed, it will remain that way forever; but for wetland ecosystems to survive, these areas would have to become undeveloped once again."

Sea level rise could also cause land that is above sea level to erode. Along the coast of Maryland, winter storms and occasional hurricanes erode the beach and deposit the sand off shore. Waves during calm periods "dredge" the sand off the nearshore bottom and redeposit it on the beach. Sea level rise results in a net erosion of the beach by allowing storm waves to strike further inland and by decreasing the ability of calm waves to rebuild the beach[12] . Figure 5 illustrates the upward and landward shift of the beach profile that accompanies sea level rise, commonly known as the Bruun Rule (Bruun 1962). Along most U.S. beaches, a thirty-centimeter (one-foot) rise in sea level would cause approximately thirty meters (one hundred feet) of erosion, although the actual amount depends on the wave climate and beach profile. Rather than erode in place, coastal barrier islands would migrate landward, as storms push from the ocean side to the bay side.

Figure 5. The Bruun Rule: A Rise In Sea Level Causes Beach Erosion.



If the sea rises one foot, so will the offshore bottom. The sand necessary to raise the bottom (area b') can be supplied by artificial beach nourishment or by waves eroding the upper part of the beach (area b).

Sources: Adapted from Schwartz, 1967. "The Bruun Theory of Sea Level Rise as a Cause of Shore Erosion," Journal of Geology, 75:76-92.

Perhaps the most economically important consequence of sea level rise would be increased flooding and storm damage. The direct impact of a one-meter rise in sea level would be to raise storm flood levels by one meter. However, several other indirect effects could further increase damages. Erosion from sea level rise would leave some coastal property more vulnerable to storm waves. Coastal stormwater drainage systems would operate less effectively. Finally, higher water tables and surface water levels would decrease natural drainage.

Other consequences of a greenhouse warming could also have impacts on flooding. Warmer temperatures would intensify the hydrologic cycle and increase worldwide rainfall by 10 percent or more (Rind and Lebedeff 1984). Although predictions for particular areas are not possible, rainfall would presumably increase in some coastal areas. Furthermore, because hurricanes require an ocean temperature of 270C (790F) to form (Wendland 1977), a global warming may extend the hurricane season or result in hurricanes forming at higher latitudes. However, hurricanes depend upon many other factors, all of which must be assessed before meaningful statements about future hurricane frequency will be possible.

EPA has investigated several possible responses to erosion and flooding caused by sea level rise. Gibbs (1984) estimates that the economic impact on Charleston, South Carolina, could be one to two billion dollars over the next century, but that anticipatory zoning and engineering measures could cut the potential losses in half. Webb and LaRoche examined the drainage systems of a watershed in Charleston. They concluded that a thirty centimeter (one foot) rise by 2025 would necessitate modifications (mainly additional pipes) to the drainage system that would cost $3 million to implement (Webb, LaRoche n.d.). However, if these modifications are incorporated into the planned overhaul of the system, the additional cost would only be $300,000.

The possible importance of salinity increases caused by sea level rise is poorly understood. The Delaware River Basin Commission has estimated that a thirteen-centimeter (five-inch) rise in sea level would cause the salt front in the Delaware River to migrate two to four kilometers (one to two miles) upstream. A rise of one meter could cause salt to move over twenty kilometers upstream, possibly threatening parts of Philadelphia's water supply, as well as aquifers in New Jersey recharged by the river (Hull, Titus, and Lennon n.d.). However, possible responses to such salinity increases have not been assessed, nor have the impacts on other estuaries.

Finally, a rising sea level would raise water tables. Flooding of basements and subway systems may be more frequent, necessitating additional pumps in some areas. No one has investigated the possible impacts on public sewer system in coastal areas.

OCEAN CITY CASE STUDY

Available research indicates that the impacts of even a one-foot rise in sea level would be important, but that the most adverse consequences could be avoided if communities take timely actions in anticipation of sea level rise. Unfortunately, most local governments do not have the resources to undertake sophisticated assessments of the potential implications. Regardless of the potential savings, the cost of undertaking a study is a hurdle that can prevent decision makers from considering the issue.

Development of low-cost erosion forecasting methods could substantially reduce the cost of assessing the impact of sea level rise. Although these methods lack the precision of more sophisticated analyses, their accuracy may be sufficient for long-range planning, where other variables such as economic growth and population are also uncertain.

To assess the potential for inexpensive assessments of sea level rise impacts, EPA contracted with three experts at low-cost erosion forecasts. This section describes the results of the three studies, each o-f which could be applied to other beach communities at a cost of $5,000-$10,000. Chapters 2 through 4 provide additional detail.

Present Trends

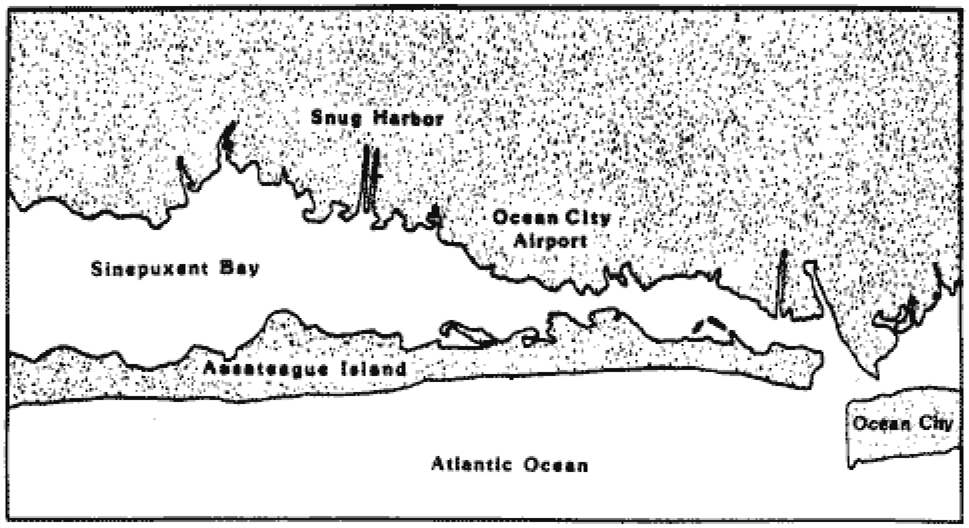
Like all ocean beaches, the beach at Ocean City exhibits a seasonal pattern. Winter storms erode the beach, while the calm waves of spring and summer rebuild it. In the long run, however, the shoreline has shown a slow but steady erosion trend. In the last fifty years, the beach has eroded over thirty meters (one hundred feet).

Leatherman (Chapter 2) and Everts (Chapter 3) offer very different explanations for the causes of this erosion. Leatherman argues that the erosion is caused by the long-term sea level rise of thirty-six centimeters (over one foot) in the last century. Everts estimates that substantial quantities of sand are being transported along the shore and off Fenwick Island, and that sea level rise is only causing 20 to 25 percent of the erosion. Leatherman acknowledges that alongshore losses are taking place, but suggests that the Delaware portion of the island, not Ocean City, is losing sand for this reason. Everts' perspective represents the general viewpoint of officials in Ocean City and the State of Maryland; however, Leatherman could also be correct if long-term sea level rise caused the alongshore transport of sand now observed.[14]

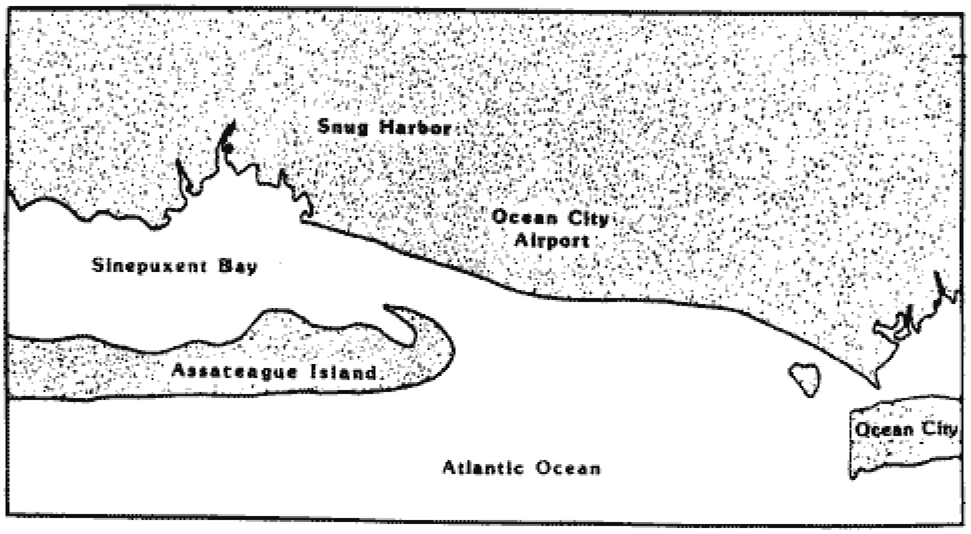
Another possible cause of the erosion could be the opening of Ocean City inlet (between Ocean City and Assateague Island) in 1933. A new inlet provides a sink for sand until tidal deltas (shoals) have been fully formed. Although the inlet was created by a hurricane, the construction of jetties along both ends has kept it open. It is generally recognized that the inlet and jetties have accelerated the erosion of Assateague Island to the south (Leatherman 1984)," which is illustrated in Figure 6; it is possible that they have also contributed to the erosion of Ocean City to the north.[16]

Figure 6. Current Shoreline and Projected Erosion At Assateague Island, Assuming Current Trends Continue.

1980 Shoreline



Projected Year 2000 Shoreline



Source: Revised from: Stephen P. Leatherman, "Shoreline Evolution of North Assateague Island, Maryland," Shore and Beach, (July) 1984, pp. 3-10.

Leatherman examined maps of Ocean City's shoreline dating back to 1850, estimating that in the last 130 years the shoreline has eroded 75 meters (250 feet), which implies a retreat rate of 0.6 meters per year. However, the shore has not retreated by an equal amount each year. Everts points out that since 1962, the shoreline of Ocean City has retreated by only 0.2 meters per year, and the shore of Bethany Beach, Delaware (to the north) has been advancing 0.3 meters per year. From 1929 to 1962 on the other hand, the shore retreated at a rate of one meter-per year.

In an appendix to Chapter 2, Bresee presents data showing the position of the shoreline and contours where the water is 10, 20, and 30 feet deep, for the years 1929, 1962, 1965, 1978, and 1979 at seventeen locations along the beach at Ocean City. Although coverage and season differed from year to year, it is possible to compare the data for 1962 and 1978 for the area south of 86th Street. Table 3 presents summary statistics of the erosion that has occurred during that time. Although the shoreline only retreated 9 meters (35 feet), the underwater portion of the beach eroded 35-45 meters (110-150 feet). In spite of the substantial variation of erosion along the shore, these results are statistically significant.

Table 3. Retreat of the Beach at Ocean City, Maryland
Between 21st and 86th Streets: 1962 to 1978[1]

Meters (feet)

		Contours		
	Shoreline	-10 ft	-20 ft	-30ft[2]
Mean Retreat	9.1 (30.0)	40.0 (131.1)	46.1 (151.1)	34.4 (112.9)
Standard Deviation Of Observations	17.0 (55.9)	26.5 (87.0)	35.3 (115.8)	62.7 (205.6)
Standard error Of the Estimate of the Mean Retreat[3]	5.7 (18.6)	8.8 (29.0)	11.8 (38.6)	23.7 (77.7)
Statistical Confidence Level (CL) for the Mean Retreat Exceeding Zero (%)[4]	90≤CL≤95	99.5≤CL≤99.95	99.5≤CL≤99.95	90.0≤CL≤95
Statistical Confidence Level (CL) for the Mean Contour Retreat Exceeding The Mean Shoreline Retreat[5]	---	99.5≤CL≤99.95	97.5≤CL≤99	75.0≤CL≤80

1. Based on nine transects between 21st and 86th Streets. Transects at 3rd and 6th Streets are omitted because they are influenced by the jetty at Ocean City inlet.
2. Based on seven transects because data are not available at 55th and 66th Street transects.
3. Estimated as the standard deviation divided by the square root of the number of observations.
4. Estimated using the t statistic: t = mean/standard error of the estimate.
5. Estimated using the reported differences in retreat rates for the contours and the shoreline for each transect. The hypothesis tested is that the mean difference in the retreat rates is zero.

Leatherman points out that a continuous erosion rate would not be expected. Substantial erosion generally occurs during a major storm, with the calm waves gradually rebuilding (most of) the beach in subsequent years. Because there has been no major storm since the March 1962 northeaster (the worst storm on record), one would expect the shoreline to advance (or retreat more slowly). The slower rate of shoreline retreat does not necessarily imply that the entire beach system is eroding more slowly. The sand washing from off shore back onto the shore would generally imply that the offshore part of the beach system should be eroding more rapidly than the shore itself. For this reason, Leatherman uses the long-term rate of historical shoreline retreat in projecting future erosion.

Everts identifies human activities that may also be causing the visible portion of the beach to erode more slowly than the underwater portion. After the 1962 storm, the Corps of Engineers placed about one million cubic meters of sand on the upper part of the beach system. Furthermore, in the last several years, Ocean City has used bulldozers to push sand landward from the shore, expanding the visible portion of the beach at the expense of the underwater portion. Finally, groins may also tend to steepen the profile. If groins have their intended effect, they slow erosion of the upper part of the beach; however because they extend at most to the -10 foot contour, they do nothing to slow erosion of the rest of the profile.

The analyses by Leatherman and Everts imply that current observations of shoreline retreat may be causing people to underestimate the severity of current long-term erosion trends. If they are correct in concluding that the -20 and -30 foot contours have retreated substantially, a severe storm could restore the profile and cause severe erosion. In Chapter 4, Kriebel & Dean estimate the erosion that would result from a severe storm, using their storm climatology model, which accurately predicted the erosion that Hurricane Eloise caused along the coast of Florida. Kriebel & Dean project that a recurrence of the March 1962 northeaster (a 50-year storm) would cause the dune line to erode 20-35 meters (70-120 feet) for dunes with heights of 3.0-4.5 meters (10-14 feet). Even the presumably more imminent 10-year storm would cause 15 meters (50 feet) of erosion.

Table 4. Projected Erosion At Ocean City
Meters (feet) of Shoreline Retreat Relative to its Current Position

	Current Trends							
	2000		2025		2050		2075	
Bruun[1]	4.9	(16)	11.0	(36)	17.0	(57)	23.0	(77)
Everts	21.0	(68)	46.6	(153)	72.5	(238)	98.5	(98.5)
Leatherman[2]	12.0	(39)	26.0	(85)	40.8	(134)	55.5	(55.5)
Kriebel & Dean	20.0	(66)	46.6	(153)	70.4	(231)	95.4	(95.4)
	Mid-Range Low							
Bruun1	6.7	(22)	22.0	(72)	42.7	(140)	70.4	(231)
Bruun Adjusted[3]	23.0	(74)	57.6	(189)	98.1	(322)	147.0	(483)
Everts	26.0	(84)	72.5	(238)	132.0	(434)	215.0	(707)
Leathermen	20.0	(64)	55.5	(182)	105.0	(345)	174.0	(572)
Kriebel & Dean	22.3	(73)	54.9	(180)	92.7	(304)	-	(460)
	Mid-Range High							
Bruun[1]	12.0	(22)	32.3	(106)	62.8	(206)	105.0	(346)
Bruun Adjusted[3]	27.0	(90)	68.0	(223)	118.0	(388)	181.0	(593)
Everts	29.0	(95)	83.2	(273)	156.0	(511)	268.0	(878)
Leatherman	27.0	(89)	76.2	(250)	147.0	(483)	249.0	(813)
Kriebel & Dean	26.2	(86)	65.8	(216)	107.0	(353)	168.0	(550)

1. Bruun Rule is included for completeness. Because it includes only the impacts of sea level rise, it needs to be adjusted for along shore and other losses in areas like Ocean City.
2. Leatherman's estimates are based on shoreline maps dating back to 1850. If he had used only the period since 1962, his estimates would be much lower. He deemed the longer series more appropriate because the –10, -20, and -30 foot contours have continued to erode at the long-term rate of shoreline retreat.
3. Bruun Rule Adjusted includes 2.6 feet per year due to factors other than sea level rise. Because 2.6 is derived from Everts, Bruun Adjusted is equal to Everts for current trends.

Future Projections

Table 4 summarizes the estimates of future erosion presented in Chapters 2. 3, and 4. For current trends, Leatherman's projections are more conservative than Everts' or Kriebel & Dean's. Leatherman estimates that the shore would erode 25 meters (85 feet) by 2025, whereas the other researchers estimate a retreat of about 45 meters (150 feet). However, he projects a greater increase in erosion due to sea level rise. Using EPA's mid-range low scenario (which is close to the National Academy of Sciences estimate), Leatherman, Everts, Kriebel & Dean, and our adjustment of the Bruun Rule project erosion in the 55 to 72-meter (180 to 238-foot) range for the 30-centimeter (1-foot) rise in sea level that would occur by 2025. For the mid-range high estimate, the four estimates, range from 66 to 83 meters (216-273 feet). By 2075, the erosion estimates range from 140 to 215 meters for the mid-range scenario, and from 170 to 250 meters for the mid-range high scenario.

Because Ocean City's policy is to maintain its current shoreline, Everts and Kriebel & Dean also estimated the quantity of sand necessary to maintain the shore at Ocean City in its current location. Although Leatherman did not estimate sand requirements, we have calculated sand quantities implied by his estimates of shore retreat. As with the erosion projections, we have also adjusted Everts' application of the Bruun Rule to include alongshore losses of sand.

Table 5 displays the estimates of sand necessary to maintain Ocean City's shoreline through 2075, assuming that the beach profile remains the same an ' average. All of the estimates for the mid-range low scenario are in the range of 3-4 million cubic meters (4-5 million cubic yards) by 2000 and 8.4-10.0 million cubic meters (11-13 million cubic yards) by 2025. For the mid-range scenario, the estimates are 4.0-4.6 million cubic meters (5-6 million cubic yards) by 2025 and 10.0-12.2 million cubic meters (13-16 million cubic yards) by 2025. However, there is less agreement concerning what sand will be necessary if current trends continue. Kriebel & Dean's estimates are approximately twice that implied by the Leatherman analysis. This discrepancy is probably due to the fact that Kriebel & Dean assume that substantial sand will continue to be transported out of the area, whereas Leatherman assumes that on average, only sea level rise will cause a significant loss of sand. The Corps of Engineers Baltimore District notes that 2-3 million cubic yards of sand would be necessary to counter losses of sand without sea level rise. To put these quantities into perspective, Kriebel & Dean estimate that about one million cubic meters would be necessary to protect against a 100-year storm that remained for 24 hours.

Table 5. Sand Required To Maintain Current Shoreline (millions of cubic yards)

	2000	2025	2050	2075
Current Trends				
Bruun[1]	1.0	2.2	3.3	4.6
Everts	4.0	9.3	14.0	19.0
Kriebel & Dean	4.8	10.5	11.4	22.5
Leatherman Adjusted[2]	2.4	5.2	7.8	11.0
Mid-Range Low				
Bruun Adjusted[3]	4.6	12	20	29
Everts	4.6	11	19	28
Kriebel & Dean	5.5	13.3	22.1	33.2
Leatherman Adjusted	4.3	11	21	35
Mid-Range High				
Bruun Adjusted	5.5	13	23	35
Everts	5.2	13	22	34
Kriebel & Dean	6.3	15	25.9	40.2
Leatherman Adjusted	5.6	15	29	48

1. Bruun Rule is included only for completeness. It is not intended to estimate erosion in areas with significant along-shore losses.
2. Leatherman Adjusted is calculated by multiplying the ratio of Leatherman/Bruun estimates of erosion by the Bruun estimate of beachfill requirements.
3. Bruun Adjusted is equal to Everts for current trends.

All of the methods yield estimates within a factor of two, except for the unadjusted Bruun rule, which is not designed for communities with significant alongshore losses of sediment. Although more sophisticated methods may yield more precise estimates, the estimates provided by the Leatherman, Everts, and Kriebel & Dean approaches may be adequate for first-order consideration of seal level rise impacts.

Because the focus of this study is beach erosion, not flooding, the researchers did not examine other impacts that may also be important to Ocean City or other coastal communities. These impacts might include bay-side flooding, wave damage, and the risk of inlet breach.

Implications

Ocean City's most important asset is probably its beach. Every weekend in the summer, approximately 250,000 visitors flock to this coastal town to swim and sunbathe. For this reason, state and local governments have recognized the beach as a resource that must be maintained. Because moving buildings back as the shore erodes is economically infeasible, the governments have opted for erosion control measures.

The expected rise in sea level will substantially increase the costs of these measures and change the relative merits of various shore protection strategies. But unlike many less densely developed coastal barriers, Ocean City's structures (and its stated policy of protecting its shoreline) need not be threatened by sea level rise. The high recreational and property values would economically justify shore protection for the foreseeable future.

The Corps of Engineers estimates that the first 4 million cubic meters of sand would cost approximately $26 million ($6.5 per cubic meter), that the next 5 million cubic meters would cost about $35 million ($7 per cubic meter), and that another 2.2 million cubic meters could be obtained for about $25 million ($11.2 per cubic meter) (U.S. Army Corps of Engineers 1980). Thus, the cost of maintaining the beach at Ocean City would be about $20 million through 2000 and $60 million through 2025 if the EPA mid-range low scenario (similar to the National Academy of Sciences estimate) are correct. Even if the mid-range high scenario occurs, the beach could be protected through 2025 for about $85 million.

Although these cost estimates are not negligible, the implied cost of $1-2 million per year is small when compared with the economic activity that takes place at Ocean City. At a rate of seven million visitors per years the cost of protecting Ocean City's shore would appear to be less than 30('. per visitor. If sea level rises as projected, a beach protection plan would thus almost certainly be cost-beneficial. The Corps of Engineers estimated that the benefits from their proposed beach restoration would be $8 million per year, even though they did not consider accelerated sea level rise. The benefits from addressing the greater erosion that could occur with sea level rise would be much, greater.

Ocean City and the State of Maryland have tentatively decided to build groins at a cost of $400,000 each, as an interim measure until the Corps beachfill plan is implemented. To the extent that current erosion is caused by sand moving along the shore and out of Ocean City, these groins might enable the city to "keep its own sand" and curtail erosion. However, groins do not prevent erosion caused by sea level rise (Sorensen, Weisman, and Lennon 1984). Although most of the researchers in Chapters 2, 3, and 4 believe that sea level rise is only causing one quarter of the erosion today, they all agree that if sea level rises as projected, it will gradually become the overriding factor. Thus, if sea level rises, pumping sand onto the beach will eventually be necessary. This sand, however, would bury the groins and shorten useful lifetimes compared to what previous analyses have indicated

Future sea level rise would also change the types of benefits gained by undertaking shore protection measures. For example, the Corps of Engineers determined that the benefits of their recommended beachfill plan would far exceed the costs; but because most of these benefits would be from increased recreational use of the beach, not flood protection, they did not consider the plan to have high priority. The prospect of sea level rise implies that without additional protection, much of Ocean City will become much more vulnerable to storm damage. Thus, the flood protection benefits of beach restoration may be much greater than previously estimated.

In the long run, sea level rise may imply that it will be wise to construct new buildings somewhat inland of what would otherwise be the preferred location. For example, it may be advisable to build parking lots on the seaward side of new high-rises, which would allow a builder to use the entire lot but leave the building less vulnerable to erosion and flooding (and the building would cast its afternoon shadow onto the parking lot, not the beach). The fact that Ocean City officials will probably always be able to justify expenditures for the protection of Ocean City's many large buildings does not mean that they should not look for ways of reducing the eventual costs. After the cheapest twelve million cubic meters of sand are exhausted, the costs may start to climb. Furthermore, if communities in Delaware follow Ocean City's example and attempt to keep their own sand, the amount of Delaware sand washing into Maryland would decrease.

The steepening beach profiles may increase the difficulty of forming a public consensus to address erosion and sea level rise. Ocean City may become increasingly vulnerable to storms as the greater part of the beach erodes; yet as long as the visible part remains stable, few property owners will feel threatened, even if tidal gauges and scientific reports show a rise in sea level. A major storm could disrupt this complacency, especially if, as Leatherman projects, substantial permanent erosion occurs. If major property damage also occurred, there would be many opportunities to adjust to sea level rise in the rebuilding phase.

The fundamental difficulty of planning for sea level rise is that the probability and magnitude of the phenomenon are uncertain. Nevertheless, it is a risk that should be taken seriously when people make decisions. Although we have less experience with sea level rise than with other factors such as storms, our understanding of the causes and our ability to predict the likely range are already greater for sea level rise than for many factors that are routinely considered in major decisions, including the severity of the next major storm.

Sea level rise is a risk against which some policies may provide more effective insurance than others. Although groins were determined to be more cost effective than was beach nourishment at controlling Ocean City's alongshore erosion, the latter would also control erosion caused by sea level rise, whereas groins would not. As with all insurance policies, coastal decision makers must weigh the costs and risks of various alternatives and decide on a case-by-case basis whether it is prudent to insure against the risks of sea level rise.

NEXT STEPS

A rising sea level could cause the beach at Ocean City to erode hundreds of feet in the next few decades if control measures are not taken. The cost of controlling erosion is likely to be tens of millions of dollars through the year 2000 and perhaps as much as sixty million dollars through 2025. Although the commercial and recreational resources of Ocean City could easily justify such expenditures, opportunities to reduce these costs should be investigated. Erosion control strategies, post-disaster policies, and long-term planning are all areas where ongoing efforts should consider the risk of future sea level rise.

Erosion control measures should probably have the highest priority. Standard analytic procedures can be employed to examine whether the risk of sea level rise warrants a reconsideration of current strategies. Delaying such an analysis could have substantial costs: every year the city and state spend hundreds of thousands of dollars on groins that may be subsequently buried if sea level rises.

Incorporating sea level rise into post-disaster policies could be very helpful. In the aftermath of a major storm, people will be much better educated about the risks of erosion and sea level rise; and an educated public is much more likely to support efforts that properly address these long-term risks. However, the need to act quickly may preclude the careful consideration necessary to adequately adjust to rising sea level. These policies must be formulated before the storm.

Finally, Ocean City's long-term planning should consider sea level rise. Over the next 50-100 years, rising sea level could have an impact an coastal areas as important as the sudden popularity of beaches that took place starting in the 1950s. Although sufficient sand has been identified to address erosion expected in the next forty years, the financial health of Ocean City in the longer run will require identification of additional low-cost supplies. The ultimate question for coastal barrier communities like Ocean City will be whether to raise the entire island in place as the sea rises, or to plan around a retreating shore. But sea level rise also has important implications for decisions involving building location and design, future population, roads, canals, and wetland protection.

Adjustments to sea level rise may not always be easy. But they are more likely to be successful if people start to plan while the phenomenon is still a future risk, rather than wait until it is a current reality.

NOTES

1. Expenditures of sport fishermen have increased from $3 billion in 1960- to $18 billion in 1980. Expenditures of hunters have increased from $1 billion to $9 billion over the same period.
2. The number of recreational boats in U.S. waters has increased from 8.8 million in 1970 to 13.2 million in 1983. Expenditures in 1983 were $9.4 billion.
3. PL 90-448, Section 1302
4. PL 92-53, 16 USC 1451, Section 303.
5. For Massachusetts, see M.G.L. Ch. 131, S 40 Reg 310 C.M.R. 9,10(2) or Mass General Laws.
6. See: Clark, J.A., W.E. Farrell, and W.R. Peltier, 1978. "Global Changes in Post Glacial Sea Level: A Numerical Calculation." Quarternary Research 9:265-287. Note, however, that William Tanner of Florida State University suggests that there is a 3 percent chance that these factors could cause a rise or fall of one meter in a century. Personal Communication, William Tanner, Geology Department, Florida State University.
7. Studies on the greenhouse affect generally discuss the impacts of a $C0_2$ doubling. By "effective doubling of all greenhouse gases" we refer to any combination of increases in the concentrations of the various gases that causes a warming equal to the warming of a doubling of CO_2 alone. If the other gases contribute as much warming as $C0_2$, the effective doubling would occur when $C0_2$ concentrations have reached 450 ppm, 1.5 times the preindustrial level.
8. Robert Thomas, Jet Propulsion Laboratory, personal communication with John S. Hoffman, EPA..
9. Robert Thomas, Jet Propulsion Laboratory, personal communication with John S. Hoffman, EPA..
10. Computer printout underlying calculations from Seidel and Keyes, op. cit.

11. See: Titus, J.G., 1984. "Planning for Sea Level Rise Before and After a Coastal Disaster." In Barth, M.C. and J.G. Titus, op. cit.
12. The ability of waves to rebuild the beach is reduced in that a complete restoration of the original profile location would require the nearshore .water depths to be greater than they had been before the sea rose. As sea level rises, so must the nearshore bottom.
13. However, a town planner in Westerley, Rhode Island, estimates that a thirty-centimeter rise could contaminate over one hundred septic tanks along the town's shoreline. Griscom, Clement. Presentation to Rhode Island Sea Grant Conference on Sea Level Rise, November 29, 1984.
14. Sea level rise can contribute to alongshore transport if deeper water levels create sinks for sand in inlets and tidal shoals. Furthermore, unless slopes are uniform everywhere, sea level rise will tend to erode some areas more than others. The areas that erode the least will tend to later experience alongshore losses to areas that have eroded the most.
15. Conversations with local, state, national park, and Corps of Engineers officials, as well as citizen groups, indicate that most people believe that the jetty at the south end of Ocean City has filled with sand that would have otherwise washed onto Assateague. Robert Whalin, Director of the Coastal Engineering Research Center, however, states that recent research by his office shows that the jetties are not the only cause of erosion. Letter from Robert Whalin, Director of CERC, to James G. Titus, EPA, May 1985.
16. Although the predominant alongshore drift is to the south, the flow is occasionally to the north. During these periods, the inlet carries sand that would otherwise flow to Ocean City to shoals off shore.
17. Ed Fulford, Baltimore District, Corps of Engineers, letter to James G. Titus, EPA, May 1985.
18. Sandy Coyman, Town of Ocean City, Personal Communication.
19. Ed Fulford, Baltimore District, Corps of Engineers, letter to James G. Titus, EPA, May 1985.

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CHAPTER 2:

GEOMORPHIC EFFECTS OF ACCELERATED SEA LEVEL RISE ON OCEAN CITY, MARYLAND

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Introduction

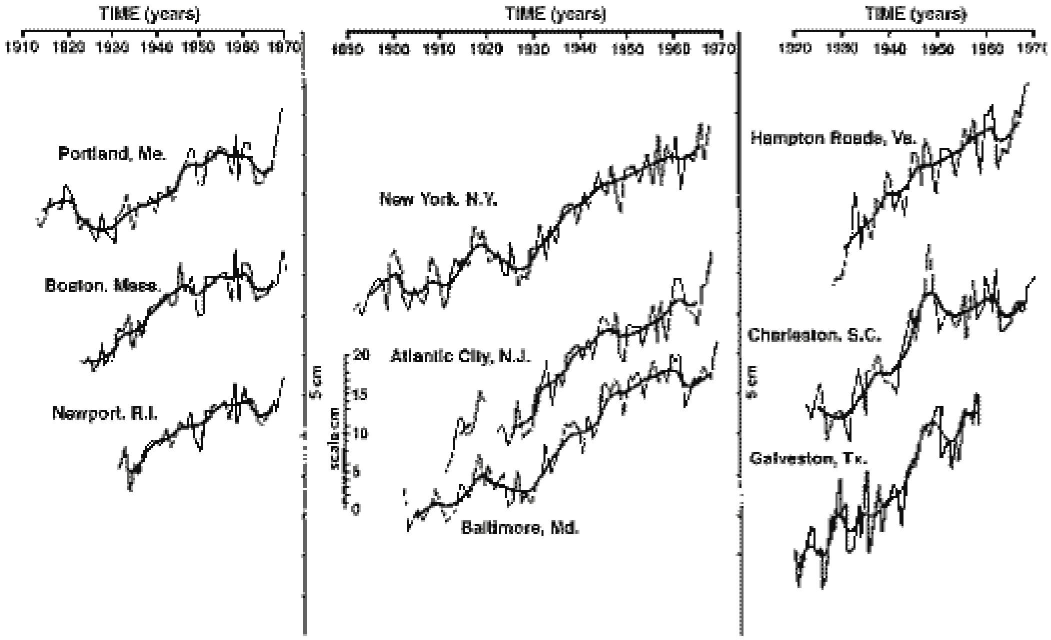
Coastal zones are inherently dynamic environments, being characterized by differing geomorphic processes and coastline configurations. To account for this wide variability in site and process, this study has combined analyses of historical trends and empirical approaches to model projected changes along Ocean City, Maryland. It evaluates the shoreline changes for a range of projected rates of sea level rise (baseline, mid-low and mid-high) at particular time periods (2025, 2050, and 2075).

Once digitized and transformed by a sophisticated shoreline mapping program, Metric Mapping (Leatherman 1983a), former shoreline positions portrayed on historical maps form the basis for projecting potential shoreline excursion rates as a result of sea level rise. These extrapolated rates can then be assessed in light of the possible impact that recent human modification may have on future trends.

This chapter first describes briefly the physical characteristics of the study area and then discusses projected shoreline responses to various EPA-derived sea level scenarios. It also contains an appendix describing the offshore changes associated with long-term sea level rise.

Sea level has always been rising or falling throughout geologic time relative to the land surface. The last major change in sea level occurred during the most recent Ice Age, when sea level was approximately 100 meters (three hundred feet) lower than at present. Although the rate of rise during the last several thousand years has apparently slowed, recent sea level changes based on tidal gauge data show a definite upward trend during this century (Fig. 1). Sea level may now be rising as fast as at any time during the last several thousand years (Gornitz, Lebedeff, and Hansen 1982).

Figure 1. Recent Sea Level Changes Along the U.S. Coast, Based On Tidal Gauge Data (from Hicks 1978)



An additional reason for concern over the recent rate of sea level rise is the increasing level of carbon dioxide in the atmosphere. If recent trends (largely resulting from the burning of fossil fuels) continue, some scientists believe that the atmospheric C02 could double in the next century. The - National Academy of Sciences has estimated that this doubling will raise the earth's average surface temperature by 1.50-4.50C (Charney 1979). Other gases could double the warming from C02 alone.

The sea level rise scenarios were taken from Hoffman et al. (1983); nine rise/year combinations were selected from the projected sea level rise curves. Table 1 presents the algebraic sum of the projected sea level rise and subsidence to yield the relative sea level rise for Ocean City. The table indicates, for example, that absent any accelerated sea level rise (i.e., the baseline scenario), by 2025 sea level will have risen by 0.53 feet. In the mid-range low scenario, sea level will have risen by 1.13 feet by 2025. This amount of rise would inundate or otherwise, dramatically alter low-lying coastal regions. Appendix I contains the nomenclature for shoreline interactions with sea level rise.

Table 1. Relative Sea Level Rise Scenarios
Cumulative Rise Over 1980 Level[1]

Time	Current Trend	Mid-Range Low Estimate	Mid-Range High Estimate
2000[2]	0.24 ft	0.40 ft	0.55 ft.
2025[2]	0.53 ft.	1.13 ft	1.55 ft.
2050[2]	0.83 ft	2.14 ft	3.00 ft
2075[2]	1.13 ft	3.55 ft	5.05 ft

1. Sea level rose 0.59 feet from 1930 to 1980, according to data from nearby tidal gauges (Hicks, Debaugh, and Hickman 1983) and interpolated using regional crustal deformation data (Holdahl and Morrison 1974).
2. These estimates, from the Environmental Protection Agency (Hoffman, Keyes, and Titus 1983), illustrate cumulative rise and include a 1.8 mm/yr local subsidence rate (1980 is the base year).

SITE DESCRIPTION

Ocean City, Maryland, is located on an Atlantic coastal barrier called Fenwick Island. It extends from the Delaware line to Ocean City Inlet (Fig. 2). Although Ocean City has been a resort community since the 1800s, it has experienced explosive growth during the last 15 years with the construction of high-rise condominiums (Fig. 3). The extensively developed barrier accommodates summer populations that often exceed 250,000 an peak weekends, although the permanent population is less than 6,000.

Although Ocean City has a tremendous economic investment in new real estate, there are only limited opportunities for reducing the potential of losing this existing development to flooding. Strong pressure will continue to be exerted for the continued development and redevelopment of Ocean City because of its established position as a major East Coast resort, its proximity to the major metropolitan areas of Washington, D.C., and Baltimore, Maryland (Humphries and Johnson, 1984), and because the National Parks Service owns the rest of Maryland's Atlantic Coast.

Barrier islands are dynamic landforms, subject to storm-surge flooding and sand transport processes. These coastal features are particularly vulnerable areas for human habitation, since they extend seaward of the mainland and are composed entirely of loose sediment (Leatherman, 1982). Coastal hazard planning on barrier island resorts, such as Ocean City, Maryland, often fails to recognize natural geological and geomorphic processes and their consequences on the built environment and related habitation. In defense of planning methods, coastal hazard analysis often suffers from lack of easily accessible and comprehensible data.

Figure 2. Location of Study Area Along The Delmarva Peninsula

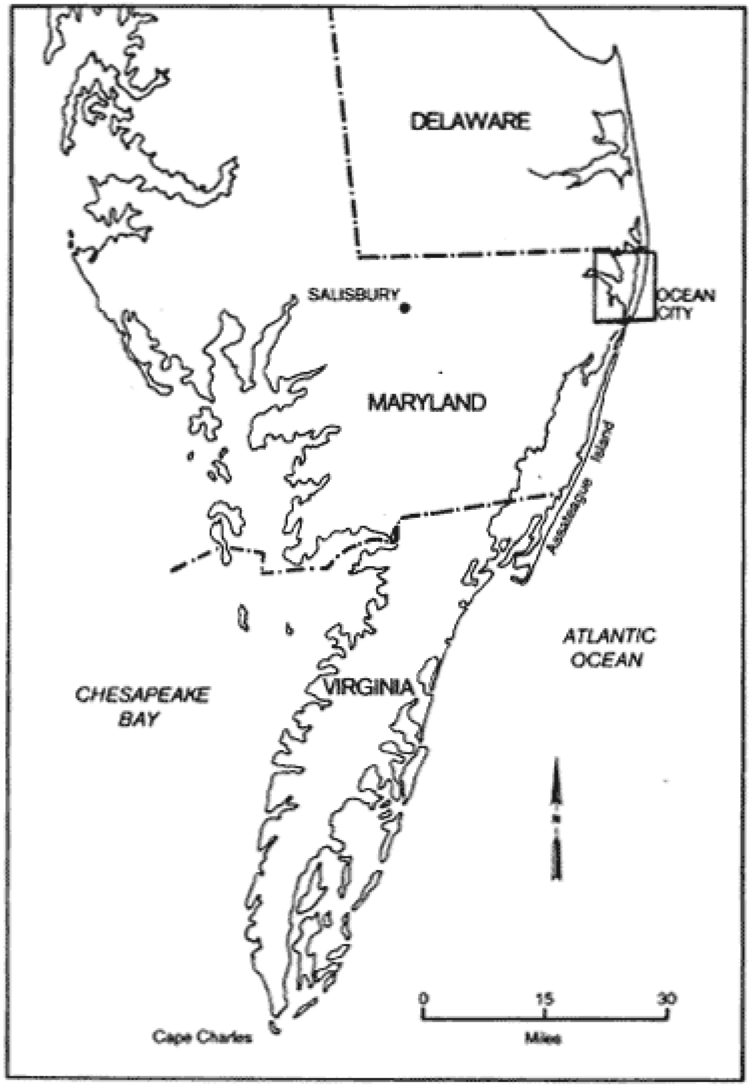


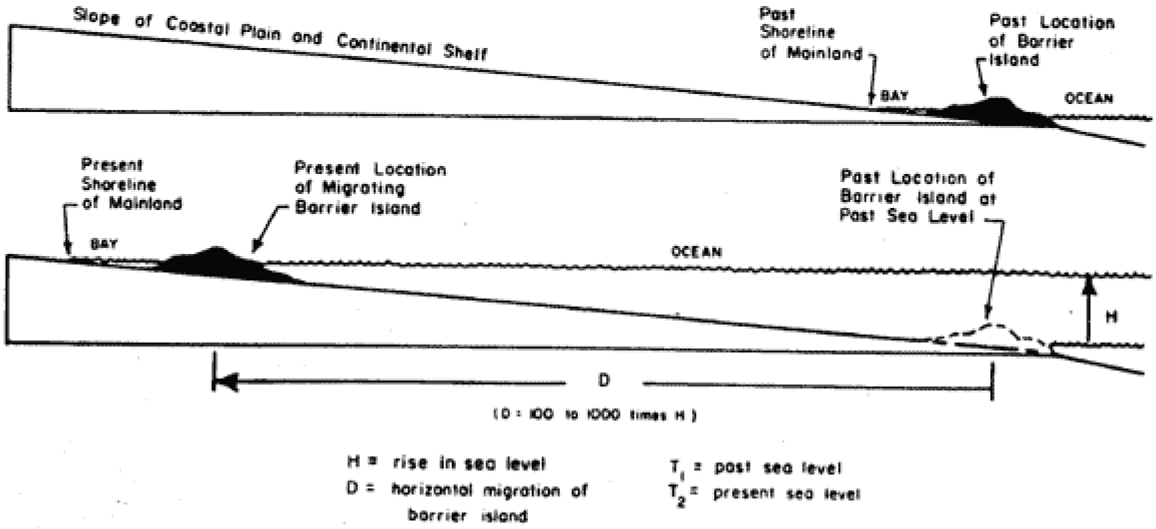
Figure 3. High-Rise Condominiums and Hotels Have Been Built
Only A Few Hundred Feet From The Water's Edge
(1974 photograph near 100 Street, Ocean City)

Physical Processes

Fenwick Island is characterized by low-lying topography fronting a shallow, microtidal embayment (Isle of Wight Bay). It is subject to flooding with even small rises in sea level. A slight vertical rise in sea level would result in significant horizontal displacement of the shoreline (Fig. 4). Also, storm surges superimposed on higher mean sea levels will tend to increase shoreline erosion, resulting in major economic losses.

The net transport of sand along the Atlantic Beach of Ocean City is to the south, although there are several reversals in this trend. The average annual net longshore transport is estimated to be 150,000 yd^3 (U.S. Army Corps of Engineers 1980). Since the stabilization of Ocean City Inlet with jetties in 1934-35, there has been a pronounced alteration of the adjacent shorelines for several miles in each direction. Updrift of the jetties at south Ocean City, a large amount of sedimentation has occurred. This shoreline progradation has necessitated the lengthening of the Ocean City fishing pier, and the north jetty is now impounded to capacity. A large portion of the sand moving southward in the littoral drift system is being swept seaward by the ebb tidal jet to form an enormous shoal (estimated volume is 8,000,000 cubic yards [Dean Perlin, and Dally 19781). Since little of this sand is bypassing Ocean City Inlet, the northern portion of Assateague Island is being starved of sediment and pushed landward (Leatherman 1979).

Figure 4. Landward Barrier Migration
Up The Gradually Sloping Coastal Plain
Over Geologic Time With Sea Level Rise.



ANALYSIS OF SHORELINE RESPONSE

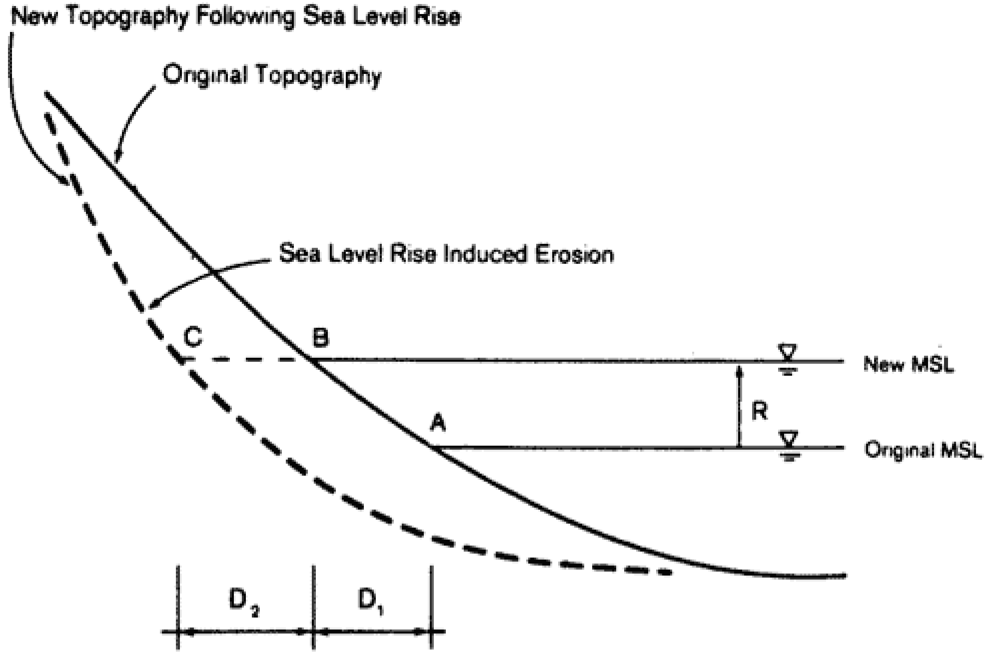
Barrier islands, such as Fenwick Island upon which Ocean City has been constructed, change position and shape, depending upon the relationship between sand supply, wave energy, and sea level. Since there are essentially no new sources of sediment for the barrier beyond that already in the sand-sharing system or in transit through the coastal sector (littoral drift), shoreline position responds to storms, coupled with long-term changes in water level.

Although storms are responsible for major coastal alterations, it is not certain that storms in the absence of water-level changes could continue to alter the shoreline in an onshore/offshore direction. Wave-driven longshore transport, which would erode headlands and build spits or fill concavities, would continue to operate in any case, so that static shoreline conditions would never be achieved. However, beach stability in a two-dimensional sense (Bruun Rule; see Chapter 1, Figure 5) should theoretically be reached; Seelig (1982) has shown that beach equilibrium can be achieved under wave-tank conditions.

Perhaps a constructive way of viewing the allied roles of sea level sets the stage for profile adjustments by coastal storms. Long-term sea level rise places the beach/nearshore profile out of equilibrium, and sporadic storms accomplish the geologic work in, a quantum fashion. Certainly major storms are required to stir the bottom sands at great depths off shore and hence fully adjust the profile to the existing water level. Therefore, our underlying assumption is that beach equilibrium will be the result of water-level position in a particular wave-climate setting.

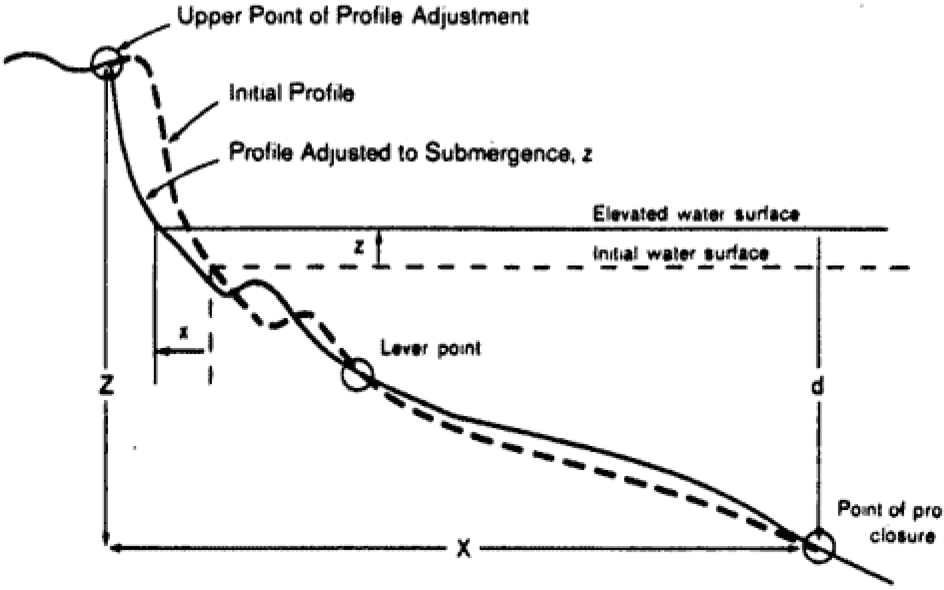
Figure 5 illustrates the combined effects of erosion and submergence due to sea level rise. The term DI represents the landward translation of the shoreline due to a simple inundation of the land; the response time is instantaneous. Hence, direct submergence of the land occurs continuously through time and is particularly evident in coastal bays where freshwater upland is slowly converted to coastal marshlands. This change is termed "upland conversion."

Figure 5. Shore Adjustment With Sea Level Rise



The second displacement term, D2, refers to a change in the profile configuration according to Bruun (1962). The Bruun Rule provides for a profile of equilibrium in that the volume of material removed during shoreline retreat is transferred onto the adjacent shoreface/inner shelf, thus maintaining the original bottom profile and nearshore shallow water conditions. Figure 6 is a more accurate depiction of this two-dimensional approach of sediment balancing between eroded and deposited quantities in an onshore/offshore direction without consideration of longshore transport. There can be an appreciable lag time in the shoreline's response to disequilibrium conditions.

Figure 6. Shore Adjustment To Change in Water Level. (after Hands 1976)



Research along the Great Lakes may prove instructive in estimating response rates of shorelines to water-level changes. Due to climatic periods of dry and wet conditions, lake levels have fluctuated by as much as six feet in little over a decade. During 1969 lake levels again were high, resulting in significant erosion of sandy beaches and cliffs along many lake shores. The Great Lakes are not subject to astronomical tides to any degree, so that this complicating variable was eliminated. Hands (1976) found that the Bruun Rule is confirmed by field surveys of beach profiles during rising lake levels. The volume of sand eroded from the beach nearly matched off shore deposition. Hands (1976) also found that deposition extended off shore to a distance roughly equal to twice the height of a five-year storm wave. The lag time in shoreline response to lake level was rather rapid (approximately three years) because the lakes are subject to frequent storm activity in the fall and winter before surface icing.

The Great Lakes research may prove to be a useful analog in considering the response of open ocean shorelines to long-term sea level rise with qualifications. The Ocean City beaches are characterized by unconsolidated sandy sediments, which are easily mobilized during major storms. The extent of beach response depends only on the ability of waves to supply sufficient energy to the system to accomplish the required work (to obtain profile equilibrium in accordance with water-level position). Therefore, shore-response lag times are tied to storm intensity and frequency.

Along the mid-Atlantic Coast, both extratrapical (northeasters) and tropical (hurricanes) storms are responsible for generating large waves capable of significant beach erosion. Ocean City is subject to several northeasters each winter, many of which cause moderately high tides and flooding. The March 1962 northeaster was more severe and damaging than any previously known storm to have affected the area. This winter storm was complex in structure and unusual in behavior (Bretschneider 1964). It produced a storm tide of 7.8 feet NGVD (National Geodetic Vertical Datum), since the wind-driven tides were superimposed on a high spring tide.

Hurricanes generally produce higher tides than northeasters but are much less frequent. The last hurricane of significance to affect Ocean City was Hurricane Donna, which occurred on September 12, 1960 (Table 2).

Table 2. Major Storms of Record For Ocean City, Maryland[1]

Storm	Type[2]	Storm Surge[3] (ft)	Damage Estimate
23 Aug. 1933	H	6.3	$ 500,000
21 Sept. 1938	H	7	minor
14 Sept. 1944	H	7	$ 250,000
12 Sept. 1960	H	7	$ 340,000
6-8 March 1962	N	7.8	$11,290,000

1. From U.S. Army Corps of Engineers 1980
2. Type: H = hurricane; N = northeaster
3. Water level above NGVD.

Figure 7 shows the tidal frequency curve for Ocean City, Maryland. Tidal elevations for storms with return intervals of between 5 and 500 years are shown. The annual frequencies of hurricanes and northeasters were determined separately and then summed to obtain the overall annual frequency at that level, as depicted on this graph (U.S. Army Corps of Engineers 1980). The lull in storm occurrence along the mid-Atlantic Coast during the past two and a half decades has corresponded with the period of major coastal construction. Ocean City expanded greatly in the early 1970s with the construction of high-rise condominiums and hotels. Therefore, Ocean City's beach profile is out of adjustment with sea level changes (by more than 25 years), and this trend will continue until the area is again directly affected by a major hurricane. Therefore, there is an appreciable time lag in shoreline response, depending upon the local storm frequency, which can only be dealt with statistically (at recurring intervals--a frequency/magnitude approach).

Figure 7. Open-Coast Storm Surge Frequency
for Ocean City, Maryland
(U.S. Army Corps of Engineers 1980)

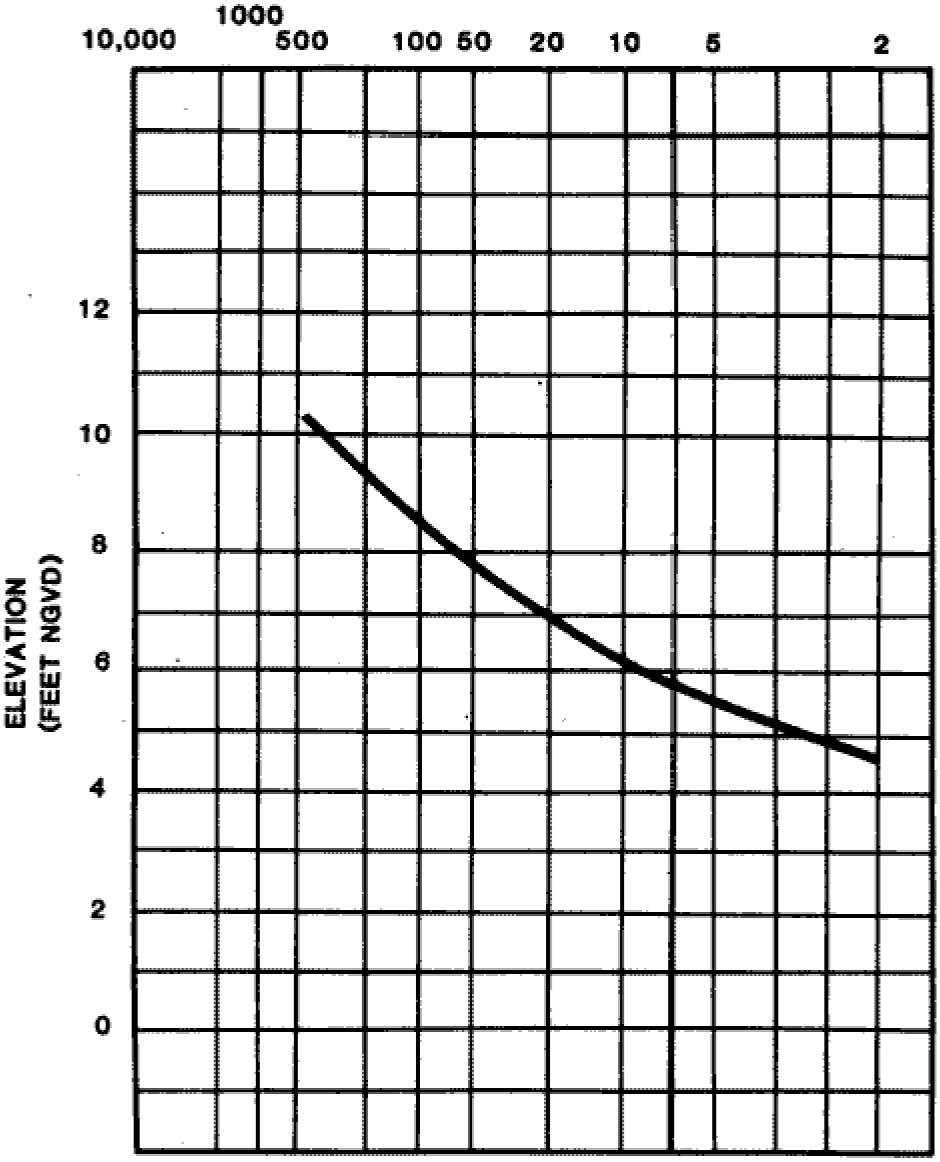
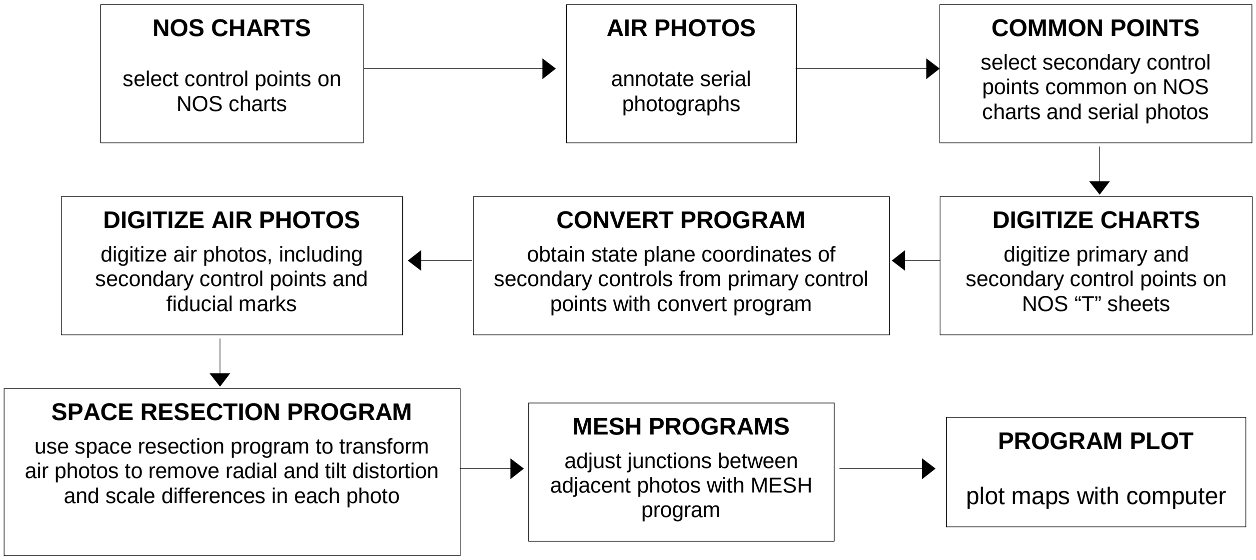


Figure 8. Metric Mapping Technique



METHODS

A shoreline mapping procedure, termed Metric Mapping, has been recently developed to quantify historical shoreline changes with a high degree of accuracy (meets or exceeds National Map Accuracy Standards) and relatively low cost (Leatherman 1983a). This automated technique has been designed to use the high-speed capabilities of a computer to simulate the best photogrammetric techniques. A flow chart depicting the steps involved in producing the computer-plotted maps is shown in Figure 8, and complete discussion of the procedure may be found in Leatherman (1984).

A large data set on historical shoreline positions (mean-high-water level) is available from the National Ocean Service. This information included U.S. Coast & Geodetic Survey charts (now called NOS "T" sheets) for the years 1849/50, 1908, and 1929/33, as well as vertical aerial photographs (1942, 1962/63, and 1977/80). Therefore, six sets of historical shorelines were available for the study area, spanning approximately the last 130 years (1850-80).

The Computer Mapping Laboratory of the University of Maryland's Department of Geography was used for shoreline data manipulation and plotting. The six shorelines were overlaid and plotted to scale on the computer-generated maps. Shorelines were differentiated by various dot-dash patterns. As a result of this research, the mapping program was further refined to provide rates of shoreline change. This refinement is not trivial, since shorelines are rarely straight; the base line for measurement must be at all places perpendicular to the, shoreline to provide accurate information. Measurements are taken orthogonal to the measurement base line (or spine) at a preselected distance, where the spine is parallel to the shoreline. For each transect, a table of statistics on shoreline change is generated, and a summary histogram for each time period is prepared. From these data sets and summary statistics of the historic trend, a projection of future shoreline changes can be made. *

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[*] This task was accomplished manually for this project, but we plan to write a computer program to simulate spatial changes in a temporal sense, using historical shoreline movements and physical relationships as the required inputs (Leatherman and Clow 1983).

While this approach is less quantitative for modeling purposes than the Bruun method, it is more realistic in a geomorphic sense. The Bruun (1962) concept is essentially a two-dimensional approach, representing the sediment balance between eroded and deposited quantities in an onshore/offshore direction, without considering longshore transport. The technique used for this study involves the empirical determination of projecting new shorelines using trend lines. In this case, the shoreline response is based on the historical trend with respect to the local sea level changes during that time period. This procedure accounts for the inherent variability in shoreline response based on differing coastal processes, sedimentary environments, and coastline exposures (Leatherman 1983b).

The relationship between sea level rise and shoreline movement is formulated by assuming that the amount of retreat from the historical record is directly correlated with the rise rate of sea level. Therefore a 3X rise in sea level will result in a 3X increase in the retreat rate, assuming lag effects in shoreline responses are small compared to overall extrapolation accuracy.

Tidal gauge records document the local (eustatic effects plus isostatic effects, such as subsidence) rate of sea level change over the period of record. Records from nearby tidal gauges indicate that sea level rose about 0.59 feet between 1930 and 1980 (Hicks, Debaugh, and Hickman 1983). A portion of this apparent rise was probably due to subsidence. The relative sea level rise scenarios for baseline (current trend), mid-range low, and mid-range high include a 1.8 mm/yr local subsidence rate (Koffman, Keyes, and Titus 1983).

RESULTS

Historical shoreline changes along Ocean City are shown in Figure 9. The average rate of Oceanside erosion over the 130 years of record has been 1.9 feet per year, but there has been much variation along this shoreline. Histograms of shoreline change indicate some reversals of this trend, particularly at stations I through 13 (Figs. 10-13). This phenomenon could be due to large-scale, low-amplitude sand waves migrating downdrift along the shoreline. However, for most of the Ocean City shoreline, the overall trend has been long-term erosion (Fig. 14).

There are clearly gradients in the longshore transport of sand due to differential wave refraction and other effects that give rise to alongshore variations in shoreline trend (Goldsmith et al. 1974). Since the littoral nodal point for the Delmarva coastal compartment is believed to be located near Bethany Beach, Delaware (U.S. Army Corps of Engineers 1980), it can be assumed that over hundreds of years the littoral influx and outflux of sand at Ocean City should be approximately equal, except near the jetty. If this is correct, then the long-term losses of sand to the off shore, evident along the Ocean City shoreline, are due to historical sea level rise, which has averaged approximately 1.2 feet per century (Hicks 1978). Therefore, future shoreline location and erosion rates can be predicted on the basis of anticipated sea level rise (Leatherman 1983b).

From 1930 to 1980, the relative sea level rise was 0.59 feet (Hicks, Debaugh and Hickman 1983). This equates to 190 feet of erosion during the last 100 years with 1.18 feet of rise; thus, a 1-foot rise would correspond to 161 feet of erosion. Using the straight-'line method of extrapolation as previously explained, then shoreline change can be projected for the nine rise/rate combinations (Table 3). The amount of shoreline recession varies from 39 feet (baseline) to 89 feet (mid-range high) for the year 2000 and from 182 feet (baseline) to 813 feet (mid-range high) by 2075. At present, the beaches along Ocean City are critically narrow, particularly during the high-energy winter months. Therefore, the current trend of recession exacerbates the problem and increases the vulnerability. Accelerated sea level rise increases the rate of retreat by two to five times, thereby significantly reducing the planning time for hazard mitigation and significantly increasing the vulnerability of the urbanized area through time.

Figure 9. Comparison of Historical Shoreline Changes
Along Ocean City, Maryland
(1850-1980)

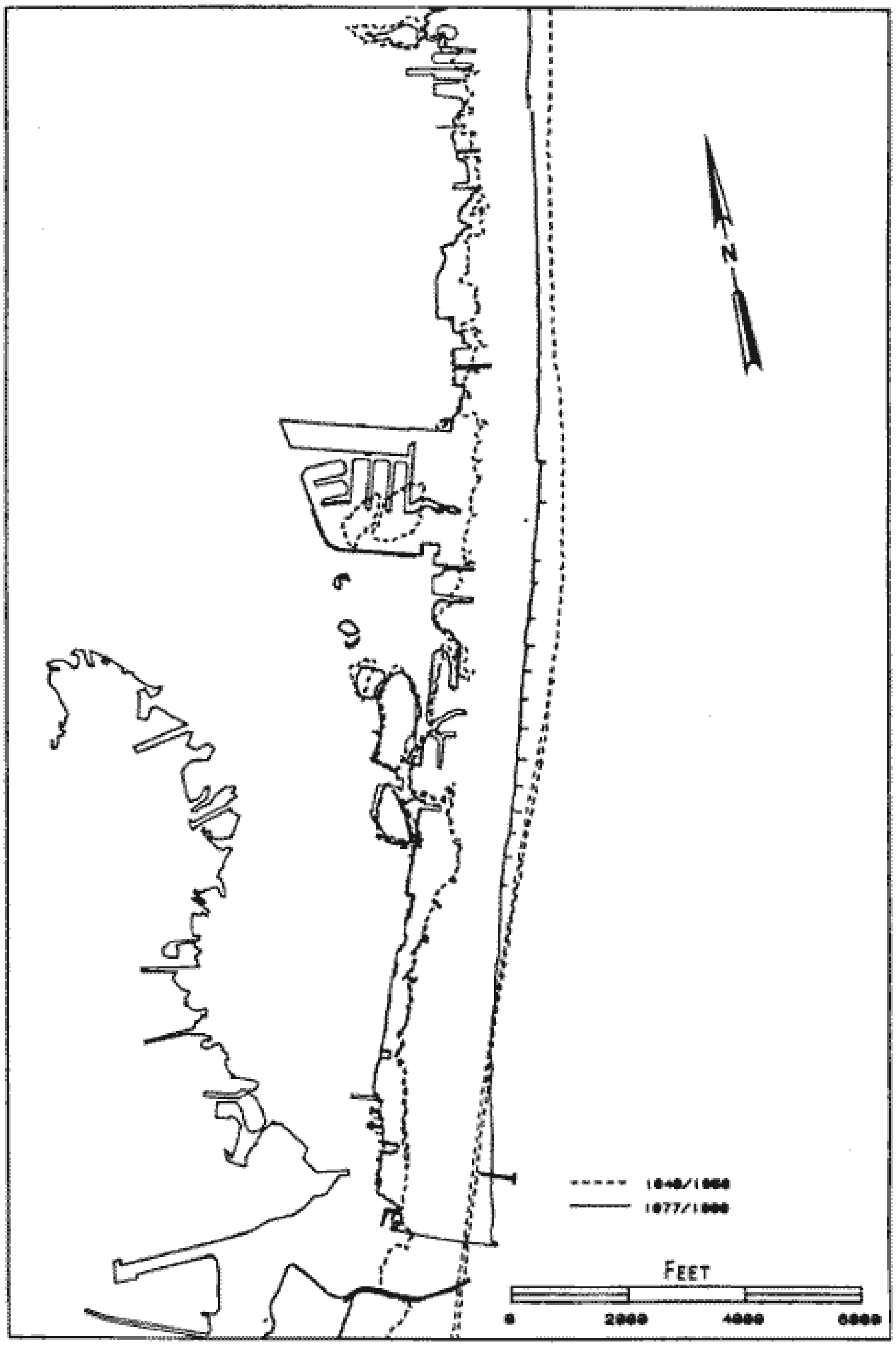

Figure 10. Index Map of Ocean City Showing Transects Used by Program That Measures Shoreline Changes

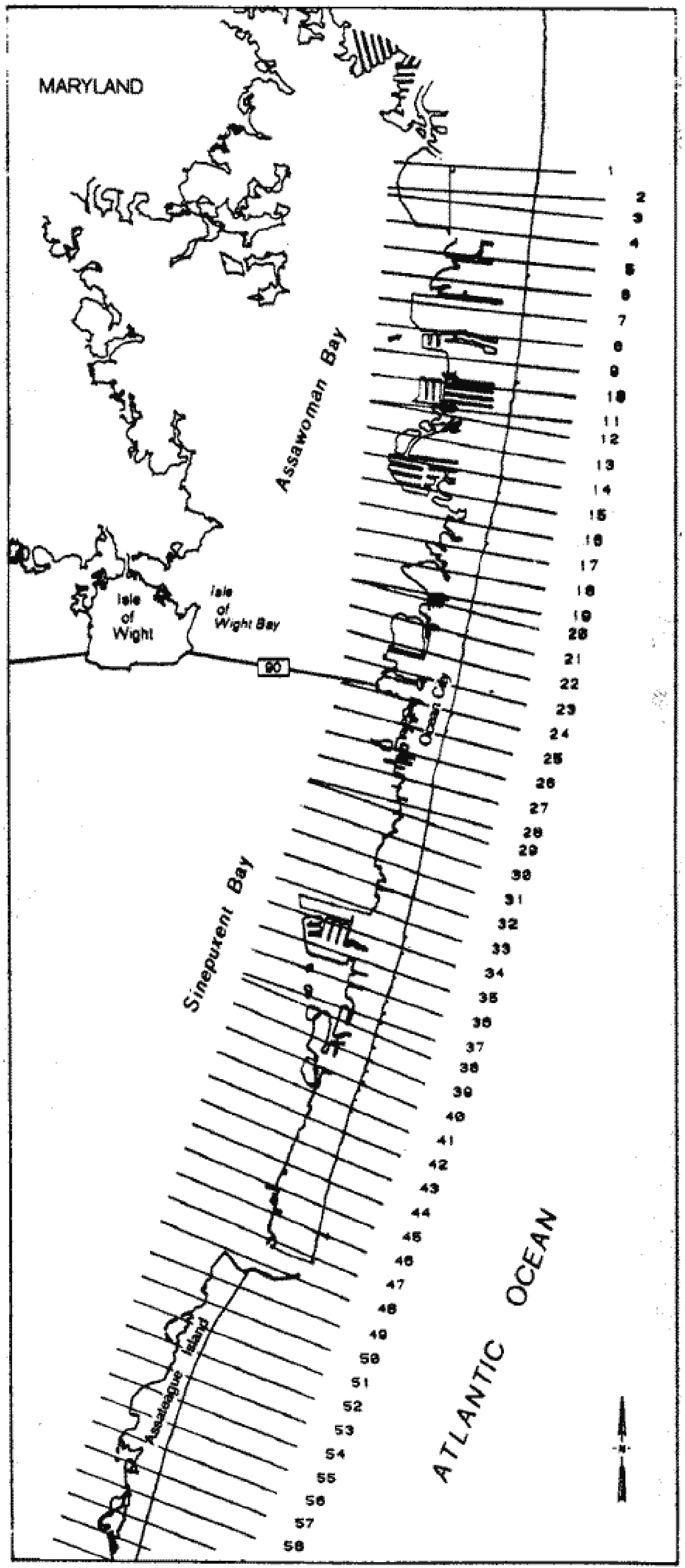

Figure 11. Histogram of Historical Shoreline Changes (1929 – 1942) Transects 1 to 45 Are Along Ocean City, Maryland.

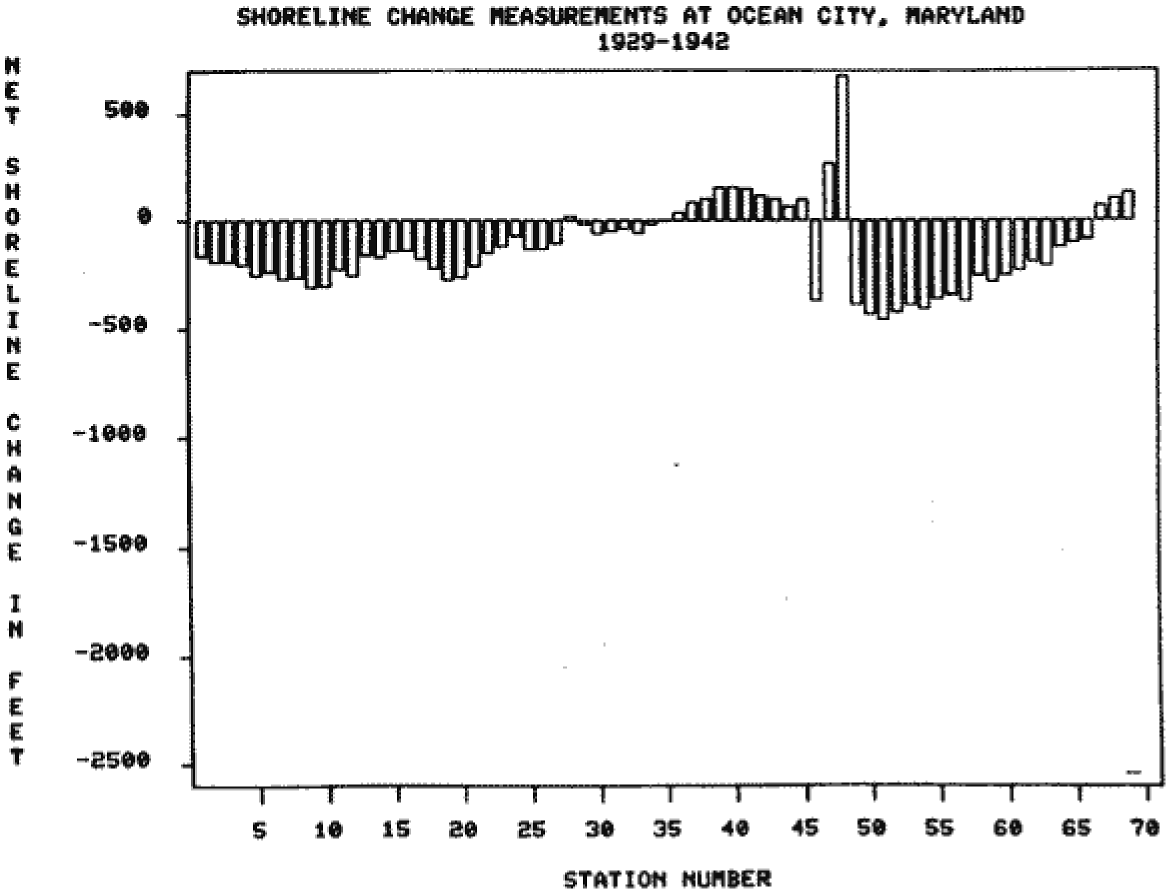

Figure 12. Histogram of Historical Shoreline Changes (1942 – 1962)
Transects 1 to 45 Are Along Ocean City, Maryland.

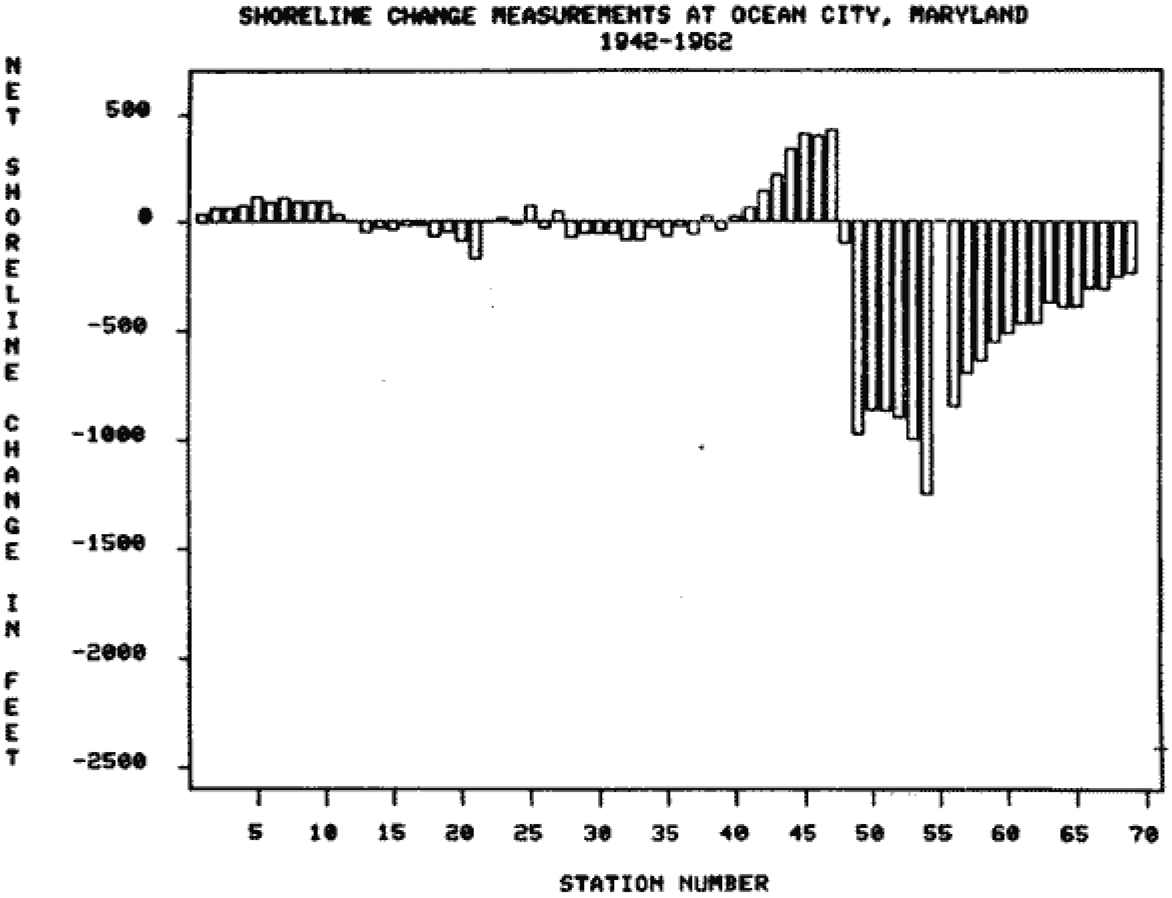

Figure 13. Histogram of Historical Shoreline Changes (1962 – 1980).
Transects 1 to 45 Are Along Ocean City, Maryland.

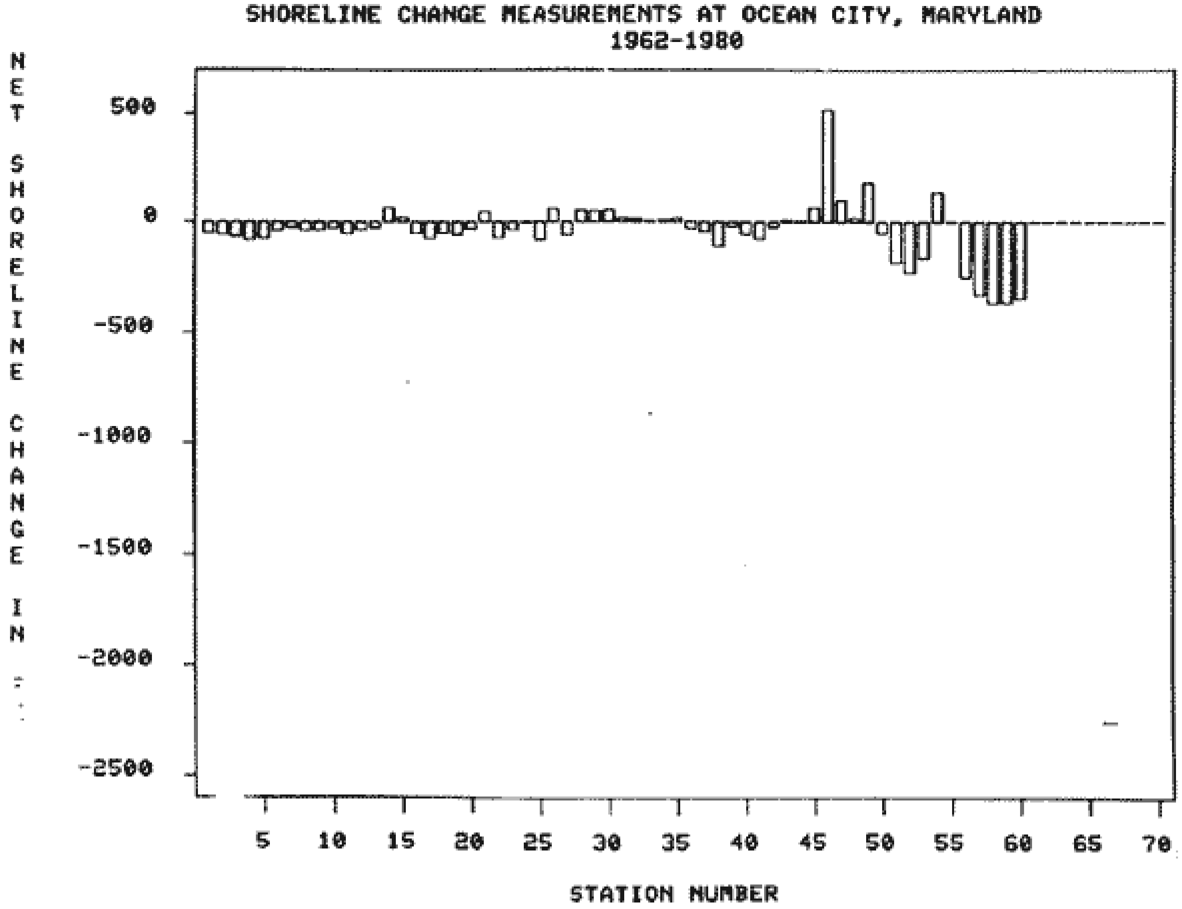

Figure 14. Histogram of Historical Shoreline Changes (1850 – 1980)
Transects 1 to 45 Are Along Ocean City, Maryland.

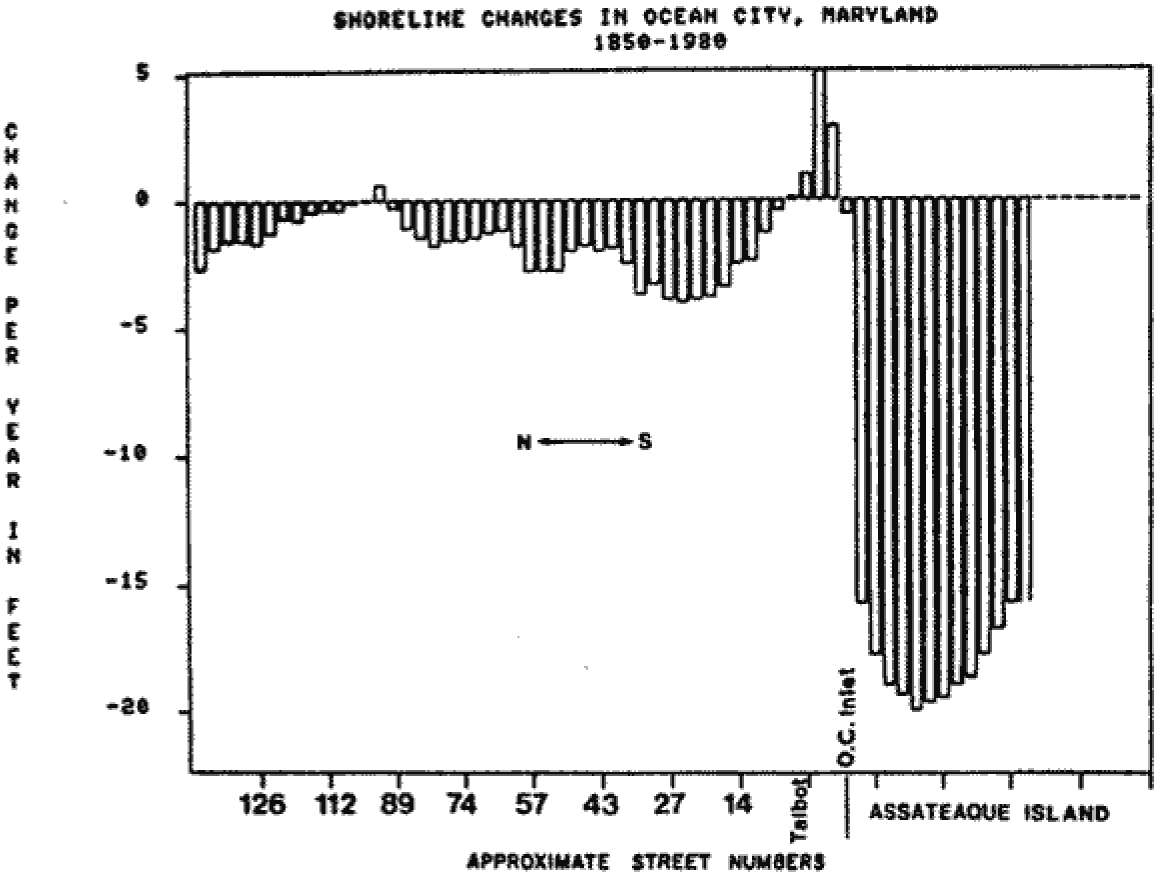

Table 3. Projected Shoreline Recession Along Ocean City, Maryland[1]

Year	Current Trend	Mid-Range Low Estimate	Mid-Range High Estimate
2000	39 ft.	64 ft.	89 ft.
2025	85 ft.	182 ft.	250 ft.
2050	134 ft.	134 ft.	483 ft.
2075	182 ft.	572 ft.	813 ft.

1. See Table 1 for rates of sea level rise.

While the historical trend of recession has been set at 1.9 feet per year, there has not been an appreciable change in shoreline position since 1961/62 (Fig. 14). In other words, the historical rate of erosion has not been realized in the last few decades. This marked departure from the trend may be due to human modifications of the shore, notably groins, sand scraping, and some beach fill. However it is more likely that the noted lull in hurricane activity since 1960 is the; key factor.

This proposition is supported by an analysis of historical bathymetric changes. While these data are not as readily available as shoreline movement information, and their accuracy is more in question, significant trends emerge from a historical bathymetric comparison of the area off shore of Ocean City (Table 4). It is clear that the shoreface is steepening through time. The landward movement of the 20-foot-deep contour is greater than that of the 10-foot-deep contour, which in turn has migrated farther than the mean-high-water line.

Table 4. Contour Shifts (1929 - 1965) From Trident Engineering (1979)

Contour	Over 36-Year Period	Average Shift Per Year
Near High Water Line	86 ft.	2.4 ft.
-10 foot contour	252 ft.	7.0 ft.
-20 foot contour	350 ft.	9.7 ft.

We have conducted some checks of the Corps of Engineers' profiles, used by Trident Engineering (1979), as compared to the original Coast and Geodetic Survey boat sheets and have obtained similar measurements (Appendix II). It appears that the shoreline remains in approximately the same location for a period of time, while acting as a hinge as the adjacent shoreface steepens. It is not known at present what angle of shoreface inclination is the natural equilibrium orientation. Clearly, the current steepened condition cannot be considered at equilibrium, since recent bathymetric data have shown that the steepening trend has continued. Assuming that the equilibrium angle of inclination for the shoreface was reached at some point during the survey period (1850-1965), a future major coastal storm should cause the angle to decrease toward the idealized equilibrium position (Moody 1964).

It is a well established geologic principle that much geomorphic work is accomplished in quantum steps (Hayes 1967; Leatherman 1981 1982). Therefore, a major coastal storm would provide the impetus by shifting and redistributing nearshore sands to reverse the steepening trend of the shoreface. At this point, the shoreface returns to its minimum angle and then continues to slowly steepen again through time until the next major storm.

In summary, the shoreface appears to undergo bicyclic adjustment through time. A long, quiescent steepening phase, during which shoreline position is relatively stable or slowly retreating, is followed by a brief stormy period of shoreface flattening and rapid landward migration of the shoreline. Ongoing research should provide the type of data necessary to quantify this process and formulate a predictive model.

SUMMARY

The Atlantic Coast of Ocean City, Maryland, is undergoing long-term shoreline retreat as a result of sea level rise. During the past 130 years (1950-1980), the beach has eroded an average of 1.9 feet per year. Inspection of shoreline movement over this period shows that the recession is not constant through time or space. Indeed, there were periods of very rapid shoreline retreat, which probably corresponded to the major storms of record -- 1902, 1933, and 1962. In addition, the erosional trend at any one point along the shore has tended to fluctuate through time.

Many areas show reversals in trend, where an area that is characterized by high recessional rates for a period of time is later retreating more slowly, as compared to the overall trend, or accreting. These dramatic short-period (perhaps 20- to 30-year) trends may result from the alongshore migration of low-amplitude, very long wave length, sand waves. When the trough of the shoreline meander passes a certain locality, then it is characterized by erosion in excess of the trend. As the crest of the seaward-projecting horn of this crescentic feature passes the same point some time later, then the trend is reversed. Depending upon the amplitude of the sand wave and overall erosion rate, the area may be so affected as to actually exhibit pronounced accretion for a period of time. This appears as a flip-flop in the historical shoreline migrational record.

Analysis of these long-period sand waves can result in much confusion when we try to interpret short-term information, such as beach profiles. This analysis indicates that the longest accurate record available should always be used for determining shoreline trend. Short-term data are useful in documenting site-specific and temporal changes, but such data are not the best indicators of net shoreline response over the long term.

This type of analysis could be undertaken for any sandy shoreline. The easily eroded unconsolidated sediments of barrier islands make the projections straightforward, except where modified by coastal engineering structures. The underlying assumption of this analysis is that shorelines will respond in similar ways in the future, as was the case in the past, since sea level rise is the driving function, and all other parameters remain essentially constant.

This analysis has assumed that total shoreline adjustments to sea level rise would be accomplished at the particular scenario year. Clearly, there will be some lag in shoreline response to higher water levels. This time period may be on the order of 25 to 50 years, corresponding to the frequency of major hurricanes. Better information on storm frequency and magnitude would improve this analysis. Without an in-depth analysis of site-specific data on many principal variables, such as offshore profile changes, the simple extrapolation of historical trends is a reliable technique for forecasting shoreline changes.

Appendix I. Nomenclature for Shoreline Interations With Sea Level Rise

As sea level rises, a number of complex and related phenomena come into play. In the following enumeration, we present general, intuitive definitions of the major phenomena and indicate the technical terms which most closely define each. A variety of shoreline interactions result from the rising (transgression) and falling (regression) of sea level. Most of these changes probably act in concert, but individually can be seen to result in several distinct responses. Rising sea levels are accompanied by general retreat of the shoreline. This is produced by erosion and/or inundation. Classically, erosion describes the physical removal of beach and cliff material, while inundation is the submergence of the otherwise unaltered shoreline.

During periods of falling (regression) or stable sea level, shorelines may advance seaward, or prograde, as material is deposited and accrete. Shoreline propagation generally occurs along river deltas, where sediment influx is high, unless the rate of sea level rise more than offsets sediment deposition. The recent dramatic erosion of part of the Nile Delta, resulting from the loss of sediment trapped behind the Aswan High Dam, reinforces the importance of sediment supply in maintaining shoreline equilibrium in deltaic environments. During at least the last century, there has been a significant rise in sea level which has resulted in pronounced shoreline recession along most Atlantic Coast beaches (e.g., Leatherman 1979, 1983b) and indeed along the large majority of sandy beaches worldwide (Bird 1976).

Appendix II: Profile Changes at Ocean City, Maryland: 1929-1978

by
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Graphed profiles were available from the U.S. Army Corps of Engineers for the years 1965 and 1979. The profiles were drawn from seventeen transacts, measured perpendicularly to the Ocean City coast. The origin and endpoint of each transect were digitized, along with four latitude and longitude values on each street map. From these given latitudes and longitudes, the coordinates for each transect were determined by computer. Thus, the four digitized rectilinear coordinates defined where the map was in space, and then the computer let it be known where the transacts were, in terms of latitude and longitude, within that two-dimensional framework.

Map Bathymetry

After transacts were determined from the 1965 and 1979 Ocean City street maps, the seventeen transacts were hand plotted on each Ocean City map judged useful to the project. The other maps chosen were National Ocean Survey maps for 1929, 1962, and 1978. The 1848 and the 1849 maps were rejected because depth values did not reach the shoreline, original latitude and longitude markings were inaccurate, and values were measured sparsely parallel to the shoreline. Transect numbers are Ocean City street numbers.

Every value on the graphed 1965 and 1979 profiles was digitized. For the other maps, all values within rectangular envelopes 0.3 miles wide and 0.7 miles long centered along the sketched transacts were individually digitized. each map was oriented in space by digitizing four map coordinates before transect values were digitized. A modified Surface II program retrieved each transect within its envelope of stored values. It extrapolated transect values from observed values and graphed each profile.

The inaccuracies of adjusting map scales and directionally stretching transposed maps were avoided (Sallenger et al. 1975). Since the transacts and transect values were accurately determined and profiles were accurately graphed, many errors were eliminated. The largest errors remaining are mapping errors. For the purpose of slope measurement, extrapolation errors are not significant. Small irregular depressions or rises would not change profile slope calculations.

Table II-I shows the position in feet of the shoreline and -10ft., -20ft., and -30ft. contours, with respect to an arbitrary origin. Table II-2 shows the changes between 1962 and 1978, the most recent interval for which the data permit a meaningful comparison.

Table II-1. Contour Data From 3rd Street to 145th Street (in feet)

		Shoreline	- 10 ft.	- 20 ft.	- 30 ft.
S3	1929	0	700	1370	1940
	1962	400	920	1490	2940
	1965	340	790	1550	--
	1978	400	900	1540	3250
	1979	390	740	1170	--
S11	1929	60	880	1340	1960
	1962	200	690	1213	2120
	1963	230	760	1320	2060
	1978	90	620	970	2330
	1979	120	520	800	1920
S21	1929	140	520	1300	2300
	1962	170	810	1030	1910
	1965	140	670	940	--
	1970	170	722	890	2000
	1795	140	490	690	1400
S26	1929	60	790	1320	2060
	1962	180	720	1070	2190
	1963	140	660	1050	1980
	1978	90	560	890	2190
	1979	110	520	810	1750
S33	1929	700	950	1460	2160
	1962	200	880	1140	2580
	1965	200	750	1070	2030
	1978	200	630	910	1600
	1979	320	480	780	1540
S41	1929	200	990	1550	2850
	1962	200	710	1420	3110
	1965	230	710	1180	2950
	1978	200	710	1180	2900
	1979	230	920	1210	2770
S48	1929	200	950	1400	3120
	1962	290	750	1260	4560
	1965	180	650	1120	3100
	1978	920	600	1060	2890
	929	200	680	530	2040
S55	1929	220	980	1680	3320
	1962	220	780	1120	--
	1965	180	720	1070	2510
	1978	220	740	1130	--
	1979	220	530	920	2410

S65	1929	280	950	1520	--
	1962	200	810	1540	2630
	1965	220	720	1320	2540
	1978	220	640	1340	--
	1979	220	670	1420	2700
S76	1929	310	1080	1850	2920
	1962	120	720	1170	2730
	1965	150	590	1060	2630
	1978	10	470	900	2770
	1979	150	470	80	2260
S86	1929	170	900	1740	--
	1962	110	640	970	2950
	1965	140	670	1000	2930
	1978	0	380	1040	2690
	1979	140	480	890	2630
S94	1929	80	830	1260	3330
	1965	130	620	1010	2100
	1978	-	-	--	--
	1979	120	460	800	1780
S100	1929	250	940	1390	--
	1965	250	610	1070	2400
	1970	10	460	1030	1870
	1979	150	480	860	1780
S119	1929	230	1030	1430	2390
	1065	280	730	1150	2330
	1978	180	120	1030	2330
	1979	180	590	880	1550
S129	1929	250	960	1440	2420
	1965	150	570	1120	--
	1978	180	460	880	2550
	1979	150	480	670	1190
S137	1929	150	830	1190	2820
	1965	180	639	850	1770
	1978	110	430	730	1970
	1979	140	490	720	1320
S145	1929	180	800	2150	1610
	1965	120	480	740	1320
	1978	0	470	800	1510
	1979	140	450	740	1230

Table II-2. Change In The Position Of The Shoreline And -10, -20, And -30 Foot Contours From 1962 To 1978[1] (3rd Street To 86th Street)

			Contours	
Transect	Shoreline	-10 ft.	-20 ft.	-30 ft.
S3	0	-20	50	316
S11	-110	-70	-240	210
S21	0	-90	-140	90
S26	-90	-140	-180	0
S33	0	-250	-230	20
S41	0	0	-240	-210
S48	20	-100	-180	-470
S55	0	-40	-10	NA[2]
S65	20	-170	-200	NA
S76	-110	-150	-270	40
S86	-110	-260	70	-260
mean	-34.6	-115.5	-140.9	-30
mean-adjusted[1]	-30	-131.1	-151.1	-112.9

1. Negative numbers indicate retreat toward the land.
2. NA = not available.
3. Excludes transects S3 and S11 which are influenced by the jetty at Ocean City Islet.

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