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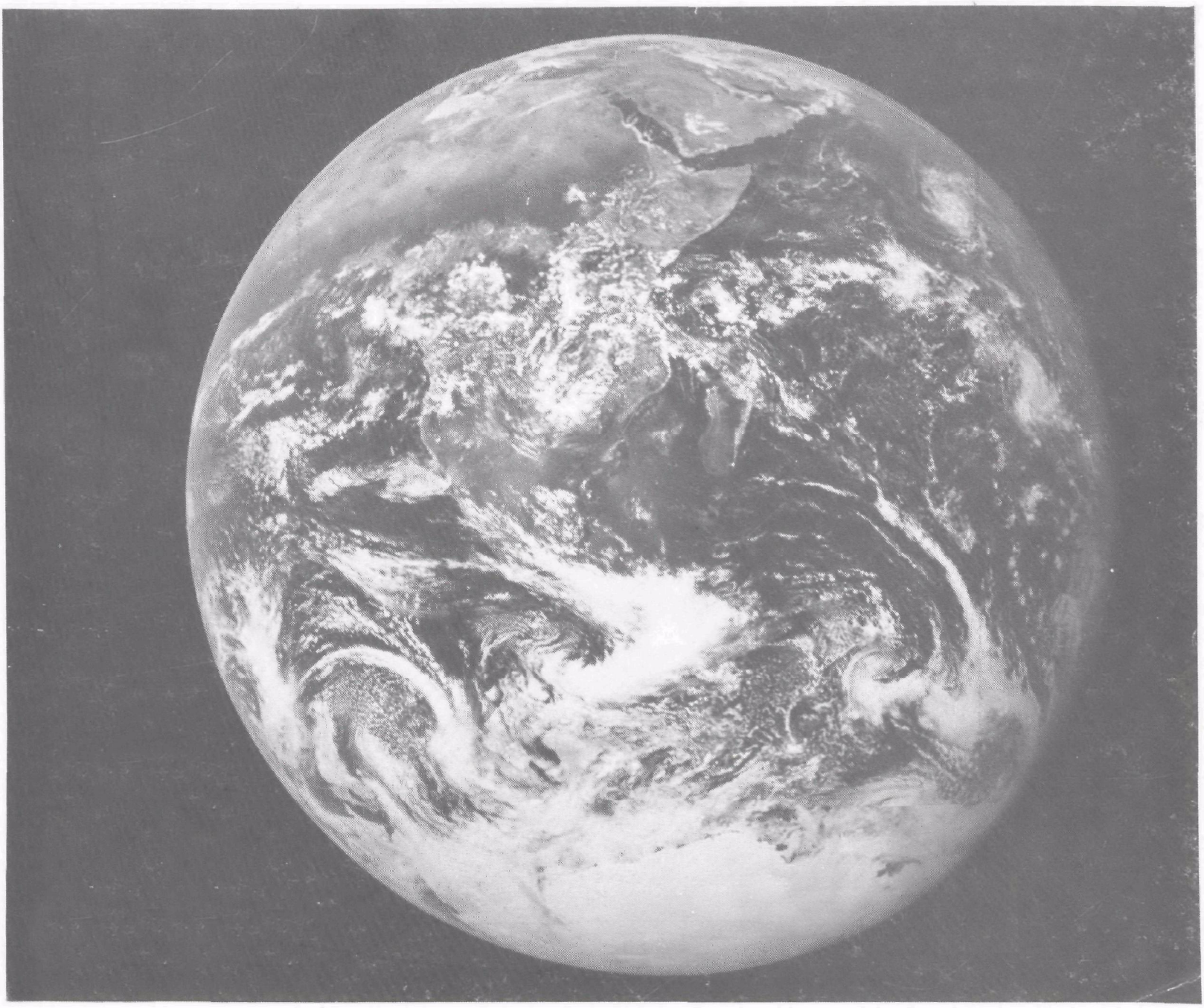
EFFECTS OF CHANGES IN STRATOSPHERIC OZONE AND GLOBAL CLIMATE

Volume 4: Sea Level Rise



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EFFECTS OF CHANGES IN STRATOSPHERIC OZONE AND GLOBAL CLIMATE

Volume 4: Sea Level Rise

Edited by
James G. Titus
U.S. Environmental Protection Agency

This report represents the proceedings of the INTERNATIONAL CONFERENCE ON HEALTH AND ENVIRONMENTAL EFFECTS OF OZONE MODIFICATION AND CLIMATE CHANGE sponsored by the United Nations Environment Programme and the U.S. Environmental Protection Agency. The purpose of the conference was to make available the widest possible set of views. Accordingly, the views expressed herein are solely those of the authors and do not represent official positions of either agency. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

PREFACE

This document is part of a four volume report that examines the possible consequences of changes in stratospheric ozone and global climate resulting from emissions of chlorofluorocarbons, carbon dioxide, methane, and other gases released by human activities. In June 1986, the United Nations Environment Programme and the U. S. Environmental Protection Agency sponsored an International Conference on the Health and Environmental Effects of Ozone Modification and Climate Change, which was attended by scientists and officials, representing twenty-one countries from all areas of the world.

This volume examines the effects of the rise in sea level that might result from a global warming. Volume 1 of the proceedings provides an overview of the issues as well as the introductory remarks and reactions from top officials of the United Nations and the United States. Volumes 2 and 3 focus on the effects of ozone depletion and climate change, respectively.

This report does not present the official views of either the U.S. Environmental Protection Agency or the United Nations Environment Programme.

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Overview of the Effects of Changing the Atmosphere

James G. Titus and Stephen R. Seidel
Environmental Protection Agency
Washington, DC USA

INTRODUCTION

Society is conducting a global experiment on the earth's atmosphere. Human activities are increasing the worldwide atmospheric concentrations of chlorofluorocarbons, carbon dioxide, methane, and several other gases. A growing body of scientific evidence suggests that if these trends continue, stratospheric ozone may decline and global temperature may rise. Because the ozone layer shields the earth's surface from damaging ultraviolet radiation (UV) future depletion could increase the incidence of skin cancer and other diseases, reduce crop yields, damage materials, and place additional stress on aquatic plants and animals. A global warming from the "greenhouse effect" could also threaten human health, crop yields, property, fish, and wildlife. Precipitation and storm patterns could change, and the level of the oceans could eventually rise.

To improve the world's understanding of these and other potential implications of global atmospheric changes, the United Nations Environment Programme (UNEP) and the U.S. Environmental Protection Agency (EPA) sponsored an International Conference on the Health and Environmental Effects of Ozone Modification and Climate Change during the week of June 16-20, 1986. The conference brought together over three hundred researchers and policy makers from approximately twenty nations. This four-volume report presents the seventy-three papers that were delivered at the conference by over eighty speakers, including two U.S. Senators, top officials from UNEP and EPA, some of the leading scientists investigating the implications of atmospheric change, and representatives from industry and environmental groups. Volume 1 presents a series of overview papers describing each of the major areas of research on the effects of atmospheric change, as well as policy assessments of these issues by well-known leaders in government, industry, and the environmental community. Volumes 2, 3, and 4 present the more specialized papers on the impacts of ozone modification, climate change, and sea level rise, respectively, and provide some of the latest research in these areas. This paper summarizes the entire four-volume report.

OZONE MODIFICATION

Atmospheric Processes

The ozone in the upper part of the atmosphere--known as the stratosphere--is created by ultraviolet radiation. Oxygen (O_2) is continuously converted to ozone (O_3) and back to O_2 by numerous photochemical reactions that take place in the stratosphere, as Stordal and Isaksen (Volume 1) describe. Chlorofluorocarbons and other gases released by human activities could alter the current balance of creative and destructive processes. Because CFCs are very stable compounds, they do not break up in the lower atmosphere (known as the troposphere). Instead, they slowly migrate to the stratosphere, where ultraviolet radiation breaks them down, releasing chlorine.

Chlorine acts as a catalyst to destroy ozone; it promotes reactions that destroy ozone without being consumed. A chlorine (Cl) atom reacts with ozone (O_3) to form ClO and O_2. The ClO later reacts with another O_3 to form two molecules of O_2, which releases the chlorine atom. Thus, two molecules of ozone are converted to three molecules of ordinary oxygen, and the chlorine is once again free to start the process. A single chlorine atom can destroy thousands of ozone molecules. Eventually, it returns to the troposphere, where it is rained out as hydrochloric acid.

Stordal and Isaksen point out that CFCs are not the only gas released by human activities that might alter the ozone balance. Increasing concentrations of methane in the troposphere increase the water vapor in the stratosphere, which helps create ozone. Carbon dioxide and other greenhouse gases (discussed below) warm the earth's surface but cool the upper atmosphere; cooler stratospheric temperatures slow the process of ozone depletion. Nitrous oxide (N_2O) reacts with both chlorine and ozone.

Stordal and Isakson present results of possible ozone depletion over time, using their two-dimensional atmospheric-chemistry model. Unlike one-dimensional models which provide changes in ozone in the global average, this model calculates changes for specific latitutdes and seasons. The results show that if concentrations of the relevant trace gases grow at recent levels, global average ozone depletion by 2030 would be 6.5 percent. However, countries in the higher latitudes (60°N) would experience 16 percent depletion during spring. Even in the case of constant CFC emissions, where global average depletion would be 2 percent by 2030, average depletion would be 8 percent in the high northern latitudes.

Watson (Volume 1) presents evidence that ozone has been changing recently more than atmospheric models had predicted. As Plate 1 shows, the ozone over Antarctica during the month of October appears to have declined over 40 percent in the last six to eight years. Watson also discusses observations from ozone monitors that suggest a 2 to 3 percent worldwide reduction in ozone in the upper portion of the stratosphere (thirty to forty kilometers above the surface), which is consistent with model predictions. Finally, he presents preliminary data showing a small decrease since 1978 in the total (column) ozone worldwide. However, he strongly emphasizes that the data have not yet been fully reviewed and that it is not possible to conclusively attribute observed ozone depletion to the gases released by human activities. While

there are several hypotheses to explain why ozone concentrations have declined, none have been adequately established; nor did any of the atmospheric models predict the measured loss of ozone over Antarctica.

Ultraviolet Radiation

Many of the chemical reactions investigated by atmospheric scientists take place only in the stratosphere because they are caused by types of radiation only found in the upper atmosphere. As Frederick (Volume 1) explains, the sun emits radiation over a broad range of wavelengths, to which the human eye responds in the region from approximately 400 to 700 nanometers (nm). Wavelengths from 320 to 400 nm are known as UV-A; wavelengths from 280 to 320 nm are called UV-B, and wavelengths from 200 to 280 nm are known as UV-C.

Frederick explains why attention has primarily focused on the UV-B part of the spectrum. The atmosphere absorbs virtually all UV-C, and is expected to continue to do so under all foreseeable circumstances. On the other hand, UV-A is not absorbed by ozone.[1]. By contrast, UV-B is partially absorbed by ozone, and future depletion would reduce the effectiveness of this shield.

We now examine the potential implications of such changes on human health, plants, aquatic organisms, materials, and air pollution.

Effects on Human Health

The evidence suggests that solar ultraviolet radiation induces skin cancer, cataracts, suppression of the human immune response system, and (indirectly through immunosuppression) the development of some cutaneous infections, such as herpes. Emmett (Volume 1) discusses the absorption of UV radiation by human tissue and the mechanisms by which damage and repair may occur.

Emmett also examines UV radiation as the cause of aging of the skin and both basal and squamous skin cancers. In reviewing the role of UV radiation in melanoma (the most frequently fatal skin cancer), he states that some evidence suggests this link, but that currently there is no acceptable animal model that can be used to explore or validate this relationship. He concludes that future studies must focus on three major factors--exposure to solar radiation, individual susceptibility, and personal behavior. Waxler (Volume 1) presents evidence of a link between UV-B exposure and cataracts.

Volume 2 presents specific research results and provides more detail on many of the aspects covered in this volume. Scotto presents epidemiological evidence linking solar radiation with skin cancers, other than melanoma. His analysis suggests that Caucasians in the United States have a 12 to 30 percent chance of developing these cancers within their lifetimes, even without ozone depletion. Armstrong examines the role of UV-B exposure to melanoma in a study of 511 matched melanoma patients and control subjects in Western Australia. He shows that "intermittent exposure" to sunlight was closely associated with this type of cancer.

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[1] However, O_2 and N_2 reflect some UV-A back to space.

In a paper examining nonmelanoma skin cancer in Kuwait, Kollias and Baqer (Volume 2) show that despite the presence of protective pigmentation, 75 percent of cancers occur on the 10 percent of the skin exposed to sunlight. A second paper on skin cancer presents experimental evidence suggesting that the mechanism by which skin cancer could occur involves disruption of the cytoskeleton from exposure to UV-A and UV-B light (Zamansky and Chow, Volume 2).

The pathways by which suppression of the immune response might be triggered are explored in papers by DeFabo and Noonan, Daynes et al., and Elmets et al (all Volume 2). Davies and Forbes (Volume 2) show that mice exposed to UV-B radiation had a decrease in lifetime that was proportional to the quantity of radiation and not directly related to the incidence of skin cancer.

Possible implications of immune suppression of diseases and the mechanisms by which it occurs are still uncertain. However, several papers in Volume 2 suggest that in addition to skin cancer and contact hypersensitivity, diseases influenced by UV-B induced immune suppression include leishmaniasis and herpes infections. Fisher et. al (Volume 2) show that at least one sunscreen effectively protects mice exposed to UV-B radiation from sunburn; but it does not stop the immune suppression from interfering with a contact hypersensitivity (allergic) reaction.

Effects on Plants

The effects of increased exposure to UV-B radiation on plants has been a primary area of research for nearly a decade. Teramura (Volume 1) reports that of the two hundred plants tested for their sensitivity to UV-B radiation, over two-thirds reacted adversely; peas, beans, squash, melons, and cabbage appear to be the most sensitive. Given the complexities in this area of research, he warns that these results may be misleading. For example, most experiments have used growth chambers. Studies of plants in the field have shown them to be less sensitive to UV-B. Moreover, different cultivars of the same plant have shown very different degrees of sensitivity to UV-B radiation. Finally, Teramura suggests that potential effects from multiple stresses (e.g., UV-B exposure plus water stress or mineral deficiency) could substantially alter a plant's response to changes in UV-B alone.

In Volume 2, Teramura draws extensively from the results of his five years of field tests on soybeans. His data show that a 25 percent depletion in ozone could result in a 20 to 25 percent reduction in soybean yield and adverse impacts on the quality of that yield. Because soybeans are the fifth largest crop in the world, a reduction in yields could have serious consequences for world food supplies. However, some soybean cultivars appear to be less susceptible to UV-B radiation, which suggests that selective crop breeding might reduce future losses, if it does not increase vulnerability to other environmental stresses.

Bjorn (Volume 2) examines the mechanisms by which plant damage occurs. His research relates specific wavelengths with those aspects of plant growth that might be susceptible, including the destruction of chloroplast, DNA, or enzymes necessary for photosynthesis.

Aquatic Organisms

Aquatic plants would also be adversely affected by increased ultraviolet radiation. Worrest (Volume 1) points out that most of these plants, which are drifters (phytoplankton), spend much of their time near the surface of the water (the euphotic zone) and are therefore exposed to ultraviolet radiation. A reduction in their productivities would be important because these plants directly and indirectly provide the food for almost all fish. Furthermore, the larvae of many fish found in the euphotic zone would be directly affected, including crabs, shrimp, and anchovies. Worrest points out that fish account for 18 percent of the animal protein that people around the world consume, and 40 percent of the protein consumed in Asia.

An important question is the extent to which current UV-B levels are a constraint on aquatic organisms. Calkins and Blakefield (Volume 2) conclude that some species are already exposed to as much UV-B as they can tolerate. Thomson (Volume 2) shows that a 10 percent decrease in ozone could increase the number of abnormal larvae as much as 18 percent. In a study of anchovies, a 20 percent increase in UV-B radiation over a 15-day period caused the loss of all the larvae within a 10-meter mixed layer in April and August.

Many other factors could affect the magnitude of the impacts on specific species, ecosystems, and the food chain. An important mechanism by which species could adapt to higher UV-B incidence would be to reduce their exposure by moving further away from the water's surface during certain times of the day or year when exposure is greatest. Haeder (Volume 2) suggests, however, that for certain species such avoidance may be impaired by UV-B radiation.

Even for those organisms that could move to avoid exposure, unwanted consequences may result. Calkins and Blakefield present model results showing that movement by phytoplankton away from sunlight to reduce exposure to a 10 percent increase in UV-B would result in a 2.5 to 5 percent decrease in exposure to the photosynthetically active radiation on which their growth depends. Increased movement requires additional energy consumption, while changes in location may affect the availability of food for zooplankton, which could cause other changes in shifts in the aquatic food chain.

To a certain extent, losses within a particular species of plankton may be compensated by gains in other species. Although it is possible that no net change in productivity will occur, questions arise concerning the ecological impacts on species diversity and community composition (Kelly, Volume 1). Reductions in diversity may make populations more susceptible to changes in water temperatures, nutrient availability, diseases, or pollution. Changes in community composition could alter the protein content, dry weight, or overall food value of the initial stages of the aquatic food chain.

Polymer Degradation and Urban Smog

Current sunlight can cause paints to fade, transparent window glazing to yellow, and polymer automobile roofs to become chalky. These changes are likely to occur more in places closer to the equator where UV-B radiation is greater. They are all examples of degradation that could accelerate if depletion of the ozone layer occurs. Andrady and Horst (Volume 2) present a case study of the potential magnitude of loss due to increased exposure to

UV-B radiation on polyvinyl chloride (PVC). This chemical is used in outdoor applications where exposure to solar radiation occurs over a prolonged period. It is also used in the construction industry in siding and window frames and as a roofing membrane.

To analyze the potential economic impact of future ozone depletion on PVC, the authors assumed that the future service life of polymers would be maintained by increasing the quantity of light stabilizers (titanuim dioxide) used in the product. As a result, the costs associated with increased UV-B radiation would be roughly equal to the costs of increased stablizers. Preliminary results show that for a 26 percent depletion by 2075, the undiscounted costs would be $4.7 billion (1984 dollars).

Increased penetration of UV-B radiation to the earth's surface could play an important role in the formation of ground level oxidants (smog). UV-B affects smog formation through the photolysis of formaldehyde, from which radicals are the main source for deriving chain reactions that generate photochemical smog. Whitten and Gery (Volume 2) analyze the relationship between UV-B, smog, and warmer temperatures. The results of this preliminary study of Nashville, Philadelphia, and Los Angeles show that large depletions in stratospheric ozone and increases in temperature would increase smog by as much as 50 percent. In addition, because oxidants would form earlier in the day and closer to population centers (where emissions occur), risks from exposure could increase by an even higher percentage increase. Whitten and Gery also report a sensitive relationship between UV-B and hydrogen peroxide, an oxidant and precursor to acid rain.

CLIMATE CHANGE

The Greenhouse Effect

Concern about a possible global warming focuses largely on the same gases that may modify the stratospheric ozone: carbon dioxide, methane, CFCs, and nitrous oxide. The report of a recent conference convened by UNEP, the World Meteorological Organization, and the International Council of Scientific Unions concluded that if current trends in the emissions of these gases continue, the earth could warm a few degrees (C) in the next fifty years (Villach 1985). In the next century, the planet could warm as much as five degrees (NAS 1983), which would leave the planet warmer than at any time in the last two million years.

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 the atmosphere retains heat. When sunlight strikes the earth, it warms the surface, which then reradiates the heat as infrared radiation. However, water vapor, CO_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 commonly known as the "greenhouse effect." Without the greenhouse effect of the gases that occur naturally in the atmosphere, the earth would be approximately 33°C colder than it is currently (Hansen et al. 1984).

In recent decades, the concentrations of greenhouse gases have been increasing. Since the beginning of the industrial revolution, the combustion of fossil fuels, deforestation, and a few other activities have released enough CO_2 to raise atmospheric concentrations by 20 percent; concentrations have risen 8 percent since 1958 (Keeling, Bacastow, and Whorf 1982). More recently, Ramanathan et al. (1985) examined the greenhouse gases other than CO_2 (such as methane, CFCs, and nitrous oxide), and concluded that these other gases are likely to double the warming caused by CO_2 alone. Using these results, the Villach Conference estimated that an "effective doubling" of CO_2 is likely by 2030.[2]

Hansen et al. (Volume 1) and Manabe & Wetherald (Volume 1) present the results that their climate models predict for an effective doubling of CO_2. Both models consider a number of "climatic feedbacks" that could alter the warming that would directly result from CO_2 and other gases released by human activities. Warmer temperatures would allow the atmosphere to retain more water vapor, which is also a greenhouse gas, thereby resulting in additional warming. Ice and snow cover would retreat, causing sunlight that is now reflected by these bright surfaces to be absorbed instead, causing additional warming. Finally, a change in cloud cover might result, which could increase or decrease the projected warming. Although the two models differ in many ways, both conclude that an effective doubling of greenhouse gases would warm the earth's surface between two and four degrees (C).

Hansen et al. project the doubling to occur between 2020 and 2060. They also provide estimates of the implications of temperature changes for Washington, D.C., and seven other U.S. cities for the middle of the next century. For example, Washington would have 12 and 85 days per year above 38°C (100°F) and 32°C (90°F), respectively, compared with 1 and 35 days above those levels today. While evenings in which the thermometer fails to go below 27°C (80°F) occur less than once per year today in that city, they project that such evenings would occur 19 times per year. (See Plates 2 and 3 for worldwide maps of historical and projected temperature changes.)

Water Resources

Manabe and Wetherald (Volume 1) focus on the potential changes in precipitation patterns that might result from the greenhouse warming. They project substantial increases in summer dryness at the middle latitudes that currently support most of the world's agriculture. Their model also projects increased rainfall for late winter.

Beran (Volume 1) reviews the literature on the hydrological and water resource impacts of climate change. He expresses some surprise that only twenty-one papers could be found that address future water resource impacts. One of the problems, he notes, is that there is a better scientific understanding of how global average temperatures and rainfall might change, than for the changes that specific regions may experience. Nevertheless, he

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[2] Studies on the greenhouse effect generally discuss the impacts of a carbon dioxide doubling. By "effective doubling" we refer to any combination of increases in concentrations of the various gases that causes a warming equal to the warming of a doubling of carbon dioxide alone.

demonstrates that useful information can be extracted by studying the implications of particular scenarios.

Nicholson (Volume 3) shows how historical changes in water availability have caused problems for society in the past. The best lesson of climatic history, she writes, "is that agricultural and economic systems must be flexible enough to adapt to changing conditions and, in the face of potential water scarcity, systems must be designed that require minimum use of resources." Wilhite (Volume 3) examines drought policies in Australia and the United States, concluding that the lack of national drought plans could substantially impair the ability of these two nations to successfully adapt to hydrologic changes resulting from the greenhouse warming.

Cohen (Volume 3) examines the potential implications of the global warming for water levels in the Great Lakes that separate Canada from the United States. Using results from the models of both Hansen et al. and Manabe & Wetherald, he concludes that lake levels could drop 10 to 30 centimeters. This drop would significantly reduce the capacity of ocean-going vessels that enter the Great Lakes. On the other hand, such a drop might be viewed as a benefit by the owners of critically eroding property whose homes are currently threatened by historically high lake levels. Street-Perrott et al. (Volume 3) discuss the historic impacts of changes in climate on the levels of lakes in North America, South America, Australia, and Africa.

Gleick (Volume 3) uses scenarios from the Hansen et al. and Manabe & Wetherald models (as well as a third developed by the National Center for Atmospheric Research) to drive a water-balance model of the Sacramento Basin in California. He finds that reductions in runoff could occur even in months where precipitation increases substantially, because of the increased rates of evaporation that take place at higher temperatures. He also points out that the models predict that changes in monthly runoff patterns will be far more dramatic than changes in annual averages. For seven of ten scenarios, soil moisture would be reduced every month of the year; for the other three cases, slight increases in moisture are projected for winter months. Mather (Volume 3) conducts a detailed analysis for southern Texas and northern Mexico; examines in less detail twelve regions around the world; and projects shifts in global vegetation zones.

Agriculture and Forestry

The greenhouse warming could affect agriculture by altering water availability, length of growing season, and the number of extremely hot days. Increased CO_2 concentrations could also have two direct impacts unrelated to climate change: At least the laboratory, plants grow faster (the CO_2 fertilization effect) and retain moisture more efficiently. The extent to which these beneficial effects offset the impacts of climate change will depend on the extent to which global warming is caused by CO_2 as opposed to other greenhouse gases, which do not have these positive impacts.

Parry (Volume 1) provides an overview of the potential impacts of climate change on agriculture and forestry. He points out that commercial farmers plan according to the average year, while family and subsistence farmers must ensure that even in the worst years they can make ends meet. Thus, the commercial farmer would be concerned about the impact of future climate change

on average conditions and average yields, while farmers at the margin would be most concerned with changes in the probability of (for example) a severe drought that causes complete crop failure. Parry notes that the probability of two or more anomalous years in a row could create disproportionately greater problems for agriculture. For example, a persistent drought in the U.S. Great Plains from 1932 to 1937 contributed to about two hundred thousand farm bankruptcies.

Parry discusses a number of historical changes in climate. The Little Ice Age in western Europe (1500-1800 A.D.) resulted in the abandonment of about half the farms in Norway, an end to cultivation of cereals in Iceland, and some farmland in Scotland being permanently covered with snow. Concerning the late medieval cooling (1250-1500) he writes: "The failure to adapt to the changing circumstances is believed to explain much of the Norse decline. The Norse continued to emphasize stock-raising in the face of reduced capacity of the already limited pastures. The option of exploiting the rich seas around them, as the Inuit (Eskimos) successfully did, was not taken up . . . This is an extreme example of how governments can fail to identify and implement appropriate policies of response." It also suggests that effective responses can reduce damages from climate change.

The paper reviews a number of studies that project impacts of climate change on agriculture. "Warming appears to be detrimental to cereals in the core wheat-growing areas of North America and Europe." If no precipitation changes take place, a one-degree warming would decrease yields 1 to 9 percent while a two-degree (C) warming would decrease yields 3 to 17 percent. Parry also discusses how particular crop zones might shift. A doubling of CO_2 would substantially expand the wheat-growing area in Canada due to higher winter temperatures and increased rainfall. In Mexico, however, temperature stresses would increase, thereby reducing yields.

A number of studies have been conducted using the models of Hansen et al., Manabe & Wetherald, and others. Although these projections cannot be viewed as reliable forecasts, they do provide consistent scenarios that can be useful for examining vulnerability to climate change. Parry indicates that investigations of Canada, Finland, and the northern USSR using the model by Hansen et al. show reduced yields of spring-sown crops such as wheat, barley, and oats, due to increased moisture stress early in the growing period. However, switching to winter wheat or winter rye might reduce this stress. Parry goes on to outline numerous measures by which farmers might adapt to projected climate change.

Waggoner (Volume 3) points out that the global warming would not affect plants uniformly. Some are more drought-resistant than others, and some respond to higher CO_2 concentrations more vigorously than others. C_3 plants, such as wheat, respond to increased CO_2 more than C_4 plants such as maize. Thus, the CO_2 fertilization effect would not help the farmer growing C_4 crops accompanied by C_3 weeds. Waggoner also examines the impact of future climate change on average crop yields and pests, and the probability of successive drought years. He concludes that although projections of future changes are useful, historical evidence suggests that surprises may be in store, and that "agricultural scientists will be expected to aid rather than watch mankind's adaptation to an inexorable increase in CO_2 and its greenhouse effect."

The impact of future climate change on yields for spring wheat in Saskatchewan, Canada, is the subject of the paper by Stewart (Volume 3). Using the output from the Hansen et al. model (Volume 1), which projects that the effective doubling of carbon dioxide would increase average annual temperatures in that region by 4.7°C, he estimates that the growing season would start two or three weeks earlier and end three or four weeks later. Although average precipitation during the growing season would increase, he also finds that the area would become more prone to drought. The impact of climatic change would be to reduce yields 16 to 26 percent. Stewart estimates that the fertilization effect of a CO_2 doubling would reduce the losses to 6 to 15 percent. Cooter (Volume 3) examines the economic impact of projected climate change on the economy of Oklahoma, concluding that the Gross State Product would decline 75 to 300 million dollars. (The state's gross product in 1985 was approximately 50 billion dollars.)

Fritts (Volume 3) examines tree rings to assess how past changes in climate have affected forests, and concludes that tree rings are useful for estimating past changes in climate. Solomon and West (Volume 3) discuss the results of their efforts to model the future impacts. Considering the impact of climate change caused by doubled CO_2 without the fertilization effect, they find that "biomass (for boreal forests) declines for 50-75 years as warming kills off large boreal forest species, before new northern hardwoods can grow into the plot."

"Warming at the transition site causes an almost immediate response in declining biomass from dieback of mature trees, and in decline of tree mass as large trees die and are temporarily replaced by small young trees," they write. "The deciduous forest site . . . results in permanent loss of dense forest. One might expect the eventual appearance of subtropical forests similar to those in Florida today, but the real difficulty is the moisture balance (which is) more similar to those of treeless Texas today, than to those of southern Florida." Solomon and West go on to show how the fertilization effect from increased concentrations of CO_2 could offset part but not all of the drop in forest productivity.

Sea Level Rise

One of the most widely recognized consequences of a global warming would be a rise in sea level. As Titus (Volume 1) notes, global temperatures and sea level have fluctuated over periods of one hundred thousand years, with temperatures during ice ages being three to five degrees (C) lower and sea level over one hundred meters lower than today. By contrast, the last interglacial period (one hundred thousand years ago) was one or two degrees warmer than today, and sea level was five to seven meters higher.

The projected global warming could raise sea level by heating and thereby expanding ocean water, melting mountain glaciers, and by causing polar glaciers in Greenland and Antarctica to melt and possibly slide into the oceans. Thomas (Volume 4) presents new calculations of the possible contribution of Antarctica and combines them with previous estimates for the other sources, projecting that a worldwide rise in sea level of 90 to 170 centimeters by the year 2100 with 110 centimeters most likely. However, he also estimates that if the global warming is substantially delayed, the rise in sea level could be cut in half. Such a delay might result either from

actions to curtail emissions or from the thermal lag induced by the oceans' ability to absorb heat.

On the other hand, Thomas also estimates that if a warming of four degrees results from a CO_2 doubling (which the model of Hansen et al. projects) and concentrations continue to grow after 2050, the rise could be as great as 2.3 meters. He also notes that an irreversible deglaciation of the West Antarctic Ice Sheet might begin in the next century, which would raise sea level another six meters in the following centuries.

Titus (Volume 1) notes that these projections imply that sea level could rise 30 centimeters by 2025, in addition to local subsidence trends that have been important in Taipei, Taiwan; Venice, Italy; the Nile Delta, Egypt; and most of the Atlantic and Gulf Coasts of the United States. The projected rise in sea level would inundate low-lying areas, destroy coastal marshes and swamps, erode shorelines, exacerbate coastal flooding, and increase the salinity of rivers, bays, and aquifers.

Bruun (Volume 4) argues that with a combination of coastal engineering and sound planning, society can meet the challenge of a rising sea. He discusses a number of engineering options, including dikes (levees) and seawalls, and adding sand to recreational beaches that are eroding, with a section on the battle that the Dutch have fought with the sea for over one thousand years. Goemans (Volume 4) describes the current approach of the Dutch for defending the shoreline, and estimates that the cost of raising their dikes for a one meter rise in sea level would be 10 billion guilders, which is less than 0.05 percent of their Gross National Product for a single year.

Goemans concludes that there is no need to anticipate such a rise because they could keep up with it. However, he is more concerned by the two-meter scenario: "Almost immediately after detection, actions would be required. It is not at all certain that decision-makers act that fast. . . . The present flood protection strategy came about only after the tragic disaster of 1953. When nobody can remember a specific disaster, it is extremely difficult to obtain consensus on countermeasures." For his own country, Goemans sees one positive impact: Referring to the unique experience of Dutch engineering firms in the battle with the sea, he suggests that "a rising sea may provide a new global market for this expertise." But he predicts that "the question of compensation payments may come up," for the poorer countries who did not cause climate change but must face its consequences.

Broadus et al. (Volume 4) examine two such countries in detail: Egypt and Bangladesh. The inhabited areas of both countries are river deltas, where low-lying land has been created by the sediment washing down major rivers. In the case of Egypt, the damming of the Nile has interrupted the sediment, and as the delta sinks, land is lost to the Mediterranean Sea. Broadus et al. estimate that a 50-centimeter rise in global sea level, when combined with subsidence and the loss of sediment, would result in the loss of 0.3 to 0.4 percent of the nation's land area; a 200-centimeter rise would flood 0.7 percent. However, because Egypt's population is concentrated in the low-lying areas, 16 and 21 percent of the nation's population currently reside in the areas that would be lost in the two scenarios.

The situation would be even more severe in Bangladesh. As Plate 4 shows, this nation, which is already overcrowded, would lose 12 to 28 percent of its total area, which currently houses 9 to 27 percent of its population. Moreover, floods could penetrate farther inland, which could leave the nation more vulnerable to the type of tropical storm that killed 300,000 people in the early 1970s, especially if the frequency of tropical storms doubled due to warmer water temperatures, which deSylva (Volume 4) projects. Broadus et al. conclude that the vulnerability of Bangladesh to a rise in sea level will depend in large measure on whether future water projects disrupt land-creating sediment washing down the Ganges.

Bird (Volume 4) examines the implications of sea level rise for other African and Asian nations, as well as Australia. While holding back the sea may be viable in Australia, he shows areas in New Guinea where people live in small cottages on the water's edge on a barrier island that almost certainly would be unable to justify construction of a dike. He also points to the Philippines, where many people have literally "taken to the water," living in small boats and maintaining fishing nets in their own plots of bay instead of land. Current wetlands, he suggests, may convert to these shallow bays, with people converting to a more water-based economy.

Leatherman (Volume 4) examines the implications of sea level rise for South America. He notes that such popular resorts as Copacabana Beach, Brazil; Punta del Este, Uruguay; and Mar del Plata, Argentina, are already suffering serious erosion. He concludes that because of the economic importance of resorts, governments will allocate the necessary funds to maintain their viability. However, he predicts that "coastal wetlands will receive benign neglect" and be lost.

Park et al. (Volume 4) focus on the expected drowning of coastal wetlands in the United States. Using a computer model of over 50 sites, they project that 40-75 percent of existing U.S. coastal wetlands could be lost by 2100. Although these losses could be reduced to 20-55 percent if new wetlands form inland as sea level rises, the necessary wetland creation would require existing developed areas to be vacated as sea level rises, even though property owners would frequently prefer to construct bulkheads to protect their property. Because coastal wetlands are important for many commerically important seafood species, as well as birds and furbearing animals, Park et al. conclude that even a one-meter rise in sea level would have major impacts on the coastal environment.

DeSylva (Volume 4) also examines the environmental implications of sea level rise, noting that in addition to wetlands being flooded, estuarine salinity would increase. Because 66 to 90 percent of U.S. fisheries depend on estuaries, he writes that these impacts could be important. He also suggests that coral reefs could become vulnerable because of sea level rise, increased temperatures, and the decrease in the pH (increased acidity) of the ocean.

Kuo (Volume 4) examines the implications of sea level rise for flooding in Taipei, Taiwan, and coastal drainage in general. Although Taipei is upstream from the sea, Kuo concludes that projected sea level rise would cause serious problems, especially because Taiwan is also sinking. He recommends that engineers around the world take "future sea level rise into consideration . . . to avoid designing a system that may become prematurely obsolete."

Gibbs (Volume 4) estimates that sea level rise could result in economic damages in Charleston, South Carolina, equal to as much as 25 percent of the annual product of the community. Anticipatory measures, however, could reduce these impacts by half. Gibbs finds that in some areas actions should be taken today, in spite of the current uncertainty regarding future rates of sea level rise, while for other areas it would be more prudent to wait until uncertainties are resolved.

Ken Smith, a realtor from coastal New Jersey, reacts to the other papers presented in Volume 4. He argues that the issue of sea level rise should be taken seriously today, but laments the fact that many of his fellow realtors make comments such as "What do you care? You won't be around to see it!" and the scientific community is "a bunch of eggheads who don't want us (to build on the coast) anyway." Smith suggests that part of the resistance to taking the issue seriously is that there are a number of "naturalists" who oppose building near the shore, and "most of the discussion seems to come from the 'naturalist' camp." Nevertheless, Smith argues that "the solutions--if there are any--should be contemplated now as part of a concerted global effort. This is a beautiful world, and we are its stewards."

Human Health and Ecological Impacts

Climate and weather have important impacts on human health. A global warming would increase the stresses due to heat, decrease those due to cold, and possibly enable some disease that require warm year-round temperatures to survive at higher latitudes. Kalkstein et al. (Volume 3) present a preliminary statistical assessment of the relationship of mortality rates to fluctuations in temperature in New York City. They find that a two to four degree (C) warming would substantially increase mortality rates in New York City, if nothing else changed. However, they caution that if New Yorkers are able to acclimatize to temperatures as well as people who currently live in U.S. cities to the south, fewer deaths would occur. Kalkstein et al. write that knowledgeable observers disagree about whether and how rapidly people adapt to higher temperatures; some people undoubtedly adjust more readily than others.

Although people may be able to adapt to changes in climate, other species on the planet would also be affected and may not be as able to control their habitats. Peters and Darling (Volume 3) examine the possibility that changes in climate would place multiple stresses on some species which would become extinct, resulting in a significant decline in biodiversity. (Mass extinctions appear to have accompanied rapid changes in temperatures in the past.)

Throughout the world reserves have been set aside where targeted species can remain relatively free of human intrusion. Peters and Darling ask: Will these reserves continue to serve the same function if the climate changes? In some cases, it will depend on whether the reserve's boundaries encompass areas to which plants and animals could migrate. Some species may be able to migrate "up the mountain" to find cooler temperatures; coastal wetlands could migrate inland. A northerly migration of terrestrial species would be possible in the undeveloped arctic regions of Alaska, Canada, and the Soviet Union; but human development would block migration of larger animals in many areas.

POLICY RESPONSES

Papers by UNEP Deputy Director Genady Golubev and EPA Administrator Lee Thomas (both in Volume 1) provide official views on the nature of the effects from projected changes in the atmosphere and the role of their institutions in addressing those changes. Golubev notes that while "the global issues are complex, uncertainty exceeds understanding, and patience is prudence," there is an other side to the story: "Our legacy to the future is an environment less benign than that inherited from our forbearers. The risks are sufficient to generate a collective concern that forebodes too much to wait out the quantifications of scientific research. Advocating patience is an invitation to be a spectator to our own destruction."

Golubev also points out that UNEP has worked for the achievement of the Vienna Convention for the Protection of the Ozone Layer, in which many nations have agreed to act in concert to address an environmental issue whose impacts have not yet been detected. Yet he notes that the agreement is for cooperation in research and does not yet bind nations to observe limits in production and emissions of gases that could deplete stratospheric ozone.

Thomas points out that both the potential depletion of ozone and the global warming from the greenhouse effect are examples of environmental problems that involve the "global commons." Because all nations contribute to the problem and experience the consequences, only an international agreement is likely to be effective. He urges scientists around the world to discuss this issue with their colleagues and key officials.

Richard Benedick, Deputy Assistant Secretary in the U.S. Department of State (Volume 1), describes the emerging international process addressing the ozone issue. Although the process for addressing climate change has not yet proceeded as far, he writes, "from my perspective as a career diplomat, it appears that the greenhouse effect has all the markings of becoming a high visibility foreign policy issue. . . . How we address this issue internationally depends to a great extent on our success or failure in dealing with the ozone depletion issue."

J.P. Bruce (Volume 1) of Environment Canada presents the issue of atmospheric change in the context of air pollution in general. He writes that ozone modification and climate change are "urgent issues," especially because important long-term decisions are being made today whose outcomes could be strongly affected by changes in climate and the ozone layer. Bruce recommends that emissions of CFCs be reduced, and concludes that "a new approach, a new ethic towards discharging wastes and chemical materials into the air we all breathe must soon be adopted on a international scale."

Two U.S. Senators also provide their reactions. John Chafee from Rhode Island (Volume 1) describes hearings that his Subcommittee on Environmental Pollution held June 10-11, 1986. "Why are policy makers demanding action before the scientists have resolved all of the questions and uncertainties?" he asks. "We are doing so because there is a very real possibility that society--through ignorance or indifference, or both--is irreversibly altering the ability of our atmosphere to perform basic life support functions for the planet." Albert Gore, Jr. from Tennessee, who has chaired three congressional hearings on the greenhouse effect, explains why he has introduced a bill in

the U.S. Senate to establish an International Year of the Greenhouse Effect. "The legislations would coordinate and promote domestic and international research efforts on both the scientific and policy aspects of this problem, identify strategies to reduce the increase of carbon dioxide and trace gases, investigate ways to minimize the impact of the greenhouse effect, and establish long-term research plans." Senator Gore closes by quoting Sherwood Rowland (discussed below): "What's the use of having developed a science well enough to make predictions, if in the end all we're willing to do is stand around and wait for them to come true?" Both Senators call for immediate action to reduce global use of CFCs.

John S. Hoffman (Volume 1) emphasizes the inertia of the atmosphere and oceans. Because there are time lags between changes in emission rates, atmospheric concentrations, and changes in ozone and global warming temperatures, the types of management strategies must be different from those that are appropriate for controlling, for example, particulate pollution, where the problem goes away as soon as emissions are halted. CFC emissions would have to be cut 80 percent simply to keep concentrations from increasing. Although constant concentrations would prevent ozone depletion from worsening, Hoffman points out that even if we hold the concentrations of greenhouse gases constant once the earth has warmed one degree, the planet would warm another degree as the oceans come into equilibrium. Thus it might be impossible to prevent a substantial warming if we wait until a small warming has taken place.[3]

The final section of this volume presents the papers from the final day of the conference. Peter Usher of UNEP recounts the evolution of the ozone issue. Following Rowland and Molina's hypothesis that chlorofluorocarbons could cause a depletion of stratospheric ozone in 1974, UNEP held a conference in 1977 that led to a world plan of action to assess the issue and quantify risks. Since that time, UNEP has held numerous coordinating meetings leading up the the Vienna Convention. However, Usher suggests that motivating international effort on the greenhouse effect will be more difficult: "Prohibition of nonessential emissions of relatively small amounts (to control ozone depletion) is one thing, limiting emissions of carbon dioxide from coal- and oil-burning is quite another."

Dudek and Oppenheimer of the Environmental Defense Fund (U.S.) analyze some of the costs and benefits of controlling emissions of CFCs. They estimate that by holding emissions constant, 1.65 million cases of nonmelanoma skin cancers could be prevented worldwide, and that the cost of these controls would be 196 to 455 million dollars, depending on the availability of alternative chemicals.

Two former high-ranking environmental officials in the United States argue that we should be doing more to address these problems. John Topping recommends that CFCs in aerosol spray cans, egg cartons, fast-food containers, and other nonessential uses be phased out, and that people recognize that

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3 Titus (Volume 1) and Thomas (Volume 4) also explore inertia, noting that even if temperatures remained constant after warming somewhat, sea level would rise at an accelerated rate as the oceans, mountain glaciers, and ice sheets came into equilibrium with the new temperature.

along with energy conservation, nuclear power is the most likely alternative to fossil fuels over the next generation or two. He also recommends that society take steps to minimize the impacts of climate change and sea level rise, for example, by requiring environmental impact statements to consider the likely impacts.

Gus Speth, president of the World Resources Institute, recommends international efforts to stop tropical deforestation; a production cap for chlorofluorocarbons; increased energy conservation; advanced technologies for producing electricity from natural gas; and tighter regulations to limit carbon monoxide from automobiles, which would indirectly limit increases in atmospheric methane. He agrees with Topping that environmental impact statements for projects that could contribute to or be affected by climate change or ozone modification should consider these impacts.

Doniger and Wirth, from the Natural Resources Defense Council (U.S.), argue that the current uncertainties are no longer a reason to wait for additional information: "With the stakes so high, uncertainty is an even more powerful argument for taking early action." These authors conclude that sharp reductions in CFCs are necessary, pointing out that even with a production cap, atmospheric concentrations of these gases will continue to grow. Therefore, Doniger and Wirth propose an 80 percent cut in production over the next five years for CFCs 11 and 12, the halons, and perhaps some other compounds, with a complete phaseout in the next decade.

Richard Barnett of the Alliance for a Responsible CFC Policy (which represents CFC using industries) agrees that we should not delay all action until the effects of ozone depletion and climate change are felt; but he "would hardly characterize the activities over the last twelve years as 'wait and see' . . . The science, as we currently understand it, however, tells us that there is additional time in which to solidify international consensus. This must be done through discussion and negotiation, not through unilateral regulation."

Barnett adds that industry should "take precautionary measures while research and negotiations continue at the international level. We will continue to examine and adopt such prudent precautionary measures as recapturing, recycling, and recovery techniques to control CFC emissions; transition to existing alternative CFCs that are considered to be more environmentally acceptable; practices to replace existing systems at the expiration of their useful lives to equipment using other CFC formulations; practices in the field to prevent emissions where possible; encouragement of CFC users to look for processes or substances that are as efficient, safe, and productive--or better--than what is presently available."

Barnett concludes that "these environmental concerns are serious, but their successful resolution will require greater global cooperation in conducting the necessary research and monitoring, and in developing coordinated, effective, and equitable policy decisions for all nations."

We hope that this paper has provided the reader with a "road map" through the papers of this four-volume report on the potential effects of changing the atmosphere. But we have barely scratched the surface of each, just as the existing research has barely scratched the surface in discovering and

demonstrating the possible risks of ozone modification and climate change. A continual evolution of our understanding will be necessary for our knowledge to stay ahead of the global experiment that society is conducting.

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Future Sea Level Rise and Its Early Detection by Satellite Remote Sensing

Robert Thomas
Space Department
Royal Aircraft Establishment
Franborough, Hants UK

ABSTRACT

During the past 100 years, sea level appears to have risen by 10-15 cm, probably due to the combined effects of thermal expansion of ocean surface waters and net melting of glaciers and ice caps, associated with a small increase in global temperatures. This trend will almost certainly continue and accelerate if steadily increasing levels of carbon dioxide and other "greenhouse" gases in the atmosphere cause warming of the magnitude widely predicted by climate modellers (see Hansen et al. Volume 1). Rising air temperatures will cause increased melting from glaciers and ice caps, and rising seawater temperatures will cause thermal expansion of the oceans. Moreover, warmer ocean waters could melt and weaken the many floating ice shelves that surround Antarctica, permitting increased ice discharge from glaciers. This paper estimates the total sea level rise that could occur during the next century as a result of these factors.

If, as predicted by many climate models, global temperatures increase by an average of about 3°C, there is a good probability that sea level will rise by approximately 1 m by the year 2100. Ultimately, such a rise would become very apparent to coastal populations, but the initial change would be slow. Consequently, it is important to devise an "early warning system" for prompt detection of changes that will precede a detectable rise in sea level. These include changes in:

- Surface temperatures on land, oceans, and ice sheets
- Sea-ice distribution
- Extent of summer melting on the polar ice sheets
- Areal extent and surface elevations of the ice sheets in Greenland and Antarctica.

All of these parameters can be measured from space by satellites that are operating now or are planned for launch during the next few years.

INTRODUCTION

Greenhouse gases trap heat within the atmosphere. Carbon dioxide (CO_2) is the most prevalent greenhouse gas, but there are more than a dozen others present in the atmosphere. Most are becoming increasingly abundant, and if present trends continue, their combined effect could be equivalent to a doubling of present-day CO_2 levels by about 2050. Most climate models indicate that this would ultimately cause global warming of between 1.5° and 4.5°C. Moreover if greenhouse gases continue to increase beyond 2050, global warming will be even greater. How long it takes for the warming to be realized will depend largely on the ocean. If only the mixed layer (the upper 100 m or so) is affected, then the global warming would be realized with a lag of only a few decades. But if, by contrast, the deep ocean responds rapidly to increasing air temperatures, then global warming could be delayed by a century or more, much of the additional heat being used to warm the ocean instead of the atmosphere. Further uncertainty is introduced by the effects of clouds, which cannot be accurately simulated with present models. However, although we cannot be absolutely certain that sustained increases in greenhouse gases will significantly affect the climate, there is a strong probability that they will. In this paper, I review possible effects of this warming on sea level.

Heat trapped by greenhouse gases raises the temperature of the atmosphere and the ocean (Figure 1). The response of sea level to this warming is strongly determined by the partition of available heat between these two processes. If most of the heat remains in the atmosphere, air temperatures rise rapidly and sea level is affected most by increased melting of ice. Alternatively, rapid transfer of heat into the sea would increase ocean temperatures, and sea level would rise because of thermal expansion and by accelerated Antarctic ice discharge associated with increased melting from beneath the floating ice shelves. Moreover, sea-ice distribution both influences, and is affected by, thermal interactions between atmosphere and ocean.

At present we cannot determine the partition of heat between ocean and atmosphere. Consequently, even for well-defined rates of increasing greenhouse gases, we cannot accurately predict the response of either the climate or sea level. Nevertheless, we can estimate probable limiting rates of sea level rise by examining "reasonable" climate scenarios that would either favor or inhibit sea level change.

Past Trends in Global Sea Level

Numerous studies of long-term tide-gauge measurements suggest that global sea level has risen 10-15 cm during the last hundred years (e.g., Barnett 1983). The reasons for this have been variously described to thermal expansion of a warming ocean (Gornitz, Lebedeff, and Hansen 1982); melting of ice from Greenland and Antarctica (Etkins and Epstein 1982) or from small ice caps and glaciers in lower latitudes (Meier 1984); or systematic downwarping of coastlines due to the effects of sedimentation (Pirazolli 1986). There is a consensus that the observations can be explained by the combined effects of

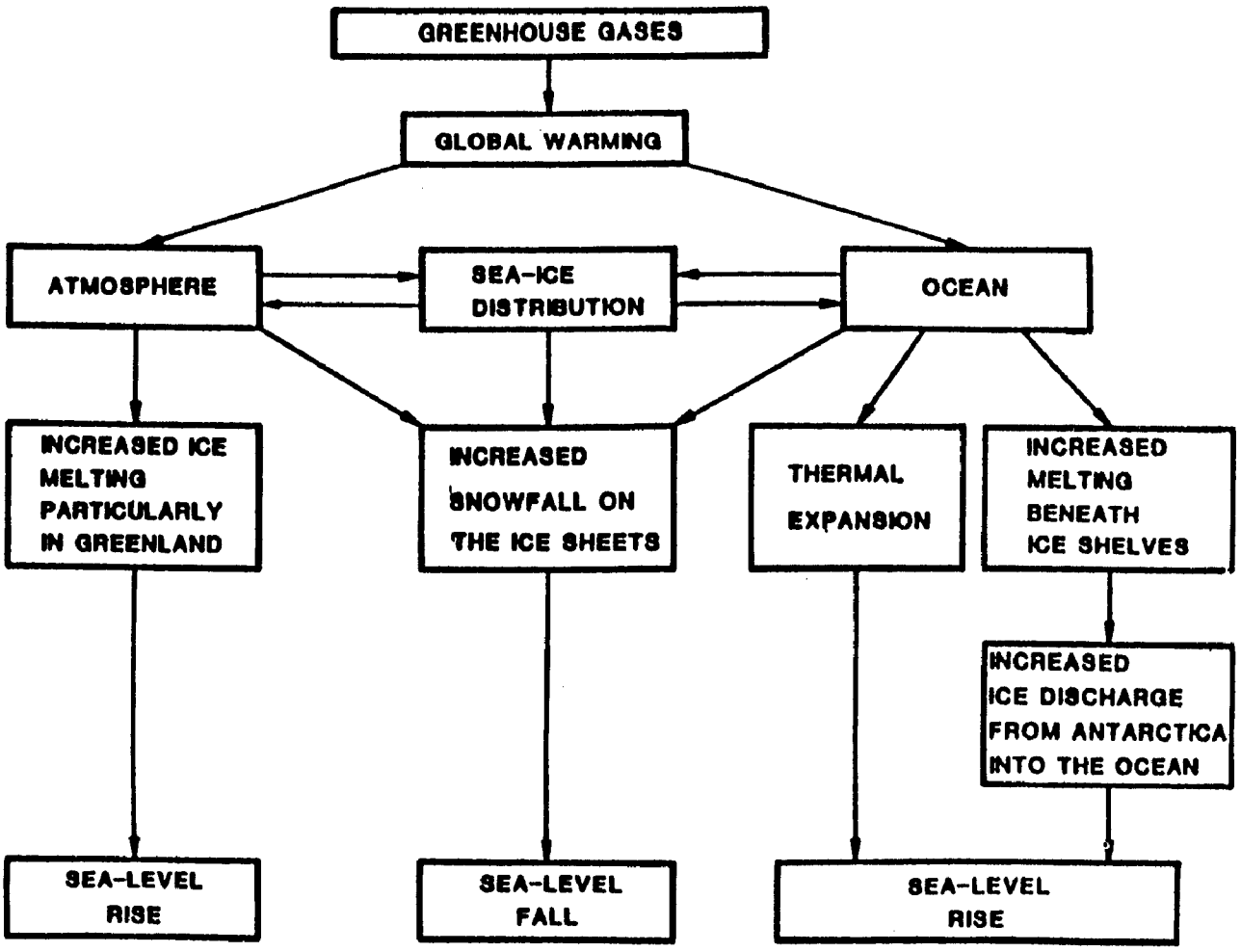

Figure 1. The Major Processes Relating Greenhouse Warming to Average Worldwide Sea Level

melting from small ice caps and glaciers and of thermal expansion of ocean waters. But there are no data confirming that this is so.

We do know that glaciers and small ice caps have retreated during the past 100 years, but we cannot accurately estimate their contribution to sea level rise. Information from the ocean presents a yet more confusing picture. There appears to have been an increase in sea surface temperatures since 1900, but part of this apparent increase may be due to changes in measuring techniques. Moreover, the longest time series (26 years) of deep hydrographic stations (near Bermuda) provide a very noisy signal, with large decadal temperature oscillations superimposed on a net cooling in the upper 1,000 m, and a more systematic warming trend at greater depths (Roemmich 1985). Further north, repeat measurements along a traverse across the north Atlantic reveal a cooling and freshening since 1972 at all depths down to 4,000 m (Swift 1984). Considerably more measurements from many parts of the ocean will be required before these differing trends can be explained.

Estimates of ice-sheet mass balance in Greenland and Antarctica are no less ambiguous. There is good evidence both for retreat of the ice margin in west Greenland and for an increase in surface elevation near the ice sheet summit, and the present consensus is for an approximate balance between snowfall and losses by melting and iceberg calving. However, errors are so large that the Greenland ice sheet could be thickening or thinning sufficiently to cause a sea level fall or rise of up to 0.4 mm/yr (Reeh 1985). Antarctic mass balance is even less well measured. Here, consensus opinion is that ice volume is slowly increasing, but available data cannot rule out thickening or thinning equivalent to a sea level change ranging from a drop of 3 mm/yr to a rise of 1.5 mm/yr.

The possibility that the observed apparent sea level rise is due to a tendency for coastal downwarping has intuitive attraction, since there is a continuous transfer of sediments towards the coast. However, the spatial correlation of observed sea level increase suggests that there has been eustatic sea level rise during the past 100 years (Barnett 1983).

In summary, there probably has been a sea level rise of 10-15 cm during the past 100 years. Some of this increase (perhaps 4 or 5 cm) was caused by net melting of glaciers and small ice caps, and the rest was probably associated with thermal expansion of a warming ocean. Our greatest uncertainty regards possible contributions from the ice sheets in Greenland and Antarctica. Indeed, the comparatively small apparent change in sea level provides better evidence for near-equilibrium mass balance of the ice sheets than is available from many decades of glaciological observations.

THE EFFECTS OF A CLIMATIC WARMING

No matter what was responsible for the recent apparent rise in sea level, it is certain that a significant climate warming will cause an increase in ocean volume. Rising air temperatures will increase surface melt rates on glaciers, small ice caps, and the Greenland ice sheet; a warming ocean will increase in volume by thermal expansion, and it will cause an increase in melt rates from beneath the vast floating ice shelves around Antarctic. This in itself will not change sea level, but as the ice shelves thin and weaken, ice discharge from their tributary glaciers will increase, causing sea level to rise. (See Figure 2 for a graphic illustration of the contribution that each

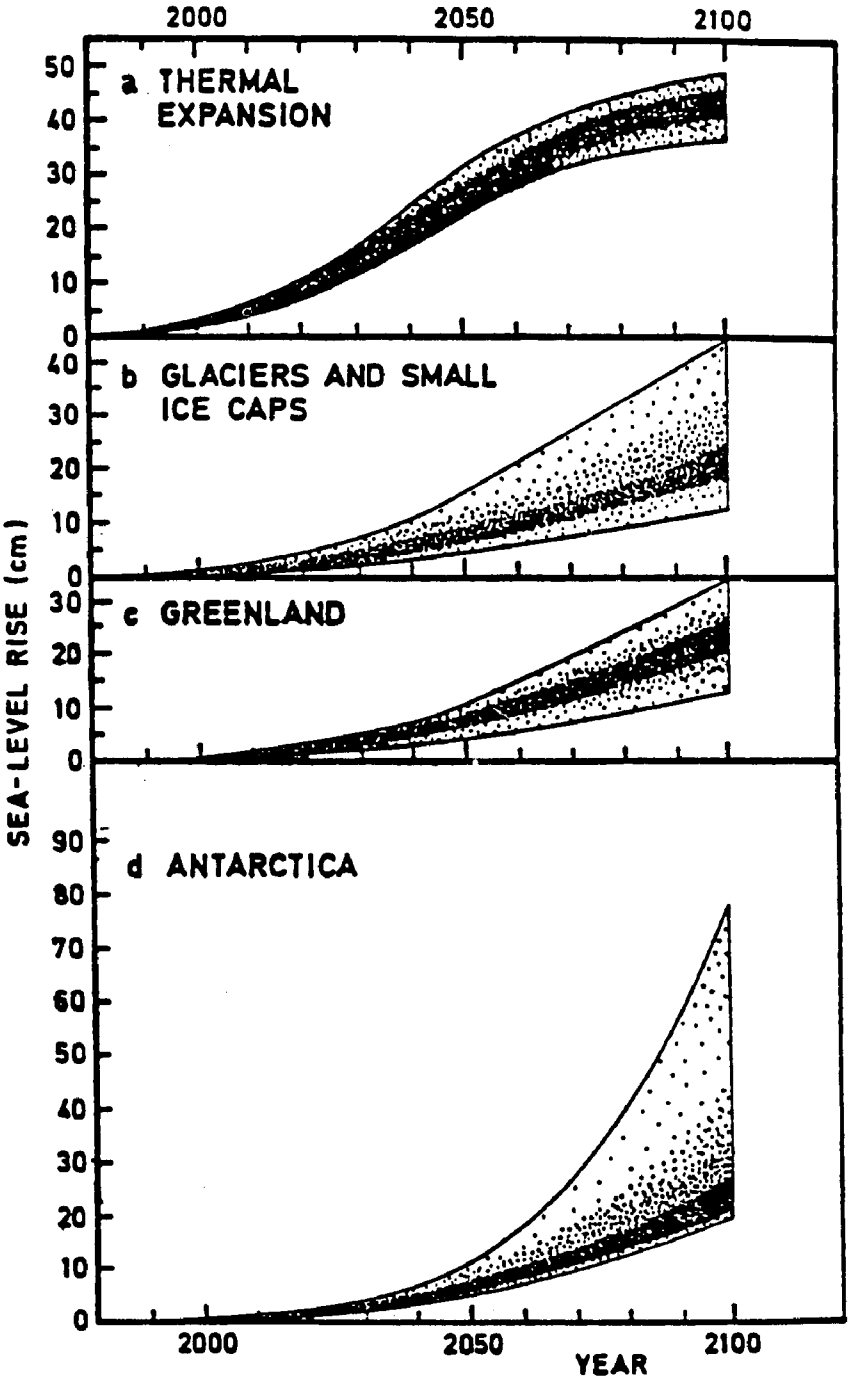

Figure 2. Estimates of Eustatic Sea Level Rise During the Next Century. This four-part figure depicts sea level rise due to: (a) thermal expansion; (b) melting of glaciers and small ice caps; (c) melting from the Greenland ice sheet; and (d) increased ice discharge from Antarctica.

Surface air temperatures are assumed to increase linearly until 2050, to an average value 3°C higher than at present, and then to remain constant. Melting from beneath Antarctic ice shelves is assumed to increase in the same way to either 1 m/yr or 3 m/yr greater than the present rate. The dark shading indicates the "most probable" response, based on our current understanding of these processes.

of these factors makes to sea level rise.) In order to assess the contribution to sea level rise from each of these effects, I shall make some assumptions about climate change during the next century.

Present trends in atmospheric concentrations of greenhouse gases suggest that together, they may have an effect equivalent to a doubling of CO_2 by the year 2050, possibly sooner. Most climate studies have indicated that, once equilibrium has been achieved, earth-surface temperatures will increase by an average of 1.5°-4.5°C, depending on a variety of feedback mechanisms. Warming will occur with a lag of a few decades if only the ocean mixed layer is also warmed, but with a lag of at least 100 years if there is efficient heat transfer to much greater depths. Climate models take account of this transfer by allowing heat to leak into the deep ocean at a rate determined by an effective diffusion coefficient K (Oeschger et al. 1975). Estimates of K show a large geographical variation, with values near the poles up to 100 times greater than those near the equator (Hansen et al. 1984). However, in order to examine the transient climate responses to increases in greenhouse gases, simple unidimensional models are used with a "global" value of K of 1 to 2 cm^2/sec. These studies indicate that the thermal inertia of the ocean delays climate warming by 100 years or more (Hansen et al. 1984; Siegenthaler and Oeschger 1984).

In order to provide a "baseline" estimate of sea level rise during the next century, I assume that earth-surface temperatures increase by an average of 3°C by the year 2050 and remain constant thereafter. Warming in the polar regions will be amplified by a factor of two, and ocean conditions will change sufficiently to increase melt rates beneath Antarctic ice shelves from present-day values of a few tens of centimeters per year by between 1 and 3 meters per year. Moreover, I assume that snow accumulation on the ice sheets remains unchanged. These conditions correspond to:

- A growth in greenhouse gases consistent with many current estimates, but with an arbitrary termination of growth in 2050
- A swift climatic response to these gases.

This probably represents a "reasonable" scenario, with some attempt being made next century to limit growth rates of greenhouse gases. Continued growth beyond 2050, a larger climate sensitivity to CO_2 doubling, or a greater polar amplification could result in a more rapid sea level rise. Alternatively, a significantly delayed climate response to increasing CO_2 and probably increased snow accumulation over the ice sheets would reduce the increase in sea level. In a later section, I try to indicate probable impacts of these more extreme cases.

Ocean Response

Heating of both the mixed layer and the deeper ocean will cause sea level to rise by thermal expansion. The calculations of Hoffman, Wells, and Titus (1985) using a value of diffusivity (K) = 1.7 cm^2/sec yield a sea level rise of almost 30 cm for a global warming of 3°C by 2055, and I have adapted their estimates to compile Figure 2a. After 2050, sea level continues to increase, but at a slower pace, since further heating is mainly by leakage of heat into the deeper ocean (given the assumption that temperatures remain constant after 2050).

Such a major climatic change is bound to be accompanied by changes in ocean circulation, atmospheric pressure, and surface winds. These also will affect sea level. They will not affect the ocean volume; they will simply redistribute it. At present, we cannot predict these effects, but regionally, they may cause a raising or lowering of sea level of up to a few tens of centimeters superimposed on the eustatic change.

Changes in sea-ice distribution, rainfall, winds, temperatures, and freshwater inflow will all affect the density structure and mixing rate in the upper layers of the ocean. These, in turn, will affect how rapidly heat diffuses into the deeper ocean. So the effective diffusivity, K, may change with time. In particular, the present-day areas of high diffusivity at high latitudes may be capped by layers of low-density surface water which would inhibit cooling of deeper water by convective overturning (Figure 3). The net result could be a significant increase in the amount of heat penetrating beneath the Antarctic ice shelves.

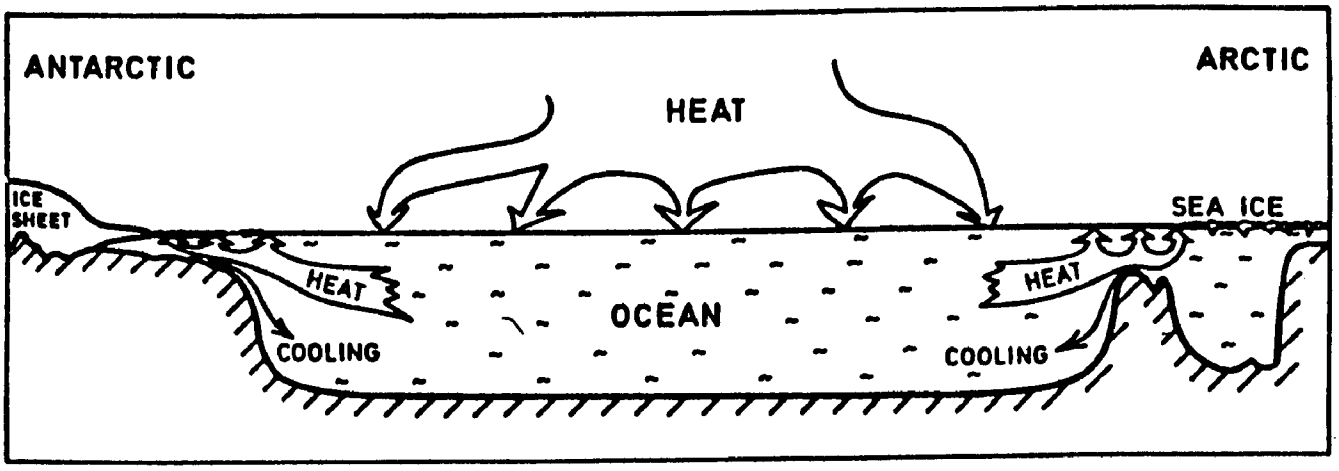

Figure 3. Heat Transfer Within the Ocean

There is rapid cooling in specific areas within the polar regions where convective overturning brings warm water to the surface. A significant change in climate could alter ocean stratification sufficiently to inhibit this process and trigger a long-term warming of the deep ocean. This in turn would cause a major increase in melting from beneath the Antarctic ice shelves.

Surface Melting from Glaciers and Ice Sheets

Meier (1984) calculated that, during the past 60 years, melting of glaciers and small ice caps has contributed to sea level rise at an average rate of about 0.5 mm/yr. He further estimated that a rise in air temperatures of 1.5° to 4.5°C could lead to glacier wastage equivalent to 1.7-5.2 mm/yr of sea level rise and a total rise by the year 2100 of 8-25 cm. In the climate scenario that I have adopted, temperatures rise more rapidly than assumed by Meier, which yields a rise in sea level of 12-42 cm by 2100. In Figure 2b, however, I indicate the preferred value to be about 20 cm because, as Meier stresses, the area of glacier ice would progressively diminish, and precipitation on many of the glaciers may increase. The preferred value of 20 cm is, of course, arbitrary, but the actual rise is unlikely to be much greater, since the total volume of glaciers and small ice caps is estimated as equivalent to between 30 and 60 cm of sea level.

Meier's estimates did not include possible increases in melting from the ice sheets in Greenland and Antarctica. At present, there is negligible wastage from the Antarctic ice sheet by surface melting, and temperatures are so low that a 3°C rise in global temperatures may not cause significant wastage by 2100. In Greenland, by contrast, about half the wastage is by melting, at an average rate exceeding 1 m/yr, from approximately 15% of the ice-sheet surface. The effect of a warming climate would be twofold: higher temperatures would increase the melt rate; and the equilibrium line separating accumulation from ablation would be elevated, exposing a greater percentage of the ice-sheet area to melting. There may also be an increase in glacier flow rates (and hence more ice discharged into the sea) associated with enhanced lubrication by drainage of greater amounts of surface meltwater to the glacier bed. We cannot at present assess the importance of this process, but we should flag it as one of the many wild cards in the deck of greenhouse-warming impacts.

Bindschadler (1985) developed a simple model to predict the response of the Greenland ice-sheet to warmer climates. Using available measurements of the atmospheric lapse rate, he estimated that the equilibrium line would be elevated between 500 m and 1,000 m for a 6°C rise in air temperatures over Greenland. Because of the anticipated polar amplification of global warming, this corresponds to a 3°C rise in average global temperatures. Bindschadler estimated that the resulting excessive melting would cause a sea level rise of 1.3 mm/yr for a 500-m elevation in equilibrium line, and 3.5 mm/yr for 1,000 m. Bindschadler estimated that the rate of sea level rise would be approximately 30% greater if the rate of iceberg calving is related to meltwater discharge, as suggested by Sikonia's (1982) study of calving glaciers. The total rise by the year 2100 would thus be between 13 cm and 34 cm (Figure 2c).

Accelerated Ice Discharge from Antarctica

Most of the ice flowing from Antarctica drains via (relatively) rapidly moving ice streams into floating ice shelves (Figure 4). The ice streams push the ice shelves seaward past their irregular sides and over and around areas where the ice shelf has run aground on shoaling sea beds. To do this, the ice streams build up a "gravitational head" by becoming thicker than they would if the ice shelves were not there. Consequently, removal or weakening of the ice shelves would permit the ice streams to thin and discharge their excess thickness into the ocean. In many cases, an ice stream would contribute a small amount to sea level rise and then acquire a new thickness profile in equilibrium with the modified ice-shelf conditions. For other ice streams, however, particularly many of those in West Antarctica which flow over rock that is well below sea level, they may thin sufficiently to float free of bedrock. Then, if the ice shelves continue to weaken, most of the ice in West Antarctica could progressively drain into the ocean. This possibility is often raised as the major disastrous consequence of climatic warming. Indeed, it may ultimately occur, but many studies have shown that it would take several hundred years (see for instance, Thomas, Sanderson, and Rose 1979; Bentley 1984).

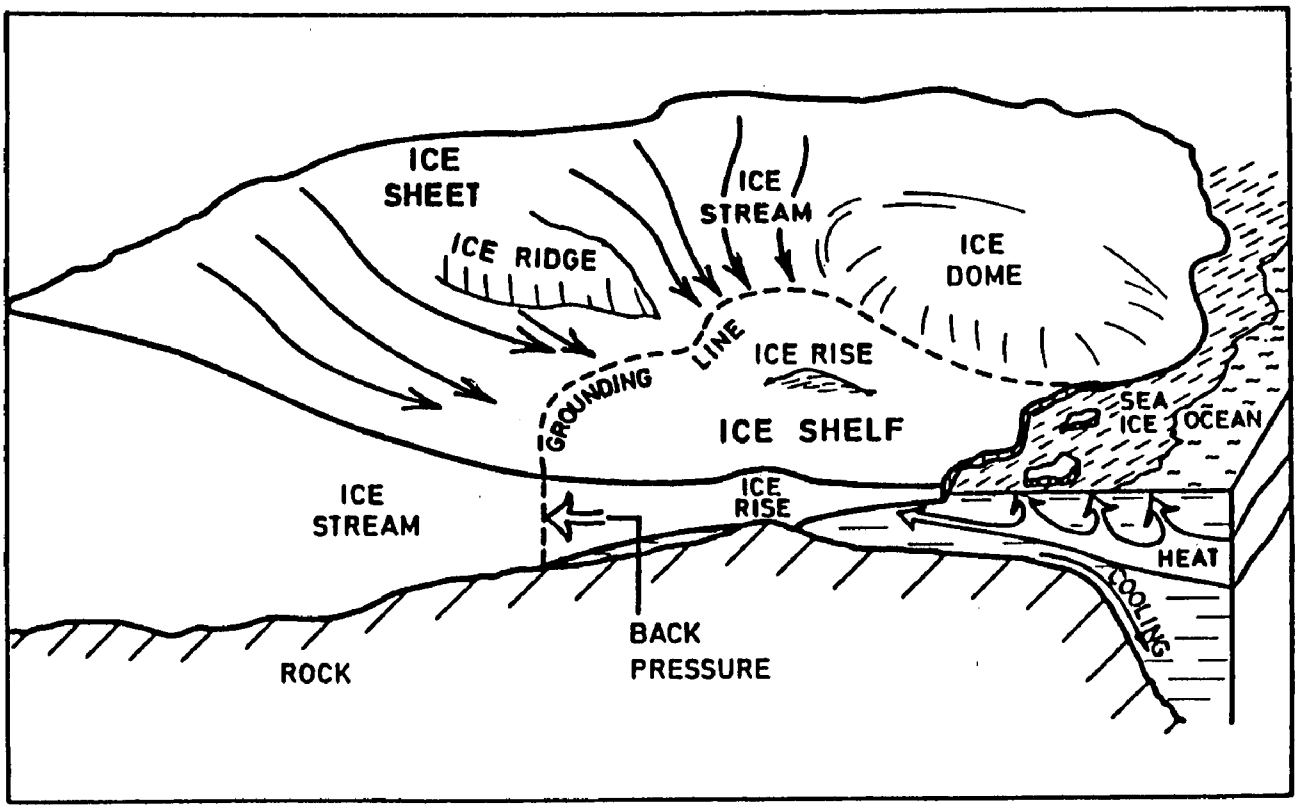

Figure 4. An Ice Stream Flowing into a Floating Ice Shelf

This ice stream is grounded on bedrock that is well below sea level, as occurs today in many parts of Antarctica. The larger ice shelves occupy large embayments which, together with locally grounded ice rises, restrict seaward motion of the ice. This results in a back pressure exerted on the ice stream. Weakening of the ice shelf by increased basal melting would reduce the back pressure and permit more rapid ice discharge along the ice stream.

At present, the Antarctic ice shelves are able to survive because there is virtually no melting from their upper surfaces, and melting from beneath is limited by the restricted amount of ocean heat that reaches the ice shelves. This is because the ocean bordering Antarctica is very weakly stratified, permitting convective overturning of warm deep water, which loses heat to the sea ice and the atmosphere before penetrating beneath the ice shelves. This is the principal mechanism by which the deep ocean is cooled (See Figure 3). One consequence of climatic warming may be a more strongly stratified southern ocean (Gordon 1983; Jacobs 1985). This could have two consequences: it could limit cooling of the deep ocean and, hence, accelerate the rate of ocean warming (and associated thermal expansion) and it could allow significantly more heat to penetrate beneath the ice shelves and increase basal melting rates.

In order to estimate associated rates of sea level rise, Thomas (1985) assumed that climatic warming would increase basal melt rates beneath all ice shelves, starting in the year 2000, by either 1 m/yr or 3 m/yr by 2050. The value of 1 m/yr was chosen because it is consistent with Gordon's (1983) estimate of possible ocean warming close to Antarctica and MacAyeal's (1984) analysis of the dependence of basal melting on ocean temperatures. The value of 3 m/yr represents an extreme upper limit, with circumpolar deep water reaching the ice shelves without major cooling, as appears to be happening today on the west coast of the Antarctic Peninsula.

In the simplest case, Thomas assumed that ice discharge rates from ice streams into the ice shelves would increase sufficiently to replace ice lost by enhanced melting. A more elaborate model attempts to simulate the dynamic response of the tributary ice streams and to estimate the corresponding ice discharge rates. The two models are in close agreement, with an estimated total sea level rise by the year 2100 of about 20 cm for ice shelf melting of 1 m/yr, and about 80 cm for shelf melting of 3 m/yr (Figure 2d). Thomas also attempted to asssess the consequences of a massive increase in iceberg calving from the ice shelves. If this occurred in 2050, then total sea level rise by 2100 for either melting rate could be close to 2 m. However, such calving is unlikely unless air temperatures rise considerably higher than is predicted during the next century. Of course, if temperatures continue to rise beyond the year 2100, the ice shelves probably will ultimately break up, thus causing a much larger rise in sea level.

Our present understanding of ocean/ice interactions indicates that melting beneath the very large ice shelves is unlikely to increase by more than 1 m/yr, but I stress that our understanding is still rudimentary. Nevertheless, in Figure 2d, I indicate the lower curve as preferred.

Sea Level Rise Through 2100

Summing the plots for each of the four processes in Figure 2 gives the estimate of total sea level rise shown in Figure 5. The total sea level rise by 2100 for the assumed scenario of climate change is estimated to be 0.9-1.7 m, with a preferred value close to 110 cm.

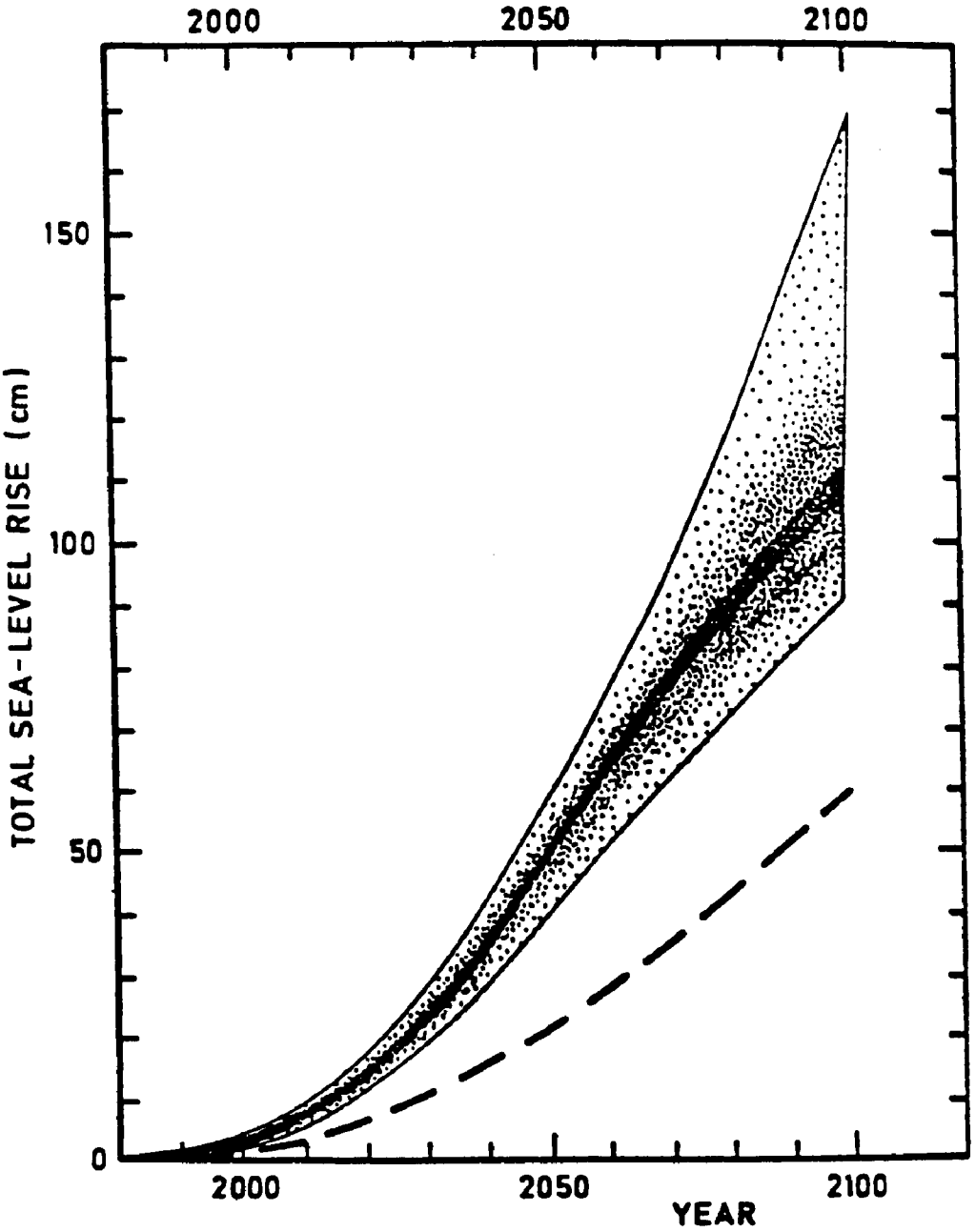

Figure 5. Total Sea Level Rise During the Next Century

The dark shading indicates the most probable response to the climate scenario described in the caption to Figure 2. The broken line depicts the response to a warming trend delayed 100 years by thermal inertia of the ocean. A global warming of 6°C by 2100, which represents an extreme upper limit, would result in a sea level rise of about 2.3 m, but errors on this estimate are very large.

FACTORS THAT MAY INFLUENCE THE RATE AT WHICH THE SEA RISES

No extreme assumptions were made in deriving the above estimate. Therefore, I suggest that we should take very seriously the possibility that sea level will rise by approximately 1 m during the next century. Clearly many factors could either delay or accelerate this rise: I now try to establish some probable limits by quantifying these factors.

Delayed Warming

The assumed climate sensitivity of a 3°C average warming for an effective doubling of CO_2 represents a fair consensus of the many attempts that have been made to model the climate response. Moreover, there is a good probability that equivalent doubling of CO_2 will occur next century. However, there will almost certainly be a lag of many decades between the CO_2 doubling and climatic warming (Hansen et al. 1984; Siegenthaler and Oeschger 1984) due to diffusion of heat into the deep ocean. This will have two important effects: Air temperatures prior to 2100 will be lower than I have assumed, reducing the amount by which the sea will rise because of surface melting from glaciers, small ice caps, and the Greenland ice sheet. In addition, the ocean mixed layer will warm more slowly than assumed earlier, and a greater proportion of available heat will escape into the deep ocean.

In order to assess how sensitive sea level is to these effects, I recalculate the curves in Figure 2 and obtain a 3°C increase in average global temperature by 2150, one hundred years later than in the earlier scenario. For Greenland, I have attempted to correct the estimates for drainage of meltwater into the underlying, porous firn by requiring meltwater to saturate the firn before any runoff into the ocean can occur. In this case, the Greenland ice sheet contributes 9 ± 4 cm to sea level rise by 2100, and glaciers and ice caps contribute an additional 14 ± 8 cm. This last estimate is close to the preferred value in Figure 2b, which was constrained to be low by the limited volume of this source of meltwater. The thermal expansion values calculated by Hoffman, Wells, and Titus (1985) for their low scenario provide an estimate appropriate to global warming of 2.3°C by 2100, which corresponds closely to a 3°C increase by 2150. Their estimate of total sea level rise by 2100 due to thermal expansion is approximately 28 cm. For the Antarctic contribution, I assumed that basal melt rates will increase to 1 m/yr by 2150, and I have not considered the possibility of higher melting rates beneath the large ice shelves, since these would require major changes to ocean characteristics around Antarctica. Sea level rise by 2100 from Antarctic ice discharge then becomes approximately 13 cm. Moreover, the effects of enhanced snow accumulation over Antarctica associated with climate warming could reduce this to less than 10 cm (National Research Council 1985, p. 64). The sum of these modified estimates, which probably represent a lower bound, yields a total approximately equivalent to a 60-cm rise by 2100.

Increased Warming

Three factors could result in a sea level rise significantly greater than the "baseline" value of 110 cm by 2100:

- Continued growth in greenhouse gases beyond an equivalent CO_2 doubling by 2050

- Polar amplification greater than doubling of the global warming
- Greater climate sensitivity to doubled CO_2.

To estimate the effect of these factors, I assume a 4.5°C climate sensitivity to doubled CO_2 with a threefold polar amplification, and an equivalent 150% increase of CO_2 by 2100. This represents an extreme scenario, and I shall try to retain realism by imposing a 30-year delay on climate response, and a requirement that Greenland meltwater saturate porous firn before draining into the ocean. The large increase in high-latitude temperatures implies that there probably would be appreciable surface melting in Antarctica. However, I do not attempt to estimate how much; instead, I assume it will balance effects of increased snow accumulation.

Extrapolation of the impact on glaciers and ice sheets of such an extreme warming is at best approximate, and I stress that errors on the resulting estimate are large. Many small glaciers and ice caps would disappear with an associated sea level rise of about 35 cm. All of the Greenland ice sheet would become an area of net ablation by 2100, contributing approximately 9 mm/yr to sea level rise (Bindschadler 1985), with a total associated increase of perhaps 45 cm. For the Antarctic, I adopt the upper limit of an 80-cm rise by 2100 shown in Figure 2d, corresponding to an increase in ice-shelf basal melting of 3 m/yr. This may be a low estimate primarily because such warm climatic conditions could result in accelerated break-up of parts of the ice shelves to permit far greater ice discharge into the sea. Under the Hoffman, Wells, and Titus (1985) "warm scenario," thermal expansion is estimated to increase sea level by a 6°C rise in global temperatures over 100 years. The total increase in sea level by 2100 then becomes 2.3 m. I regard this as an extreme upper limit corresponding to a climatic change so severe that the effects of impacts on global weather and agriculture could well dwarf those of even such a dramatic rise in sea level. Nevertheless, it highlights the need for us to develop a better understanding of just what increased concentrations of "greenhouse" gases will do to the climate.

INDICATORS OF A GLOBAL WARMING TREND CAN BE DETECTED

No matter what the total rise in sea level turns out to be by the year 2100, it is certain that initial acceleration will be very slow. It will probably not be detectable before 2020 at the earliest. Thereafter, the rate at which sea level will rise will progressively increase to about 1 cm/yr by 2100, after which the rate will probably continue to increase. In order to plan for such a comparatively rapid rise in sea level, it would be valuable to establish an early warning program to detect the first signs of the greenhouse warming. I describe a set of satellite measurements that would contribute significantly towards such a program.

A sustained climatic warming will inevitably cause changes in surface temperatures on the oceans, ice cover, and land, with associated changes in surface winds. These changes, in turn, will affect the extent, distribution and compactness of sea ice in the Arctic and around Antarctica. Moreover, if air temperatures increase in the polar regions, there will an increase in the area of summer melt zones on the ice sheets in Greenland and Antarctica. Finally, after a considerable delay, the extent and surface elevation of these ice sheets will change, probably in a complex way. All of these parameters

can be measured from space with instruments that are operating now or are planned for launch during the next few years (Thomas 1986).

Changes in Surface Temperatures

Infrared radiometers have been flown aboard a series of polar-orbiting weather satellites since 1972. By scanning a broad swath along the orbit track, they obtain global coverage every day. These data provide estimates of surface temperatures on the oceans, land, and ice. Unfortunately, calibration problems make it difficult to intercompare data from different sensors. Moreover, atmospheric effects limit accuracy of the estimated temperatures to about ± 1°C. However, calibration of future instruments will be improved, and a new instrument, which will reduce the uncertainty attributable to the atmosphere, will fly aboard the European Space Agencies Remote Sensing Satellite (ERS-1) in the early 1990s. Infrared measurements are limited by cloud cover, and to overcome this a Low Frequency Microwave Radiometer (LFMR) with an all-weather capability for measuring sea-surface temperatures will be flown aboard a U.S. Navy spacecraft, also in the early 1990s.

Rigorous intercomparison of these various techniques for measuring surface temperature will improve the accuracy of the long-term measurements from weather satellites (Njoku 1985). Moreover, the large polar-orbiting satellites planned as part of NASA's Space Station and ESA's Columbus program will provide opportunities for long-term continued operation of the new infrared and microwave radiometers.

Changes in Sea Ice Cover

Estimates of the extent, distribution, and compactness of polar sea ice have been made almost continuously since 1972 using data from microwave radiometers aboard NASA's Nimbus satellites (Zwally et al, 1983a; Cavalieri, Gloersen, and Campbell 1984; Swift, Fedor, and Ramseier 1985;). These data have already revealed major interannual changes in sea ice extent, but no clear long-term trend. Similar data will be acquired by future weather satellites of the U.S. Navy and Air Force, promising a time series of sea ice observations extending over several decades.

Summer Melting in Greenland and Antarctica

Because surface slopes are very small over the vast ice sheets, a small rise in the surface elevation of the 0°C summer isotherm causes a large increase in the area subject to surface melting. Wet snow has a microwave emission that is quite distinct from that of dry snow, and the extent of summer melting can readily be mapped using data from radiometers aboard the Nimbus and U.S. Navy/Air Force spacecraft (Zwally and Gloersen 1977).

Topography and Extent of Ice Sheet

Significant change in the size of the continental ice sheets will be a comparatively slow response to climatic warming. Nevertheless, it is important, periodically (perhaps every 5-10 years) to map accurately their areal extent and surface topography. Here, it is useful to note that a 1-cm rise in sea level is equivalent to a 25-cm change in thickness over the entire Antarctic ice sheet. Moreover, actual ice-sheet changes are more likely to

occur within individual drainage basins than uniformly over the entire ice sheet. This would further increase sensitivity so that, for a sea-level change of less than 1 cm, ice thickness within the affected drainage basin would probably change by several meters, which would be readily detectable by a satellite radar altimeter (Zwally et al. 1983b).

The areal extent of the ice sheets can be accurately mapped using images obtained at visible wavelengths (from the U.S. Landsat/Eosat and the French SPOT missions), and at microwave frequencies by synthetic aperture radar (SAR). Although Landsat-type data have been obtained since 1972 there is but poor and intermittent coverage of Greenland and Antarctica. A SAR was carried aboard NASA's Seasat in 1978, but very few images were obtained over Greenland, and none from Antarctica. However, there will be several opportunities during the next decade to map the ice sheets using high-resolution radar imagery.

Changes in the Speed and Direction of Ocean Winds

Estimates of ocean surface winds can be derived from measurements of either microwave emissions or radar backscatter. The necessary passive-microwave data (providing estimates of wind speed but not direction) have been acquired since 1978 by Nimbus-7 and will be extended into the 1990s by U.S. Navy/Air Force weather satellites. A radar scatterometer aboard NASA's Seasat provided estimates of sea-surface winds over almost the entire globe every two days. Scatterometers will be included aboard three satellites planned for flight during the early 1990s.

Changes in Ocean Surface Topography

Many radar altimeters are planned for flight during the next decade and similar instruments will almost certainly be included aboard Space Station and/or Columbus polar platforms. They are designed primarily to measure very accurately the surface topography of the ocean, with the effects of waves smoothed. Range measurements from satellite to sea surface are accurate to between 2 and 10 cm. However, radar altimeter data are unlikely to reveal sea-level trends because satellite orbit errors limit the accuracy of absolute sea surface elevation to a few tenths of a meter. Nevertheless, significant changes over time in ocean currents will be detectable, since they manifest themselves as changes in the regional tilt of the ocean surface.

SUMMARY

The conclusion that sea level will probably rise by about 1 m by 2100 if climate becomes significantly warmer due to increasing atmospheric concentrations of manmade gases is not new (see for instance, Revelle 1983; Hoffman, Keyes, and Titus 1983). Earlier reports, however, focused on sea level rise due to thermal expansion with almost ad hoc estimates of the effects of melting ice. Here, I have tried to address explicity all potential contributions to a eustatic rise in sea level, incorporating results of analyses presented in a report published by the National Research Council (1985). Three conclusions can be drawn from this summary:

- Sea level will probably rise by 0.6-2.3 m by 2100, with a "most probable" rise of about 1 m.

- The increase in sea level will be very slow for the first few decades, but thereafter rates will increase progressively. This increase will probably not be unambiguously detectable until the year 2020 or later.

- There will probably be little net contribution to sea level rise during the next century from the ice in Antarctica unless conditions in the southern ocean change dramatically. If climate warming is sustained, however, ice discharge from Antarctica will ultimately become the dominant cause of sea level rise, with the possibility of a several-metre increase during the following centuries.

Because sea level rise will initially be very slow, it is important to develop an early warning system for detection of proxy indicators that will herald the predicted climatic warming. This could be achieved principally by monitoring from space these parameters:

- Surface temperatures (on the oceans, ice, and land).

- Extent and compactness of the sea-ice cover in both polar regions.

- Areal extent of summer melt zones on the Greenland and Antarctica ice sheets.

- Areal extent and surface topography of these ice sheets.

The instruments needed to measure all these parameters are either aboard existing satellites or are planned for launch during the next few years. It will be important to coordinate the observation and analysis programs for these various instruments in order to ensure compilation of a long time series of compatible measurements.

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Flooding in Taipei, Taiwan and Coastal Drainage

Chin Kuo
Virginia Polytechnic Institute and State University
Blacksburg, Virginia USA

ABSTRACT

Coastal drainage problems associated with the existing inadequate drainage system and land subsidence in the city of Taipei are discussed. Impacts on the system due to potential sea level rise are illustrated. General implications for all coastal communities of designing today a drainage system that will protect against rise in sea level or retrofitting the system in the future are examined.

INTRODUCTION

The uniqueness of flooding in the coastal areas can be characterized by two key parameters: flat terrains and tidal effects (Kuo 1984). The hydraulic head available for gravity drainage, either by storm sewer pipes or by channels, is generally small. A side effect of the poor and slow drainage is a decrease in the transport rate of sediment and debris, which further reduces the pipe and channel flow capacities. During extraordinary storms, such as a hurricane or typhoon, the tide elevation associated with the storm surge is high. As a result, flood protection measures, such as flood walls, levees, pumping stations, and flap gates are necessary. If sea level rises and/or land subsides, the head against which pumps work will further increase, creating an undesirable planning and design situation for coastal drainage (Kuo 1986). This paper discusses these coastal stormwater management problems using the city of Taipei as an example to illustrate how the existing inadequate drainage problems are intensified subject to ongoing land subsidence and future sea level rise.

BASIN CHARACTERISTICS AND BASIC HYDROLOGY DATA

The city of Taipei is situated in the Taipei Basin about 17 km from the ocean and is surrounded by the Hsintien River on the south, the Tamsui River on the west, the Keelung River on the north, and hills on the east and

southeast. The elevation in the basin ranges from 1.3 m to 7 m in the city with an average slope of 0.1% running from southeast to northwest. Three rivers (the Tamsui River is the largest) are all tidal rivers subject to moderate tidal influence. The Tamsui River has a watershed of 2726 m^2, annual mean flow of 6835 x 10^6 m^3 and a 200-year flood discharge of 25,000 cubic meters per second. Mean annual rainfall in the basin is 295 cm. Based on the recorded rainfall data, 75% of storms have their peak discharge within the first 20 minutes of the storm, due to short river reach, steep river bed, and high rainfall intensity.

The normal high tide of the Tamsui River at the Taipei Bridge is 1.32 m above sea level, which is higher than part of the city. The river stage for 5- and 200-year storms are 4.58 m and 8.43 m, respectively (Public Works Department, City of Taipei 1982).

INADEQUACIES OF THE PRESENT DRAINAGE SYSTEM

There are six major drainage subsystems in the city (Figure 1), which drain about 6,700 ha. The total length of the storm sewer trunk line is 424 m, and the total length of levee along the three rivers is 53,408 m. There are 30 pumping stations. The total volume of storm runoff pumped is 374.1 cubic meters per second (Public Works Department, City of Taipei 1982). The drainage system is by gravity for normal tidal stage in the rivers and under pumping for high river stages during the typhoon events. More pumping stations and drainage mains are under construction.

The current design criteria for the storm sewer system is based on a typical 5-year summer thunderstorm event. Pumping stations are designed for a 5-year typhoon for normal operation, and their capacity is for a 200-year storm.

Traditionally, the metropolitan area has frequently experienced major floodings along the rivers due to inadequate channel capacity and heavy rainfalls. In addition, there are a lot of problems associated with the planning, design, construction, and maintenance of the city storm drainage systems. Major problems include:

- Surface runoff within the city and flood flow in the surrounding rivers have increased due to rapid urbanization in the past 25 years. The drainage system at the downstream end of the basin does not have enough capacity to handle the runoff generated from headwater areas where most of the urbanization takes place.

- The existing drainage system, initially designed more than 50 years ago for a 2-year storm, has proven to be inadequate to accommodate the urban growth.

- There exists a serious problem of pipe clogging due to deposition of debris, sediment, residuals of construction, and other factors. At the foot of the hill, massive sediment deposition often blocks the entrances of the storm sewer pipes.

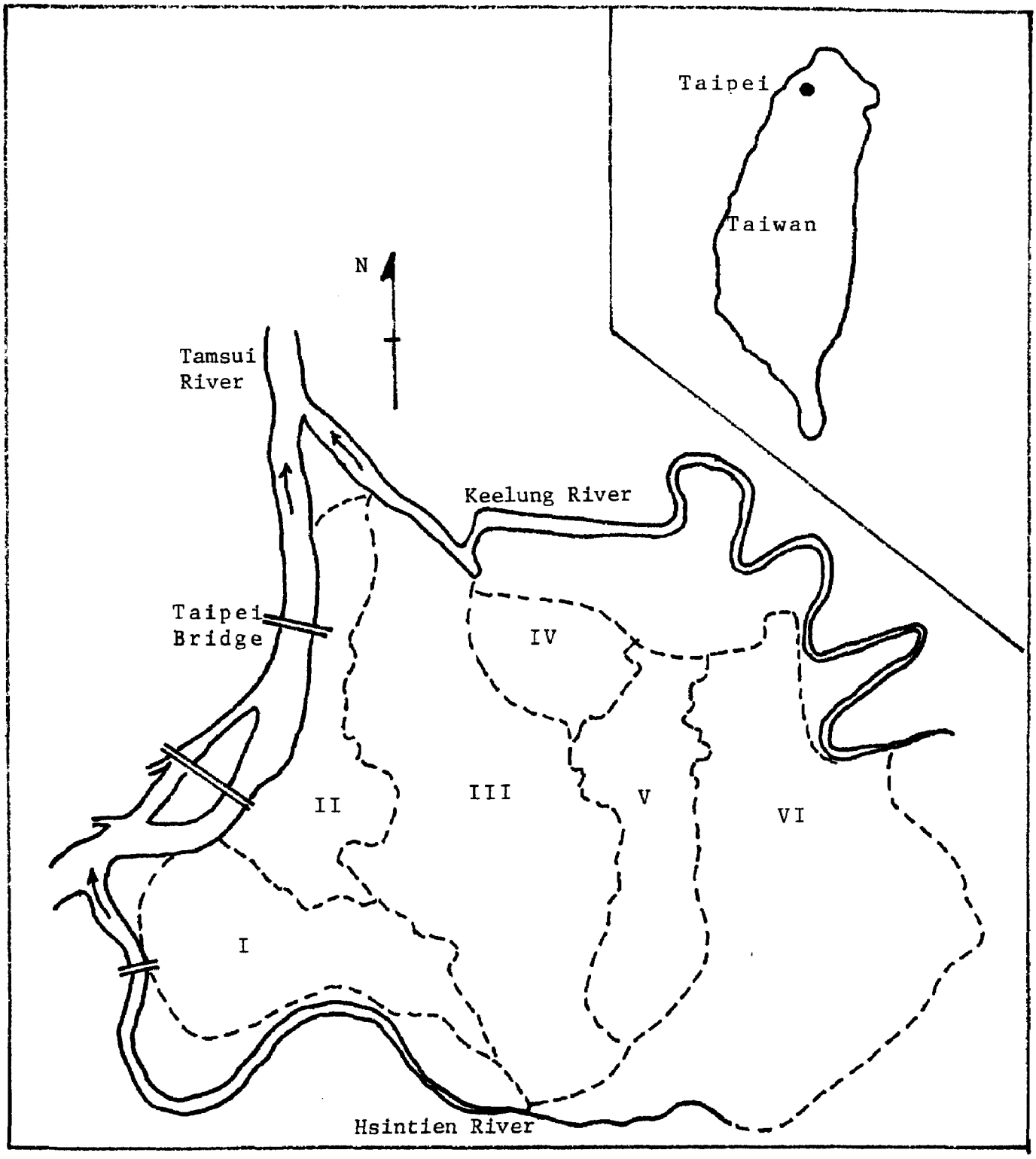

Figure 1. Sub-drainage Basins in the City of Taipei
Source: Public Works Department, City of Taipei 1982

- During the typhoon period, the river stages are high. Some areas do not have levees. Leakage of flap gates occurs frequently.

- The number of pumping stations is not sufficient and capacities of pumps are not adequate.

- Subsidence of the entire basin due to excessive groundwater pumping creates many local impoundments, lowers the river levees, reduces the hydraulic head available for gravity drainage, and increases the head against which water must be pumped. Land subsidence has aggravated the existing inadequate drainage system. Figure 2 shows that subsidence of 2 m has been observed in the field during the period of 1955-1977 (Public Works Department, City of Taipei 1980). The subsidence problem has been under control of the groundwater pumping law. However, it takes at least 20 years for the subsidence to stabilize. A computer simulation of drainage systems in Taipei has been carried out to assess the current flooding and to predict future flooding due to land subsidence (Yen et al. 1979). Using 1979 as the reference time, the authors predict that in subdrainage area III the flood area less than 3 m above sea level (which was 0.005 ha in 1979) will be 65 ha in 1989 and 346 ha in 1999. The flooding will be mainly due to land subsidence, the incapability of gravity drainage by storm sewer pipe networks, and forced drainage by pump and levee systems.

Current plans to upgrade the existing system recommend that the city increase the number of pumping stations, expand the drainage pipe networks, and improve the levee system at a cost of $41 million (U.S.) for the next eight years. The improvements would compensate for urbanization and land subsidence problems expected through the year 2000.

THE IMPACT OF SEA LEVEL RISE ON THE DRAINAGE SYSTEM IN TAIPEI

With the anticipated global sea level rise and possible increase in the amount of rainfall due to the greenhouse effect, the current design criteria will be inadequate and the city will be subjected to more intense flooding. Neither the existing system nor the upgraded design take sea level rise into consideration. The drainage problem that would result from land subsidence only (with no sea level rise) approximates the impact of sea level rise with no land subsidence. The problems will be compounded if both sea level rise and land subsidence take place simultaneously. Certainly, long-range planning is needed to incorporate into the master drainage plan a rise in sea level in the next 50 years.

There are two major types of coastal flooding due to sea level rise: storm surge, which takes place in the vicinity of the coast, and the backwater effect which occurs when floodwater from upstream backs up along the river because of a rise in water level at the basin outlet. The latter effect is observed less and less as one moves farther away from the coast. To illustrate the backwater effect due to a rise in sea level during an extraordinary typhoon event at the Taipei Bridge (17 km from the coast), results of the computer modeling of the Tamsui River (Yen and Lin 1982) are presented.

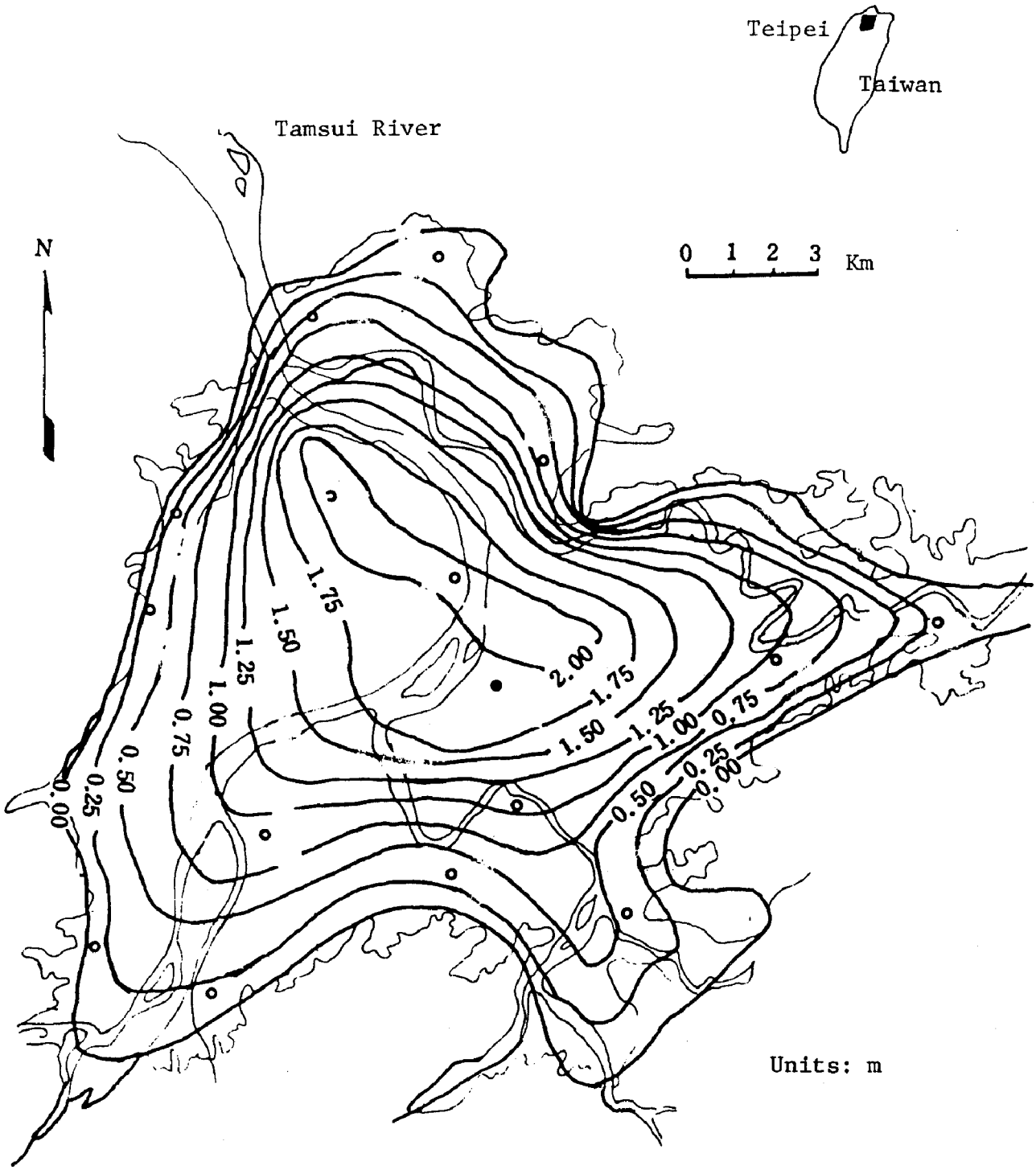

Figure 2. Land Subsidence in Taipei Basin, 1955-77
Source: Yen et al. 1979

Typhoon Gloria hit the area September 10-12, 1963. During the flood, most parts of the Taipei City and adjacent areas were inundated with 1-3 m of water, and thirty-one lives were lost. This typhoon produced the record rainfall and flooding, which is equivalent to a 200-year storm event. The observed high tide at the river mouth was about 3 m. Based on this tide elevation and the 200-year river discharge (250,000 cubic meters per second), time variation of river levels at the Taipei Bridge is shown in Figure 3, as well as river levels based on sea level rises of 1 m and 2 m. Sea level rise at the river mouth of the Tamsui River does produce a backwater effect, which would worsen the stormwater drainage problem in the city of Taipei.

As shown in Figure 3, a 30-cm rise at the river mouth would not simply translate to a 30-cm rise in river stage at the Taipei Bridge. There are a few hydraulic problems associated with the backwater effect: Floodwater in the river may overtop the levee, and the levee height would have to be raised; an increase in river stage would necessitate an increase in head for pumping; more and/or larger pumps would have to be installed; and pumping capacity would be reduced. The backwater effect lasts for many hours. The time period in which gravity drainage is sufficient is shortened and pumpings must be used more. Although the flooding caused by the sea level rise itself, as illustrated in this example, may not be great, its ultimate impact (that is, effects such as those caused by the typhoon Gloria) would certainly increase the degree of flood damage.

Cities located closer to the coast will experience a more severe impact than the city of Taipei in terms of greater backwater effect and possible storm surge threat. As described before, the city of Taipei would experience severe flood-related damage when sea level rise effects are combined with the problems of inadequate existing drainage system and land subsidence. Houston, Texas, has a similar land subsidence problem. This coastal city also is vulnerable to sea level rise (although to a lesser extent) and, as a consequence, will experience similar flood-control and stormwater management problems (Amandes 1980).

DESIGN RECOMMENDATIONS OF TWO CASE STUDIES

Precise predictions of future sea level rise are currently not available. Scientific communities need to improve the prediction capability. In addition, international bodies, such as the United Nations Environment Programme, need to investigate the costs and benefits of controlling emissions of greenhouse gases. While they do so, local officials and engineers in coastal cities need to evaluate the implications of sea level rise, so that they do not inadvertently design a system that is prematurely obsolete. Case studies conducted in the cities of Charleston, South Carolina, and Fort Walton Beach, Florida, have examined the question of whether to design a system now based on a reasonable estimation of projected sea level rise or to retrofit the system later after sea level rise has occurred.

The residentially and commercially developed Grove Street watershed in Charleston has a drainage area of 68.4 ha. Average surface slope is less than 0.5%. Ground elevation ranges from 1.52 to 3.96 m above mean sea level (MSL). The existing drainage facilities, storm sewer pipes and culverts, are undersized for the design criteria of a 5-year storm. To upgrade the system, the master drainage plan was altered to accommodate a 10-year storm event

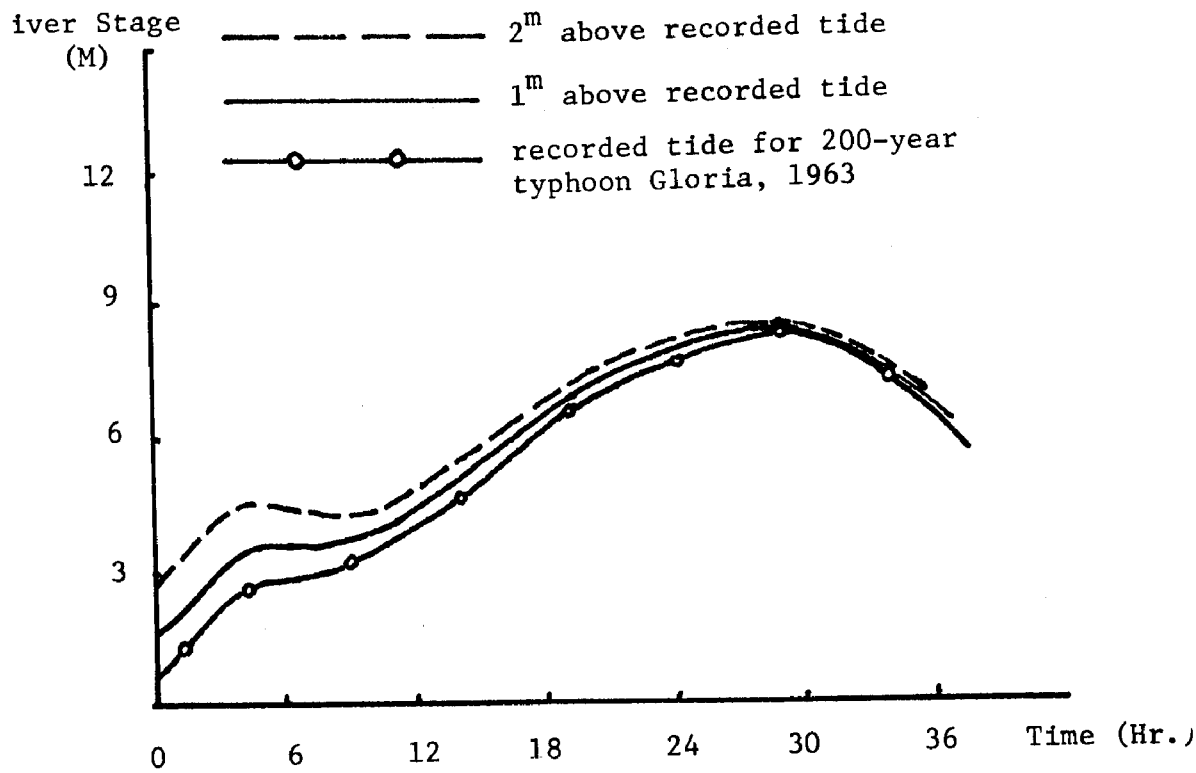

Figure 3. River Stages at the Taipei Bridge for Various Tide Elevations
Source: Yen and Lin 1982

(19.89 cm rainfall in 24 hours) and a spring-tide elevation of 1.33 m above MSL. Design scenarios, shown in Table 1, are based on a hypothetical 10% increase in precipitation, and projection of sea level rise by Hoffman, Keyes, and Titus (1983). Various alternatives were explored for each scenario to determine the most economical system to provide protection for the design storm. The retrofit alternatives that were considered were pumping stations, retention/detention basins, and pipe networks. The study concluded that best strategy was to design now for a 0.32 m rise in sea level (LaRoche and Webb, Titus et al., in press).

The Gap Creek watershed in Fort Walton Beach has a mixed commercial, industrial, and residential development; an average surface slope of 0.2%; and a ground elevation ranging from 0.61 m to 11.28 m above MSL. The groundwater table is high because of a large swamp situation to the north of the watershed. Scattered storm sewer pipes are connected to the creek, which is the major drainage way for the watershed. The current design criteria are a 25-year storm with 24-hour rainfall of 28.58 cm and a tide elevation of 0.15 m. Design scenarios are shown in Table 2. Upgrade alternatives included increasing the capacity of present retention/detention basins, adding other large detention facilities, dredging channels, and floodproofing homes. It was concluded that retrofit to the Fort Walton Beach drainage system should not be implemented until a rise in sea level takes place (Waddell and Blaylock, in press; Titus et al., in press 1985).

It is evident from the two case studies that whether or not to design a coastal drainage system against future sea level rise primarily depends upon the individual watershed of interest. As a result, planners and engineers responsible for coastal drainage need to examine the sea level rise issue during the preliminary design and planning phase in terms of its expected effect on each watershed in order to avoid excessive cost for future retrofit of the system.

CONCLUSION

Potential sea level rise is an issue that scientists, engineers, planners and decision makers worldwide need to address in a joint effort. To avoid excessive damage from coastal flooding, plans upgrading the existing system and altering the master drainage plan to account for future sea level rise must be considered. A major challenge for scientists is improving the accuracy of predictions of sea level rise. Information concerning design strategies that protect drainage systems against future sea level rise and the costs of such strategies will assist researchers and decision makers throughout the world who are trying to determine the benefits of decreasing emissions of greenhouse gases in order to reduce global warming and thus the rise in sea level.

Table 1. Design Scenarios for the Grove Street Watershed

Scenario	Year	Sea Level Rise (m)	1984 Tide Elevation (m)	Design Elevation (m)	Design Storm Depth (cm)
A. Current Sea Level and Climate Conditions	1980	0	1.33	1.33	19.89
	2025	0	1.33	1.33	19.89
	2075	0	1.33	1.33	19.89
B. Low Sea level Rise and Current Climate Conditions	1980	0	1.33	1.33	19.89
	2025	0.32	1.33	1.65	19.89
	2075	1.04	1.33	2.37	19.89
C. Low Sea Level Rise and Ten Percent Increase in Design Storm Precipitation	1980	0	1.33	1.33	21.89
	2025	0.32	1.33	1.65	21.89
	2075	1.04	1.33	2.37	21.89
D. High Sea Level Rise and Current Climate Conditions	1980	0	1.33	1.33	19.89
	2025	0.45	1.33	1.78	19.89
	2075	1.49	1.33	2.82	19.89

Table 2. Design Scenarios for the Gap Creek Watershed

Scenario	Year	Sea Level Rise (m)	Base Tide Elevation (m)	Design Elevation (m)	Design Storm Precipitation(cm)
A. Current Sea Level and Climate Conditions	1984	0	0.15	0.15	28.58
	2025	0	0.15	0.15	28.58
	2075	0	0.15	0.15	28.58
B. Low Sea level Rise and Current Climate Conditions	1984	0	0.15	0.15	28.58
	2025	0.32	0.15	0.47	28.58
	2075	1.04	0.15	1.19	28.58
C. Low Sea Level Rise and Ten Percent Increase in Design Storm Precipitation	1984	0	0.15	0.15	31.44
	2025	0.32	0.15	0.47	31.44
	2075	1.04	0.15	1.19	31.44
D. High Sea Level Rise and Current Climate Conditions	1984	0	0.15	0.15	28.58
	2025	0.45	0.15	0.60	28.58
	2075	1.49	0.15	1.64	28.58

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The Sea Also Rises: The Ongoing Dialogue of the Dutch with the Sea

Tom Goemans
SIBAS Joint Institute for Policy Analysis
Delft, Netherlands

INTRODUCTION

The Netherlands belongs to the alluvial coastal region of the North Sea, which means that the western and northwestern part of the country was formed by alluvial deposits. The rivers Rhine, Meuse, and Schedule flow through the country and out into the North Sea (Figure 1). Together they built and shaped the land with regular flooding.

The first efforts to protect this country can be traced back to the 3rd century B.C., when people built mounds to live on. During the Roman period these mounds were linked by elevated roads; dikes were also constructed along some rivers. By the 13th century, there was a more organized way of dike building, not only in a defensive way but also in a more offensive way to reclaim land from the sea (Figure 2). Any excess water could flow out of the polders during low tide period through sluices, which were closed during high tide. Both land subsidence and rising sea level made artificial drainage necessary, at first by means of windmills, later by steam-driven pumps, and today by electric pumps. The height of the dikes was based on the highest previous flood level. It is hardly surprising that most of the previously reclaimed land was frequently lost again; but every time the people fought back. It is said that the Dutch have had a constant dialogue with the sea. (See Bruun, this volume, for additional discussion of the history of shore protection.)

The history of The Netherlands is marked with storm surge disasters. The first known disaster occurred in the year 1287 and hit the whole country, drowning fifty-thousand people. In recent history, major floods occurred in the years 1877, 1881, 1883, 1889, 1894, 1906, 1916, and finally the most recent one in 1953. During the night of February 1, 1953, storm surges of unprecedented height hit the southwestern coastal region (called the Delta region because of the major rivers). Dikes were seriously damaged over a total

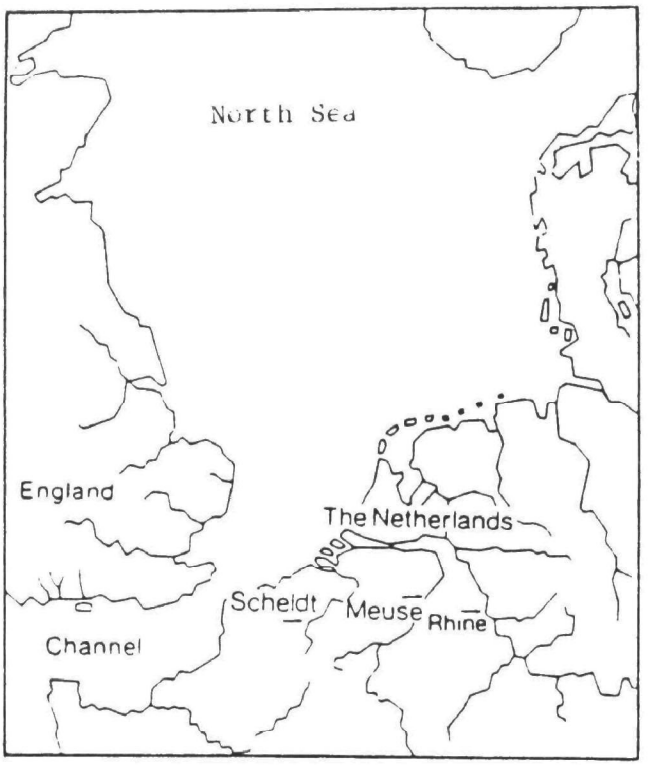

Figure 1. The Netherlands in NW-Europe

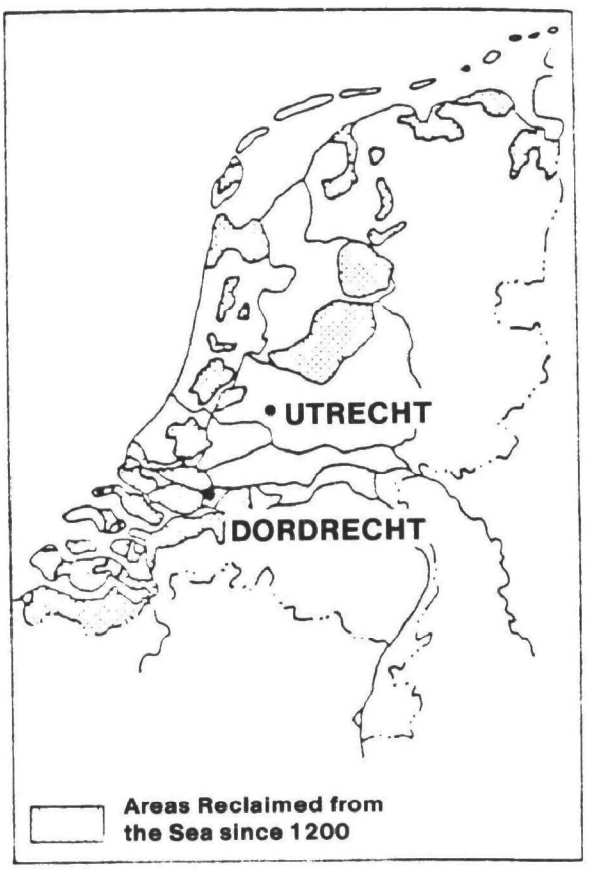

Figure 2.

length of 190 km. Through 89 breaches in the dikes, 150,000 hectares of polderland were inundated (Figure 3) causing the death of 1835 people. Total losses were estimated at some 2 billion guilders (one billion U.S. dollars) measured in 1953 currency.

Once areas below sea level are flooded they remain inundated after the flood has retreated. As the tide flows in and out through breaches in the dikes, it widens them further. Fertile farmlands are then covered with marine sands, and salt penetrates the soil. The only way to return to normal is to repair the dikes and pump the inundated areas dry, after which it still takes several years for the land to recover.

PROTECTION STRATEGY

In reaction to the 1953 disaster, the Dutch government embarked on a massive building program, the Delta plan. A special committee was given the task of establishing a design philosophy for the sea defenses along the coast. In the work of this committee two central issues were addressed: (1) shortening the coastline by closing off the estuaries in the Delta region and (2) choosing the design water level for the country's system of the sea defenses. In this paper only the second issue is addressed.

With respect to the design water level the committee used a philosophy introduced in 1939 by the Dutch hydraulic engineer Wemelsfelder. He analyzed the probability of exceedance of storm surge levels along the coast of the Netherlands and presented probability exceedance lines, using a linear scale for the water level and a logarithmic scale for frequencies of occurrence. Due to the tidal system of the North Sea, the tidal amplitude varies from 1 to 4 meters along the coast, and for each location a separate exceedance line can be constructed (Figure 4). By setting an acceptable probability of exceedance it is possible to establish a design water level.

The 1953 storm surge had an annual probability of 1:250, corresponding to a surge level of about +4 m in the disaster area. The committee concluded that the entire coast of the country was inadequately protected and recommended strengthening of the main sea defense structures. Considering the high economic value of the central part of the country (major industrial and agricultural areas, large population in metropolitan areas), the probability of exceedance was set at 1:10,000. The corresponding water level was derived from an extrapolation of the exceedance lines; this resulted in a design water level of +5m. For coastal areas north and south of central Holland, the committee used lower design water levels (corresponding to a probability of 1:4,000) because the area protected has a system of secondary dikes which limits any flood disaster there to smaller sections.

A dike that has to resist a water level of +5 m must be much higher than 5m, mainly because waves can run up and overtop the dike. Other phenomena taken into account are seiches and gust bumps, settlement of the dike material, and sea level rise for the next century. Adding all these contributions together results in design criteria for all sea defenses; since

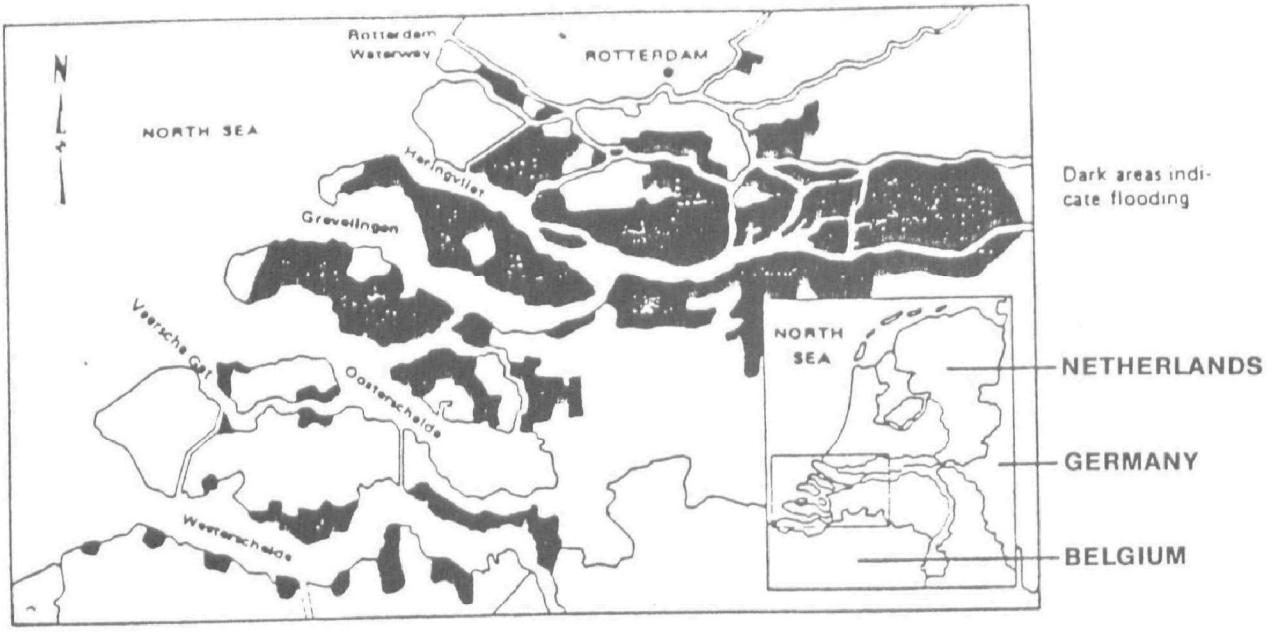

Figure 3. Flooded Area During the 1953 Disaster

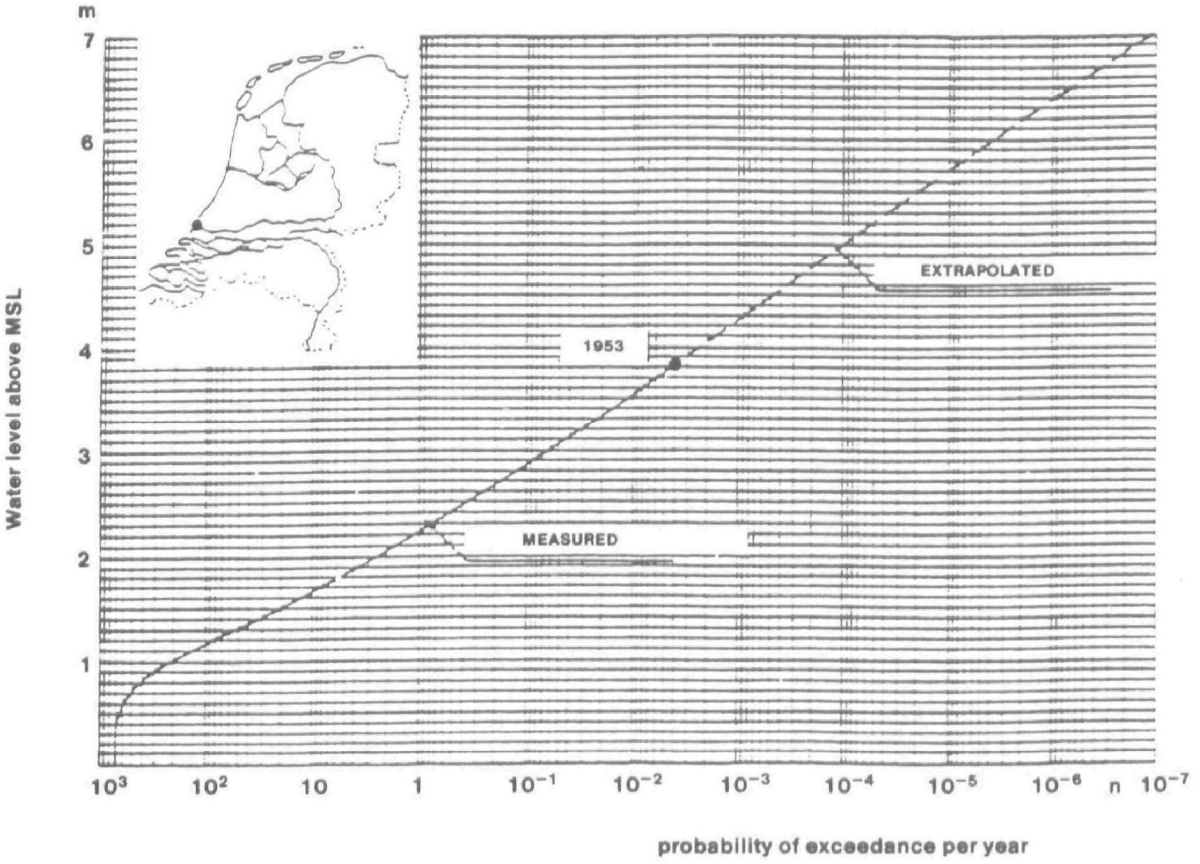

Figure 4. Storm Surge Water Levels for Hoek van Holland

the publication of the committee's final report in 1962 this is called the Delta level. For a typical dike the following figures are representative:

Storm surge level	5.00 m above MSL
Wave runup	9.90
Seiches and gust bumps	0.35
Sea level rise	0.25
Settlement	0.25
Total Height	15.75 m

The core of the typical dike is made of sand, covered with a clay layer 1 m thick. The sea side of the dike is normally also covered with asphalt and large stone blocks. The outer slope is 1:5, the inner slope, 1:3 (Figure 5). The Netherlands has about 400 km of sea dikes in addition to the 200 km of dunes, all of which require constant and careful maintenance [totals maintenance cost is presently about 70 million guilders (U.S. $35 million)]. If the country was not protected against the sea, more than half of it would be uninhabitable (Figure 6). About 8 million people live in the protected area.

IMPACT OF SEA LEVEL RISE

The Dutch coast is part of a longer coastline stretching from Belgium to Germany and Denmark. Some of the problems experienced in The Netherlands also apply to small parts of these other countries. This paper, however, only covers the Dutch situation.

Tides

The tidal system for the North Sea is rather complex with several amphidromic points. Simulation runs with a two-dimensional water movement model for the North Sea and the continental shelf show that these amphidromic points might move as a result of mean sea level rise. For most of the Dutch coast this would mean an increase of the tidal amplitude and of the relative high-water level. This phenomenon may be supported by past measurements along the Dutch coast. Whereas for the period 1933-1984 the mean sea level increased approximately 0.18 m per century, the tidal amplitude increased 0.25 m and the high-water level 0.30 m per century. Similar data were found for the coast of northwestern Germany.

Changes in Storm Surge Level

Water surges into the North Sea during storms. Calculations have shown that even for a mean sea level rise of 5 m the water setup does not increase significantly for a given wind field. From this one might conclude--in first approximation--that the exceedance line as shown in Figure 4 moves to the left when mean sea level rises. The protection level of the present sea dikes decreases when the sea level rises; Figure 7 shows this relation for central Holland. It is, however, by no means certain that storm tracks and wind fields will stay the same when the climate changes. The shape of the exceedance lines might, therefore, change as they move to the left. Wave characteristics may also change.

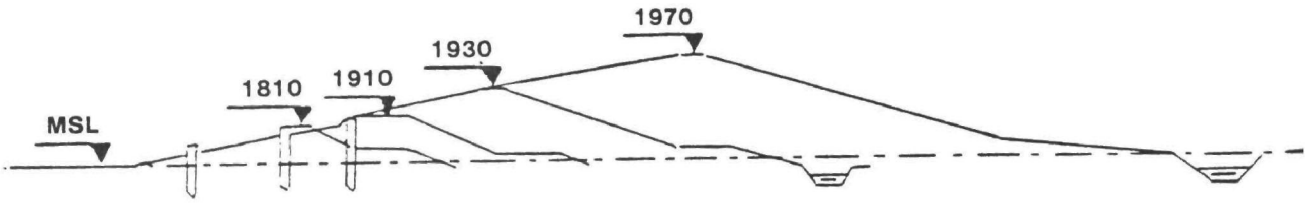

Figure 5. Cross Section of a Typical Dike in Various Years

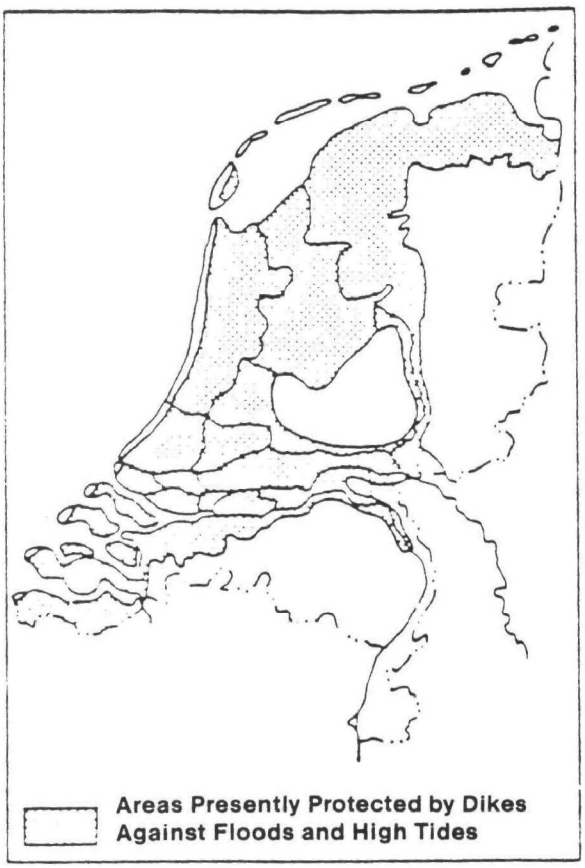

Figure 6.

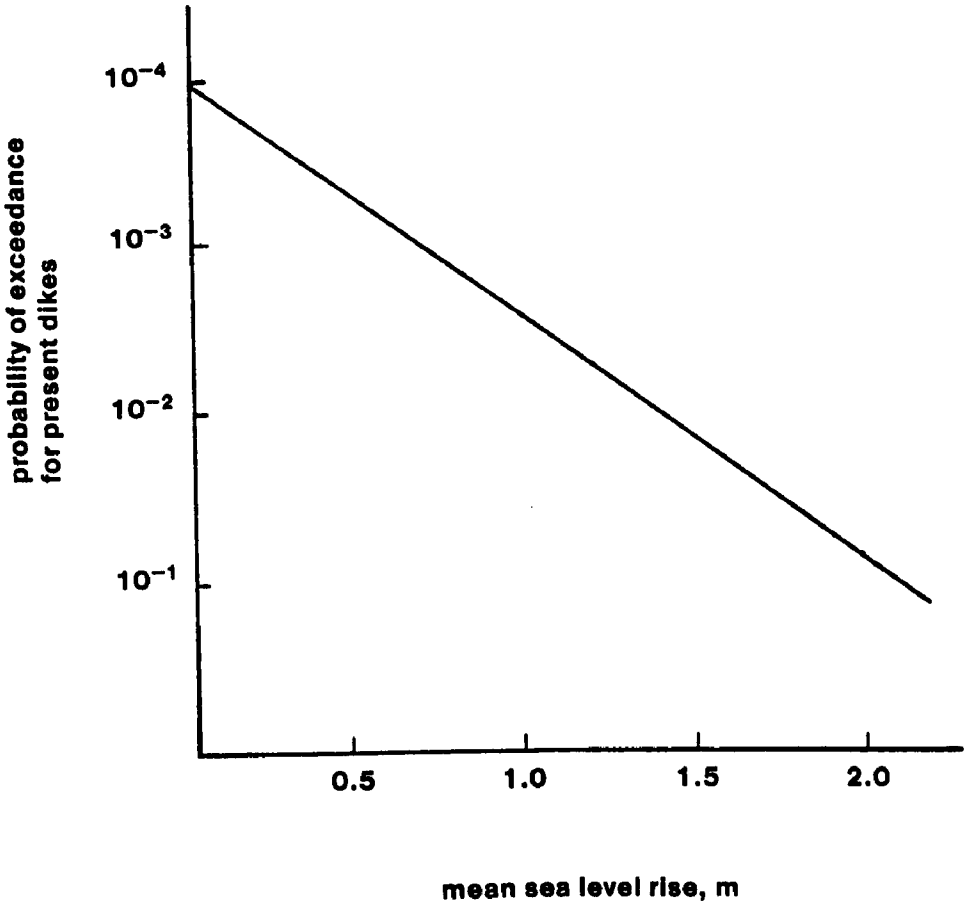

Figure 7.

Changes in Saltwater Intrusion

The tide penetrates into the country through rivers flowing into the North Sea, which means that during high water, salinity will increase for a certain point along the river. As a result of mean sea level rise, saltwater intrusion will be felt further upstream, but only when the river bed does not change. Due to sedimentation the flow cross section will tend to come back to the original one. We believe that the increased saltwater intrusion will not be a major problem for a sea level rise of up to 2 m. Occasionally, however, the availability of fresh water for agricultural purposes may be reduced.

Changes in Saltwater Seepage

The difference between the seawater level and the groundwater and surface-water level in the country determines the amount of seepage. At this moment the western and northern part of the Netherlands suffers from saltwater seepage. In order to keep surface-water salinity in the polders acceptably low, a certain amount of fresh water is needed to flush the canal system. As a first approximation, a sea level rise of 1 m would require 10% more water for flushing; a sea level rise of 2 m would require 20%. In times of drought

it is not certain that this amount of water will be available; economic losses in the agricultural sector could be the result. In any case saltwater seepage will be felt further east in the country, which makes water management--already a complex problem in the Netherlands--more difficult.

The freshwater bubble under the dune area will not be directly threatened by an increasing seawater level, unless the dunes are narrow. The dunes provide a substantial part of the drinking water needed in the country.

Morphological Changes

Part of the Dutch coast consists of dunes, varying in height between 10 m and 40 m above mean sea level. At some locations the coast line is advancing (about 40 m in the past 100 years), but at most locations it is retreating (up to 100 m). Any sea level rise will result in erosion of the dune area; the retreat may be on the order of 100-200 m for a mean sea level rise of 1-2 m. At some places the dune area is narrow and low, which means that dangerous situations could develop. At other places the dunes are more that 2,000 m wide, providing more than ample protection.

In the north of the country the Wadden Islands are continuously moving: retreating at the North Sea side and advancing at the Wadden Sea (landward) side. Hence they are slowly migrating to the mainland. Any sea level rise will accelerate this trend. In the Wadden Sea sedimentation will diminish and intertidal areas will decrease; this may have serious consequences for the population of wetland birds. The estuaries in the southwestern parts of the country will experience a large tidal volume with rising sea level, resulting in erosion of the gullies. Here as well, there will be a reduction of intertidal areas, which will adversely affect the bird population. If sea level stabilizes at a higher level for a few centuries, the wetlands may eventually return. However Thomas (this volume) and others indicate that sea level is likely to continue rising.

Changes in River Water Level

The water level for the rivers flowing into the North Sea will increase with the sea level, and because the Netherlands is so flat this will be felt far upstream. The following are some of the impacts we can expect:

- River dikes, protecting against inundation at high discharge rates, will be too low for the required protection level (presently set at 1/1,250) especially in the western part of the country.

- Clearance for fixed bridges will decrease and hamper ship traffic on the rivers.

- Drainage of the low-lying polders will be more difficult, requiring more energy and modification of pumping systems.

- A decision will have to be made about the water level for Lake Yssel (a 1,200 sq. km freshwater lake created in 1983 by building a barrier dam to shut the lake off from the North Sea).

- Harbor facilities along the rivers and especially at the coast--the port of Rotterdam is the largest in the world--will need adjustments to the higher water level.

- Shipping locks and discharge sluices will have to be rebuilt, especially for a water-level rise of more than 1 m.

REACTION TO SEA LEVEL RISE

From the preceding paragraphs it will be clear that the protection against the sea is an anchorpoint in Dutch politics. Throughout the centuries, a relatively large amount of money has been spent on defense structures and on water management. On the basis of the value of the area protected, a safety level has been chosen; construction is still going on, but around 1990 the required safety level for the whole country will be reached. An expected sea level rise of 0.25 m for the next 100 years is taken into account.

Any sea level rise in excess of that value will result in a reduced actual safety level. There is no reason to assume that the government will not stick to the present protection policy; hence the dikes will have to be heightened. In first approximation this will cost:

Mean Sea Level Rise	Expenditures
0.5 m	5 billion guilders (U.S. $2.2 billion)
1.0 m	10 billion guilders (U.S. $4.4 billion)
2.0 m	20 billion guilders (U.S. $8.8 billion)

About 60% of these expenditures are needed for the dikes and dunes, 30% for the water management, and 10% for rivers and ports. Dikes will most probably be heightened in steps of 0.5 m, each step requiring a minimum of 20 years of construction time for the country as a whole. In the extreme case of a 2 m rise in 100 years, this means a yearly expenditure of approximately 250 million guilders (U.S. $100 million), which is somewhat less than 0.1 percent of the Dutch GNP. For the less extreme cases, more time is available for one step and the yearly costs will correspondingly be lower.

From the above data it may be concluded that there is no need for anticipation. That is, we can keep up with sea level even it rises more rapidly than the present rate. The scenario of a 2-m rise in 100 years, however, results in a critical situation; almost immediately after detection, actions would be required. It is not at all certain that decision makers act that fast; in this respect the energy crises of 1973 and 1978 and the acid rain issue are good lessons. Even more relevant is the fact that the present flood-protection strategy of the Netherlands came about only after the tragic disaster of 1953 occurred. When nobody can remember a specific disaster, it is extremely difficult to obtain consensus on countermeasures. The conclusion must be that monitoring the sea level change is extremely important in order to detect "the signal" as early as possible. In addition, it would be wise to start thinking about the decision-making process that will follow detection of an accelerated rate of sea level rise.

Considering the position of the Netherlands in northwestern Europe, multilateral cooperation with the border countries Belgium and Germany will be necessary. This brings us to the fact that the impacts of sea level rise will be unequally distributed among countries in the world. No country with a coastline can escape from the phenomenon once it unfolds. Yet it is not a natural but a manmade phenomenon; it presents a perfect example of external costs, that is costs not included in the present price of energy from fossil fuel burning. Hence the question of compensation payments may come up--especially in the poorer countries--not only because of sea level rise but also in the broader context of climate change. Much will depend on how international relations develop in the next century.

Whereas the impacts of sea level rise are mostly negative, there may be one positive point, at least for the Dutch. The Delta Plan included not only heightening of dikes, but also closing off estuaries with the objective to shorten the coastline. This provided a unique opportunity for Dutch contractors, consultants, and research institutes to gain experience in innovative hydraulic engineering. Skills and knowledge are applied all over the world. A rising sea level may provide a new global market for this expertise.

ACKNOWLEDGMENT

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Planning for Sea Level Rise Under Uncertainty: A Case Study of Charleston, South Carolina

Michael Gibbs
ICF Incorporated
Washington, DC USA

ABSTRACT

The Charleston, South Carolina, area could be significantly affected by accelerated sea level rise caused by global warming. Preparing for this rise by building protective structures or adapting to the changing environment by altering investment patterns can eliminate most of the adverse impacts. This case study of the Charleston area demonstrates that in some areas actions should be taken today, despite the current uncertainty surrounding the future rate of sea level rise, while for other areas it is better to wait for the resolution of uncertainty before taking actions.

SEA LEVEL RISE: A NEW FACTOR TO CONSIDER IN COASTAL PLANNING

People throughout the world exploit coastal resources to provide many diverse services. In the United States we are balancing the competing demands on this sensitive environment through coastal zone management programs. A new factor to consider in managing coastal zones is a rapid rise in the global sea level. Although rises and falls in sea level are not new, the impending rapid rate of rise is a significant departure from recent trends. Adapting to it will be an important new challenge for coastal planners.

Over the next 50 to 100 years, global sea level may rise at a much faster rate than historical global and local rates. Waiting to observe the effects (e.g., erosion and inundation) before responding to them may not be a satisfactory management strategy because damages may occur too rapidly to allow for effective responses. However, planning ahead for sea level rise is difficult because of the considerable uncertainty regarding how rapidly the global sea level may rise. Only recently have scientists begun to quantify the potential for sea level rise and precise estimates are not yet available.

Should planners wait until better estimates of sea level rise are available, or should they identify options and act now? This paper addresses these questions using a case study of the potential economic impacts on portions of Charleston, South Carolina.[1] It examines planning options available to the city and quantifies the implications of alternative planning strategies.

Four sea level rise scenarios (shown in Table 1) were drawn from a recent EPA report for this analysis (Hoffman, Keyes, and Titus 1983). The baseline

Table 1. Potential Future Relative Sea Level Rise in Charleston, South Carolina [in Centimeters (Feet)]

Sea Level Rise Scenario	YEAR 1980	2025	2075
Baseline	0	11 (0.4)	24 (0.8)
Low	0	28 (0.9)	88 (2.9)
Medium	0	46 (1.5)	159 (5.2)
High	0	64 (2.1)	232 (7.6)

scenario, 24 cm by 2075, assumes a continuation of the recent historical rates of relative sea level rise in the Charleston area (this scenario is unlikely and is viewed as a lower bound); the low and medium scenarios, 88 cm and 159 cm by 2075, represent the likely range of future sea level rise; the high scenario of 232 cm is used as an upper bound. Although the analysis only covers the period up to 2075, the global sea level is expected to continue to rise beyond that time.

THE CASE STUDY AREA

The Charleston area consists of the land around Charleston Harbor, which is formed by the confluence of the Cooper, Ashley, and Wando Rivers (see Figure 1). Included in this area are the peninsula portion of the city of Charleston, portions of the city of Charleston in West Ashley and James Island, portions of the city of North Charleston, the towns of Mount Pleasant and Sullivans Island, and unincorporated portions of Charleston County. This analysis focuses on two portions of the study area: the peninsula and Sullivans Island.

The peninsula has a maximum elevation of up to 10 meters (33 feet) above mean sea level and includes several low-lying areas that have been reclaimed from the harbor. The only major flood protection structure, the Battery, is

[1] The Charleston case study analysis presented in this paper is an extension of the analysis described in Gibbs (1984).

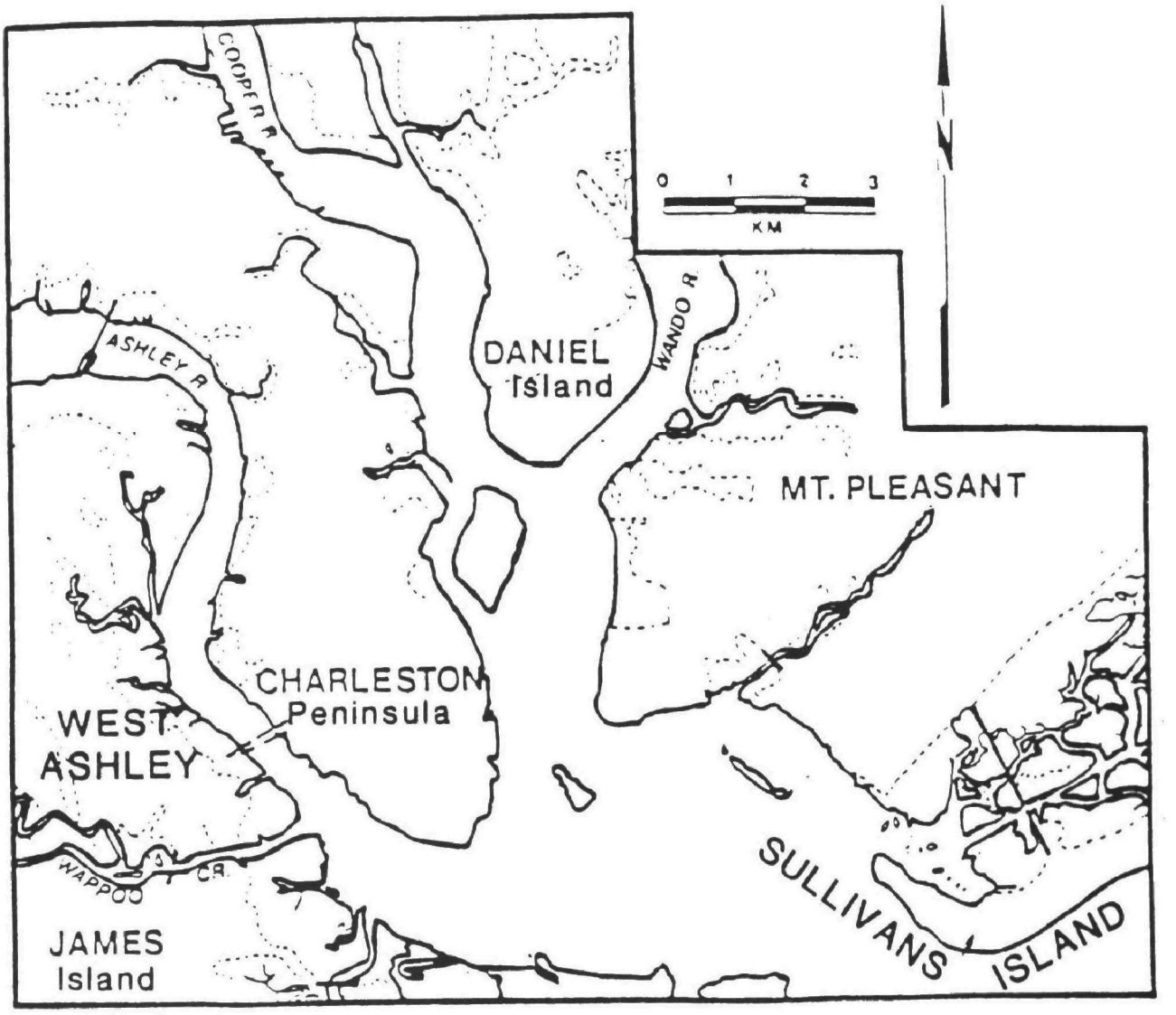

Figure 1. Charleston Study Area

located at the southern end of the peninsula. This seawall has a maximum elevation of six feet above mean sea level.

Property values on the peninsula exceed $875 million (1980 dollars). The southern end of the peninsula has a densely populated historic district and other residential, commercial, and port areas. The central peninsula consists of industrial parks and marshland, and the upper peninsula (North Charleston) has a combination of residential areas and industry, including a large naval reservation. Because most of the peninsula is already highly developed, its potential for growth is limited. Some shifts in land use are expected, primarily to more high-density development.

Sullivans Island is a narrow barrier island with an average elevation of less than 3 meters above sea level. A residential and resort community, it has been developed with single-family homes. Its zoning regulations currently prohibit high-rise and condominium construction. Current property values total approximately $65 million (1980 dollars).

Vulnerability to Sea Level Rise

The peninsula is the portion of the Charleston area least vulnerable to sea level rise. It is currently protected by the Battery at the southern end, and its port facilities provide stabilization. While the peninsula has various low-lying areas threatened by inundation and erosion, its high development density will likely make protection of the areas economically justified.

Sullivans Island, on the other hand, is a low-lying barrier island of highly erodable materials. Exposed to open-ocean wave attack, it is extremely vulnerable to sea level rise. The low- to medium-density development on the island may be insufficient to make protection with a sea wall economical. Additionally, the substantial recreational value of its beaches would be lost if a sea wall were built.

Table 2 shows the potential economic impact of sea level rise on these two areas.[2] For each area, estimates are shown for all four sea level rise scenarios. First, the estimate of the economic value for each scenario is shown. This value indicates the level of economic activity that will go on in the study area between 1980 and 2075. For example, in the peninsula area, the economic value is estimated at $2.21 to $2.27 billion in the low sea level rise scenario.

The second column in Table 2 shows the change in economic value from the baseline scenario. This change in economic value is the estimate of the impact of the sea level rise scenario. The last column displays this impact as a percent of the baseline economic value estimate.

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[2] Economic impacts include the value of shorelines movement due to erosion and inundation, increased storm damage, and changes in investment patterns. The method used to estimate economic impacts is described in Gibbs (1984).

Table 2. Potential Economic Impacts of Sea Level Rise on the Charleston Peninsula and Sullivans Island: 1980 to 2075[a]

Area	Sea Level Rise Scenario	Estimate of Economic Value (millions of 1980 dollars)	Estimate of Economic Impact (millions of 1980 dollars)	Estimate of Economic Impact (percent of baseline economic value)
Charleston Peninsula	Baseline	2,520	-	-
	Low	2,210 - 2,270	250 - 310	10 - 12
	Medium	1,770 - 1,870	650 - 750	26 - 30
	High	1,435 - 1,550	970 -1,085	38 - 43
Sullivans Island	Baseline	150	-	-
	Low	85 - 115	35 - 65	23 - 43
	Medium	40 - 90	60 - 110	60 - 110 40 - 73
	High	27 - 75	75 - 125	50 - 83

[a] Estimates represent impacts of sea level rise in the absence of actions taken to respond to sea level rise. All estimates are present values evaluated at a three percent real rate of discount.

The range of impacts shown in Table 2 (e.g., $250 to $310 million for the low scenario on the peninsula) reflects a range of assumptions regarding how investment patterns change in response to sea level rise. The upper bound of the economic impact estimate assumes that people incorporate the potential for sea level rise very slowly into their decision making. The lower bound assumes that people immediately alter their investment patterns in anticipation of future sea level rise. The actual investment behavior will likely fall within this range.

The estimates in Table 2 do not incorporate community protection systems such as levees, sea walls, zoning ordinances, or beach stabilization. The magnitude of the impacts indicate that such community responses may be warranted. The impacts are expected to be large, both in absolute terms (hundreds of millions of dollars) and in relative terms (a large fraction of the economic activity in the study area will be affected). The question is: what actions should be taken now, given current uncertainties about the future rate of sea level rise? To answer this question, the benefits of a variety of actions in each of the two areas are evaluated below.

EVALUATION OF ALTERNATIVE PROTECTION STRATEGIES

To evaluate whether it is preferred to act now (and invest funds to protect areas from potential future sea level rise) or to wait (and act later when the rate of sea level rise can be projected with greater precision), a series of protection strategies for the peninsula and for Sullivans Island were examined. Each of the strategies was evaluated across the range of potential rates of sea level rise.

On the one hand, acting now runs the risks of

- Under-Protecting -- sea level rise turns out to be more extensive than expected, and too little protection was provided
- Over-Protection -- sea level rise turns out to be less extensive than expected, and too much protection was provided, at too great an expense.

Waiting for more precise estimates of sea level rise runs the risks of

- Being unable to respond rapidly enough if the sea level rises rapidly in the future
- Making investments in structures today that are subsequently lost to the sea.

The tradeoffs among these risks, and the ability to make decisions today (in the face of uncertainty), depend on the sensitivity of the decisions to the rate of sea level rise. If the same decision (i.e., protection strategy) is preferred regardless of the future rate of sea level rise, then the decision can be made today. Alternatively, if the preferred decision is very sensitive to the expected rate, then improved estimates of sea level rise may be required before making a decision.

Protection Strategies for Charleston Peninsula

While a variety of protective measures can reduce the impacts of sea level rise on the peninsula, this analysis focuses on the most likely response, resource construction of a sea wall or levee around the peninsula. The sea wall would stop shoreline retreat as well as protect against storm surge. It would cost about $150 million (1980 dollars), based on a unit cost of approximately $6,500 per meter ($2,000 per foot) over the 22.5 km (14 miles) of coastline. Operating and maintaining the seawall structure may cost about 1 percent of the original costs, or $1.5 million per year. The questions here are whether to build it, when to build it, and how high to build it.

Three options for protection of the peninsula were examined:

- Option 1: Crash Construction Program. A protective structure is built as rapidly as possible. For this evaluation, the completion date is set at 1990. The height of the structure is assumed to be sufficient to protect from a 90-cm (3-ft) sea level rise.

- Option 2: Routine Construction Program. A protective structure is built over the next 30 years, with a completion date set at 2020. The structure is assumed to be sufficient to protect from a 90-cm (3-ft) sea level rise.

- Option 3: Delayed Construction. Planning for the construction of the structure is delayed until precise estimates of the expected rate of sea level rise are obtained. A completion date is set for 2050, and the height of the structure is assumed to be appropriate for the rate of sea level rise that is identified in the future.

The benefits of each of the options relative to doing nothing are presented in Table 3 for each of the four sea level rise scenarios. For example, if the low scenario comes true, the economic value of the development over time is estimated at $2,210 to $2,270 million assuming no structure is built. If Option 1, Crash Program, is implemented, it is estimated that the economic value would increase by $830 to $770 million. This increase is due to reduced shoreline retreat and reduced storm damage. From this increase is subtracted the present value of the cost of the program, $400 million.[3] The net increased value over no structure is consequently $430 to $370 million. Finally, the economic value of the development in the area assuming the low scenario comes true and Option 1 is performed is estimated at approximately $2.640 million ($2,210 + $430 and $2,270 + $370). The values for the other scenario/protection option combinations are interpreted similarly.

The information in Table 3 provides considerable insight into strategies for preparing for sea level rise. It shows that doing nothing is inferior to the other options across all the scenarios. Therefore, the sea wall should be built. Similarly, delaying construction to 2050 is inferior, meaning that it should be built sooner, rather than later. Table 3 also shows that Options 1 and 2 have considerable value and can offset most of the adverse economic impacts of a rise in sea level.

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[3] The costs of the options are computed as follows:

- Option 1:
  - -- Construction cost - $150 million
  - -- Present value of operating and maintenance costs of $1.5 million per year at a 3 percent discount rate equals $50 million
  - -- Shadow price of the investment equals 2.0
  - -- Present value of the cost at a 3 percent discount rate equals: (2.0) x (150 + 50) = $400 million.

- Option 2: The cost of Option 1, $400 million, delayed by 30 years at a 3 percent discount rate equals: $400 \div (1.03)^{30}$ = $165 million.

- Option 3: The cost of Option 1, $400 million, delayed by 60 years at a 3 percent discount rate equals: $400 \div (1.03)^{60}$ = $70 million.

Table 3. Estimates of the Economic Value of the Development in the Charleston Peninsula Area for Three Protective Options (millions of 1980 dollars)

Protection Options	Sea Level Rise Scenarios			
	Baseline	Low	Medium	High
No Structure				
-- Economic Value	2,520	2,210 - 2,270	1,770 - 1,870	1,435 - 1,550
1. Crash Construction Program				
-- Increased Economic Value over No Structure	570	830 - 770	1,100 - 1,030	1,090 - 1,040
-- Increased Value Net of $400 million cost	170	430 - 370	700 - 630	690 - 640
-- Economic value	2,690	2,640 - 2,640	2,470 - 2,500	2,125 - 2,190
2. Routine Construction Program				
-- Increased Economic Value over No Structure	380	600 - 550	800 - 750	870 - 810
-- Increased Value Net of $165 million cost	215	485 - 385	635 - 585	705 - 645
-- Economic Value	2,735	2,645 - 2,655	2,405 - 2,455	2,140 - 2,195
3. Delay Construction				
-- Increased Economic Value over No Structure	190	320 - 290	380 - 350	460 - 420
-- Increased Value Net of $70 million cost	120	250 - 220	310 - 280	390 - 350
-- Economic Value	2,640	2,640 - 2,490	2,080 - 2,150	1,825 - 1,900

Table 4. Community Protection Options Examined for Sullivans Island

Option	Description	Present Value of Cost a/ (millions of 1980 dollars)
1. Beach Nourishment - 1990	Initiate in 1990 a beach nourishment program to stabilize the beach face and build dunes. Included in the program is the construction of a levee to stabilize the backside of the island bordering the intracoastal waterway.	Beach Nourishment: $40 to $200 million, depending on SLR scenario. Backside Stabilization: $31 million.
2. Beach Nourishment - 2020	Initiate in 2020 a beach nourishment program to stabilize the beach face at its 2020 position and build dunes. Included in the program is the construction of a levee to stabilize the backside of the island bordering the intracoastal waterway.	Beach Nourishment: $31 to $160 million, depending on SLR scenario. Backside Stabilization: $13 million.
3. Beach Nourishment - 2050	Initiate in 2050 a beach nourishment program to stabilize the beach face at its 2050 position and build dunes. Included in the program is the construction of a levee to stabilize the backside of the island bordering the intracoastal waterway. (Not applicable for the high SLR scenario.)	Beach Nourishment: $20 to $72 million, depending on SLR scenario. Backside Stabilization: $5 million.
4. Stop Investment - 1990	Prohibit future investment on Sullivans Island following 1990. Repair of storm damage and construction of protective structures would be prohibited.	No direct costs.
5. Stop Investment - 2020	Prohibit future investment on Sullivans Island following 2020. Repair of storm damage and construction of protective structures would be prohibited.	No direct costs.

a/ Present values estimated at real discount rate of three percent.

The results for Options 1 and 2 are very close. While Option 2 is preferred to Option 1 for the baseline, low, and high scenarios, the opposite is true for the medium scenario. This pattern of preferences is reasonable because: (1) in the baseline and low scenarios, losses are very small in the early years, so waiting does not cause large losses; (2) the assumed 90-cm (3-ft) rise provides insufficient protection for the high scenario, so rushing to completion has little value if the sea wall is built to protect from a 90-cm rise and the high scenario comes true; and (3) Option 2 provides protection for the medium scenario for a substantial period of time. Therefore, it is probably better to proceed with a routine construction schedule and a target completion date of 2020 than to rush the sea wall to completion by the 1990s. This conclusion is reinforced when the added costs of a crash program are considered.

Protection Strategies for Sullivans Island

As a low-lying barrier island, Sullivans Island is very vulnerable to a rise in sea level. The medium and high rates of sea level rise would cause most of the island to be lost by 2075, assuming no protective measures are taken. The low scenario would cause substantial, although possibly more manageable, land loss (Kana et al. 1984).

This analysis focuses on two major planning options for Sullivans Island: a beach stabilization program in the form of beach nourishment, and a prohibition of future investment on the island, with the goal of returning the island to its natural (i.e., undeveloped) state. Table 4 lists variations on these protection options and their costs.

Options 1 through 3 involve beach nourishment programs, starting at different times. The costs of the beach nourishment options were estimated using the following assumptions:[4] the length of the beach is approximately 7,600 m (25,000 ft); the beach face is approximately 900 m (3,000 ft) wide; the amount of sand required to stabilize the beach increases with sea level rise (i.e., a 30-cm rise in sea level requires that 30 cm of sand be spread across the entire beach length [7,600 m] and width [900 m]); 10 percent of the placed sand is lost every year from erosion and must be replaced; the unit cost of sand is \$13 per m^3 (\$10 per yd^3) for the initial application of sand and \$6.5 per m^3 (\$5 per yd^3) for replacement sand (the higher cost of the initial application of sand includes the cost of program design and the identification of a suitable offshore source); the backside of the island is approximately 7,600 m (25,000 ft) and is stabilized at a cost of \$2,000/m (\$610/ft), including operation and maintenance costs; the shadow price (i.e., opportunity cost) of the program funds is 2.0 when evaluated at a 3 percent discount rate. Because the amount of sand needed to stabilize the beach will

[4] Unit costs are derived from Sorensen, Weisman, and Lennon (1984). The estimate of a 10 percent loss of sand every year is based on reports of previous beach nourishment projects and is conservative (i.e., probably low) for a beach facing open-ocean wave attack and possible hurricanes.

vary with the amount of sea level rise, the cost of the program differs for each sea level rise scenario.[5]

Options 4 and 5 are nonstructural alternatives. Under these options, no investment is permitted on the island following 1990 and 2020, respectively. The prohibition of investments includes prohibiting not only new investment, but also investments to upgrade existing properties and to repair storm damage. The goal of these two options is to move toward an undeveloped island, possibly designating the area as a park.

To implement either Option 4 or Option 5, the city would have to exert control over the private properties on the island, either through zoning or by purchasing the properties. The property is currently valued at over $65 million. The loss of the value of the use of the properties on the island (by prohibiting future development) is incorporated into the estimated economic values.[6] The payment of $65 million by the government to current property owners would be a transfer, and consequently does not influence the estimate of net economic impacts. Issues regarding equity and the implementability of the program are raised by the potential $65 million government payment. These issues are not addressed here.

An additional option for protecting the island would be to encircle it with a sea wall/levee system. This option would protect the structures on the island, but unlike the other options, the recreational beaches would be lost. Because the beaches are important to this area, we did not investigate this option.

To develop a strategy for preparing for sea level rise given current uncertainties, the five options were evaluated for each sea level rise scenario relative to doing nothing. The results of this evaluation are shown in Table 5. For example, the estimates for Option 1 are interpreted as follows for the low scenario:

- Implementing the option results in an increase in economic value of $185 to $158 million.
- Implementing the program costs $121 million.
- The net increased economic value is $185 - 121 = $64 million to $158 - 121 = $37 million.

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5 In the medium and high scenarios, the sea rises so much by 2075 that nearly all of the island would have to be raised in order to prevent flooding. Because these costs of raising existing structures and regrading the island are not included in the costs of Options 1 through 3, the cost of these options in the medium and high scenarios are probably underestimated. The addition of these costs would reinforce the conclusions drawn in this analysis.

6 In fact, the current method overestimates the losses caused by this strategy because the value of creating a recreational area, such as a park with beaches, is not estimated separately.

Table 5. Estimates of the Economic Value of the Development in the Sullivans Island Area for Five Protection Options (millions of 1980 dollars)[a]

Protection Option	Sea Level Rise Scenario: Baseline	Low	Medium	High
No Action				
-- Economic Value	153	84 - 115	40 - 87	28 - 75
1. Beach Nourishment - 1990				
-- Increased Economic Value over No Action	131	185 - 158	165 - 123	115 - 90
-- Cost of Beach Nourishment Program	71	121	178	235
-- Net Increased Economic Value	60	64 - 37	-13 - -55	-120 - -145
-- Economic Value	213	148 - 152	27 - 32	-82 - -70
2. Beach Nourishment - 2020				
-- Increased Economic Value over No Action	84	130 - 104	101 - 68	38 - 31
-- Cost of Beach Nourishment Program	44	84	128	162
-- Net Increased Economic Value	40	46 - 20	-27 - -60	-124 - -131
-- Economic Value	193	130 - 135	13 - 27	-96 - -56
3. Beach Nourishment - 2050				
-- Increased Economic Value over No Action	38	52 - 38	12 - 8	
-- Cost of Beach Nourishment Program	26	50	78	NA[b]
-- Net Increased Economic Value	12	2 - -12	-66 - -70	
-- Economic Value	165	86 - 103	-26 - 17	
4. Stop Investment - 1990				
-- Increased Economic Value over No Action	-35	31 - 1	72 - 25	80 - 34
-- Economic Value	118	115 - 116	112 - 112	108 - 109
5. Stop Investment - 2020				
-- Increased Economic Value over No Action	-18	31 - 9	52 - 24	43 - 33
-- Economic Value	135	115 - 124	92 - 111	71 - 108

a/ All estimates evaluated at a three percent real discount rate.

b/ Option 3 was not examined for the high scenario because by 2050 the high scenario would cause sufficient damage and land loss so as to make beach stabilization infeasible.

- The total economic value of this option is the economic value for No Action, plus the incremental value for the low scenario for Option 1, or: $84 + 64 = $148 million to $115 + 37 = $152 million.

The results for the other sea level rise scenario/protection option combinations are similarly interpreted. Of note is that there are no direct expenditures for implementing Options 4 and 5, and that Option 3 is not feasible for the high scenario.

The information in Table 5 provides considerable insight into the difficulty in preparing for sea level rise given current uncertainties. For the baseline and low scenarios, Options 1 and 2 are preferred. If initiated right away, a beach nourishment program could have an incremental value as high as $60 million. In the low scenario, the program can eliminate nearly all the adverse impacts of sea level rise. Reducing investment (Options 4 and 5) in the baseline case would be counterproductive, producing a net loss. Although reducing investment in the low scenario may produce a gain over doing nothing, its gain is not as large as the potential gain from beach nourishment. Thus, Options 4 and 5 are inferior for the baseline and low scenarios.

The opposite is true for the medium and high scenarios. For these scenarios, beach nourishment is so expensive it makes Options 1 through 3 uneconomical. Options 4 and 5 are preferred if the sea level rises at these rates.

If beach nourishment is initiated, and the medium or high scenario is found to be true in, say, 2020, officials may wish to stop beach nourishment and reduce future investments at that time. However, with this strategy, funds would be spent unnecessarily to nourish the beach between now and 2020, and investments made on the island would subsequently be lost. There is also the risk of not being able to stop the nourishment program once it has begun, because people's expectations will have been established regarding protection. Similarly, if investment is reduced today, and the baseline or low scenario is true, then officials may wish to initiate beach nourishment in, say, 2020. Again, however, if the city has purchased property, and park development has proceeded, there may be no turning back. Finally, the city may elect to do nothing, in the hope that by 2020 sufficient information will be available to make the correct choice at that time. Table 6 quantifies these various strategic possibilities.

Table 6 shows the returns from four strategies, and their expected values:

- Strategy A: Begin a beach nourishment program. This strategy is best when the future rate of sea level rise is expected to be low.

- Strategy B: Begin a disinvestment program. This strategy is best when the future rate of sea level rise is expected to be high.

- Strategy C: Wait until 2020 to act. This strategy assumes that a correct decision cannot be made today. Consequently, nothing is done (in the way of a coordinated community response) until 2020, when it is assumed that sufficient information is available about sea level

rise to correctly choose between beach nourishment (if the sea level rises by a small amount) and disinvestment (if the sea level rises by a large amount).

- Strategy D: Act correctly today. This strategy is not currently possible because it requires knowing whether the future rate of sea level rise will be below the low scenario or above the medium scenario.

The estimates of the economic value of each strategy under each sea level rise scenario are drawn from Table 5. The expected value is computed using the following subjective weights for the scenarios: baseline = 0.1; low = 0.4; medium = 0.4; and high = 0.1 (different weights would produce different expected values). Based on the expected values, which are driven by the subjective weights, Strategy C (Wait Until 2020) is preferred to Strategies A and B. Strategy B would maximize the lowest possible return (i.e., the worst one would do with B is $109 million), and Strategy A maximizes the highest return (i.e., the best one would do with A is $213 million). For Strategy A to be preferred to Strategy C (using the expected value criterion), the baseline and low scenarios must be much more likely to occur than the medium and high scenarios. Similarly, for Strategy B to be preferred, the medium and high scenarios must be most likely.

Table 6. Estimates of the Value of Alternative Protection Strategies for Sullivans Island (millions of 1980 dollars)[a]

Protection Option Chosen Today	Sea Level Rise Scenario				Expected Value
	Baseline	Low	Medium	High	
A. Beach Nourishment - 1990	213	150	30	-76	86.
B. Stop Investment - 1990	118	115	112	109	113.
C. Wait until 2020 to Act	193	130	-	-	120.
D. Able to Act Correctly Today	213	150	-	-	-
Beach Nourishment - 1990	-	-	112	109	137.
Stop Investment - 1990					

[a] All estimates evaluated at a 3 percent real discount rate.

Strategy D in Table 6 is not feasible because there is currently uncertainty about the future rate of sea level rise. However, if one were sufficiently knowledgeable to choose correctly by 1990, the expected value would increase by $17 million over Strategy C ($137 - 120 million). Therefore, although waiting is preferred to acting today and potentially making a mistake, the sooner one can act correctly, the better. In fact, having better information today could be worth $17 million for Sullivans Island.

THE NEED FOR REDUCING UNCERTAINTY

These findings indicate that in the case of Sullivans Island, there is considerable value in reducing uncertainty about future rates of sea level rise. Reliable, narrow ranges of estimates of sea level rise will enable preferred protection options to be unambiguously identified for such areas as Sullivans Island. Although the decision of whether to build a sea wall to protect the peninsula is not sensitive to the future rate of sea level rise, improved estimates may be required to establish design criteria and schedules for projects such as sea walls. Perhaps most important, improved estimates may be a precondition for initiating actions at the local level. Individuals and governments may not invest the time and resources necessary to plan for sea level rise unless and until the threats are clear and well known.

A recent book on the greenhouse effect and sea level rise contains the following recommendations (Barth and Titus 1984):

- Federal research on the physical, environmental, and economic impacts of sea level rise should be substantially expanded.

- Federal support for scientific research on the rate of future global warming and sea level rise should be greatly expanded.

To make progress, the issue of sea level rise must be elevated to its appropriate level of priority to command attention among decisionmakers and leaders. In the past, natural disasters (hurricanes and tsunamis) have provided an impetus for inclusion of such issues on local planning agendas. Although disasters may call attention to the need to begin planning for sea level rise, I hope that analyses such as this one may begin to form a basis for taking action before disasters occur.

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Impacts of Sea Level Rise on the Coasts of South America

Stephen P. Leatherman
University of Maryland
College Park, Maryland USA

ABSTRACT

South America exhibits a wide diversity of coasts from icy, deep fjords along the Chilean Pacific Coast to the muddy, tropical mangrove coast of Venezuela. Fortunately, this continent is not subject to hurricanes or typhoons; but winter coastal storms can be quite damaging, especially along the Atlantic sandy shores and cliffs of unconsolidated sediments. Accelerated sea level rise due to the greenhouse effect will increase the rate of beach erosion and cliff retreat, and result in the loss of significant coastal wetlands, principally mangroves and salt marshes.

Popular coastal resorts along sandy beaches in South America, such as Copacabana Beach, Rio de Janeiro, Brazil; Punta del Este, Uruguay; and Mar del Plata, Argentina, are already adversely affected by eroding shorelines. Copacabana Beach, perhaps the most famous beach in the world, was replenished in the early 1970s by pumping sand onshore and will require another nourishment project within a decade if current trends continue. The Argentine government has recognized the problem of critically narrow beaches at Mar del Plata, the nation's chief coastal resort, which boasts the largest casino in the world; beach fill is to be undertaken as soon as suitable supplies of sand can be located on- or offshore. These examples illustrate the nature of the problems along sandy coasts, which are similar in type and magnitude to those experienced along the U.S. coastlines.

Coastal wetlands also vary geographically in type and extent. Along little-inhabited, muddy coasts of Guyana and Venezuela, accelerated sea level rise may merely shift the coastal flora inland. Elsewhere, however, little lowland (coastal plain) exists behind the coastal fringe so that the wetlands will be squeezed out with sea level rise. The problem is particularly acute in areas like Guanabara Bay, Rio de Janeiro, Brazil, where the large, poor-class people are cutting down the mangrove forests for fuel. At the same time the Brazilian government seems to lack the environmental regulations and/or

enforcement to stop the onslaught of mangrove obliteration by urbanization (e.g., construction of factories on filled wetlands and encroachment of squatters building shanty towns).

Accelerated sea level rise poses very serious problems to a continent of peoples that are struggling to even maintain their present standard of living. The greenhouse-induced coastal changes will result in two radically different strategies: the popular coastal resorts will receive prompt attention (e.g., sand nourishment as required to maintain recreational beaches) at the expense of other critical public needs through the reallocation of scarce resources; while coastal wetlands will receive benign neglect for the most part since governments at all levels seem unable to cope with the present, severe problems in urbanized areas.

INTRODUCTION

South America is characterized by an extremely diverse coastline, ranging from the hard-rock, steeped cliffs of Peru and Chile to the low, flat coastal plain of the Amazon region. To assess the impacts of accelerated sea level rise on South America, this continent must be divided into regions that will exhibit similar responses. This partitioning of the coast is based on the geologic framework of the continent and is further stratified by considering the specific landforms and dominant processes operative within each coastal zone.

South America is almost a mirror image of North America, with some qualifications (McGill 1958). The Pacific Coast along Ecuador, Peru, and Chile is dominated by the Andes Mountains with no true coastal plain. Much of the coast is hard (crystalline) rock, resulting in steep cliffs and rocky promontories. Sandy to cobbly beaches occur as scattered pocket beaches interspersed along the cliffed coast. The U.S. Pacific Coast is quite similar to its South American counterpart as cliffs predominate; small spits at river mouths and pocket beaches at shoreline reentrants are the only low, sandy landforms along the coastal margin. Some of the cliffs, such as those in Delmar and Malibu, California, are composed of unconsolidated, erodable sediments, and urbanization of these areas involves considerable risk as the sea level rises and the cliffs retreat. Similar areas are found along the Pacific Coast of South America, but few have population centers in equivalent, hazardous locations.

In contrast to the tectonically active coast of the Pacific, the Atlantic Coast of the Americas is largely characterized by a low coastal plain, with some exceptions. Parts of New England, particularly Maine, in the United States have rocky coasts (nonerodable crystalline granitic rock), which form steep vertical cliffs in some areas. The mirror image comparison fits nicely when one considers that the southern portion of Argentina is also a hard-rock coast with similar characteristics.

The Atlantic Coast of South America is generally low, but the specific landforms are climatically controlled. The northeast Atlantic Coast of Venezuela, French Guiana, Surinam, and the Amazon region of Brazil are dominated by mangroves. This low, muddy coast is akin to the Mississippi River delta region of the U.S. Gulf Coast. While Louisiana is already experiencing major problems with shoreline retreat and coastal wetlands loss

with relative sea level rise, equivalent changes in this South American region are of little notice or importance as the coastal fringe is largely uninhabited. The most extensive beaches and concentration of people extend from Salvador, Brazil, along the Rio de Janeiro coast, including Punta del Este, Uruguay, and terminate south of Mar del Plata, Argentina.

The effects of accelerated sea level rise depend upon the specific landform type that it affects, which is determined by the regional geology and dominant processes. The regional geology can be explained by continental drift (Inman and Nordstrom 1971). The Atlantic Coast is a "trailing edge" coast and hence characterized by wide coastal plains and extensive sandy beaches and barrier islands. Coastal plains, such as the pampas of Argentina, are of low relief, gently slope, and are composed of unconsolidated (erodable) sediments. By contrast, the Pacific Coast is tectonically active and subject to both volcanic eruptions and violent earthquakes as have been recently recorded in Colombia and historically documented in California (e.g., 1906 disaster in San Francisco). This "collision coast" in plate tectonic terminology has little to no coastal plain; instead, the coastal range stretches along the U.S. Pacific Coast and the corresponding Andes Mountains in the southern hemisphere. Cliffs predominate, making the coast rather ragged in outline and steep in relief. Because sea level rise effects will be very localized and the South American Pacific Coast is not highly populated, the major concerns are wetlands loss and beach erosion along the Atlantic shore.

COASTAL WETLANDS

The Atlantic Coast of South America has two distinct types of coastal wetlands: mangroves and salt marshes. Mangroves are the principal vegetation along the deltaic coast of the tropical northeast Atlantic. While the Amazon River continues to deliver billions of tons of fine sediments to the coast yearly (which is moved in a northwest direction along this coastal compartment), evidence from field studies and air photo analysis shows shore erosion (Wells et al. 1980). As sea level rises, the entire coastal zone shifts landward up the gradual, seaward-sloping coastal plain. The mangroves rooted in the silty substrate along the open ocean are being eroded and undermined along the outer edge, which indicates active shore retreat. Therefore, the overall amount of coastal wetlands has probably changed little, with their spatial distribution changing temporally. Also, the affected areas have little population, and no major urbanized areas along the coastal margin are threatened by probable future sea level changes.

This situation changes drastically to the south, particularly in the state of Rio de Janeiro, Brazil. Here the mountain range meets the coast at places, creating the fascinating skyline of bald mountain stacks (sugarloafs) rising out of the sea. Wetlands, particularly mangroves in this tropical environment, have formed on the interface between land and sea within protected bays. (The wave climate is too high and the sediment too restrictive to allow mangrove development along the open coast in this geomorphic province.)

Mangroves in Guanabara Bay, which separates the cities of Rio and Niteroi, are already rapidly declining in areal extent due to population pressures. The large poor class uses the mangrove trees as fuel, and resi-

dents of shanty towns have clear-cut the forest in adjacent Bay areas. Furthermore, industrial expansion has resulted in the loss of wetlands as the upper margins of Guanabara Bay are filled to provide inexpensive construction sites on the new land. Brazilian federal and Rio state regulations to the contrary, the onslaught continues largely unabated to the point that thousands of square kilometers of mangroves have been reduced to a fraction of the total (estimated at less than 100 km^2 by some Brazilian coastal ecologists; Vallejo, personal communication 1985). Accelerated sea level rise will exacerbate this serious problem, because the mangroves on the tidal flats are backed by the cliffs of the coastal mountain range. Therefore, these wetlands cannot shift landward (migrate upslope as in the case of deltaic and chenier plains of the northeast coast). Instead, the mangroves will be gradually squeezed out of existence in this region due to natural conditions and artificial constraints (human development in the coastal fringe).

BEACH AND CLIFF EROSION

South Americans are fortunate that no hurricanes have been reported in this hemisphere. However, the Atlantic Coast from Salvador, Brazil, to Mar del Plata (the heavily populated coastal area with sandy beaches) is subject to winter storms. This moderate to high wave climate in a microtidal (less than 2 m tidal range) setting (Davies 1973) indicates the potential for storm-induced damage and the long-term problems of sea level rise.

The Argentine coast from south of Mar del Plata along the Atlantic Coast up to the Rio de La Plata estuary is presently eroding. Cliff erosion of the unconsolidated to loosely compacted sediments is a major concern in the Mar del Plata region (Figure 1). The pocket and mainland beaches in this region are eroding at variable rates, approaching 2-4 m per year in the most severely affected areas (Schnack 1985). In fact, the beaches of Mar del Plata are already critically narrow, and a groin field (of little utility) has been installed. The federal government has recognized the problem and is planning a major beach nourishment project as soon as suitable fill material can be located. This coastal resort, which is Argentina's most popular and hosts the largest single casino in the world, will require continued beach restoration with ever-increasing amounts of fill as sea level rise accelerates.

Just to the north of Mar del Plata, the cliffs subside to meet the gently sloping pampas of northern Argentina. These broad, flat features are the Argentine equivalents of the U.S. Atlantic coastal plain (Figure 2). Therefore, estimates of shore retreat with sea level rise should correspond closely with their North American counterparts and depend upon such factors as slope, 3-D geomorphology, and wave climate (Leatherman 1983, 1984). Holocene-age (5,000-year-old) beach ridges can be found several meters above sea level in the Mar Chiquita area. If this area has been geologically stable, as now believed (Schnack, Fasano, and Isla 1982), then these inland beach ridges on the pampas record a previous sea level high stand during the Holocene. Similar age-dated and stratigraphically equivalent beach ridges have been described in Brazil (Suguio and Ostrom 1982; Suguio and Martin 1976), but no such features have ever been documented along the U.S. East and Gulf coastal plains. While this occurrence provides ample food for thought for coastal geologists and neotectonists, the present and future evolution of these coastal plains in both hemispheres should follow similar pathways with accelerated sea level rise.

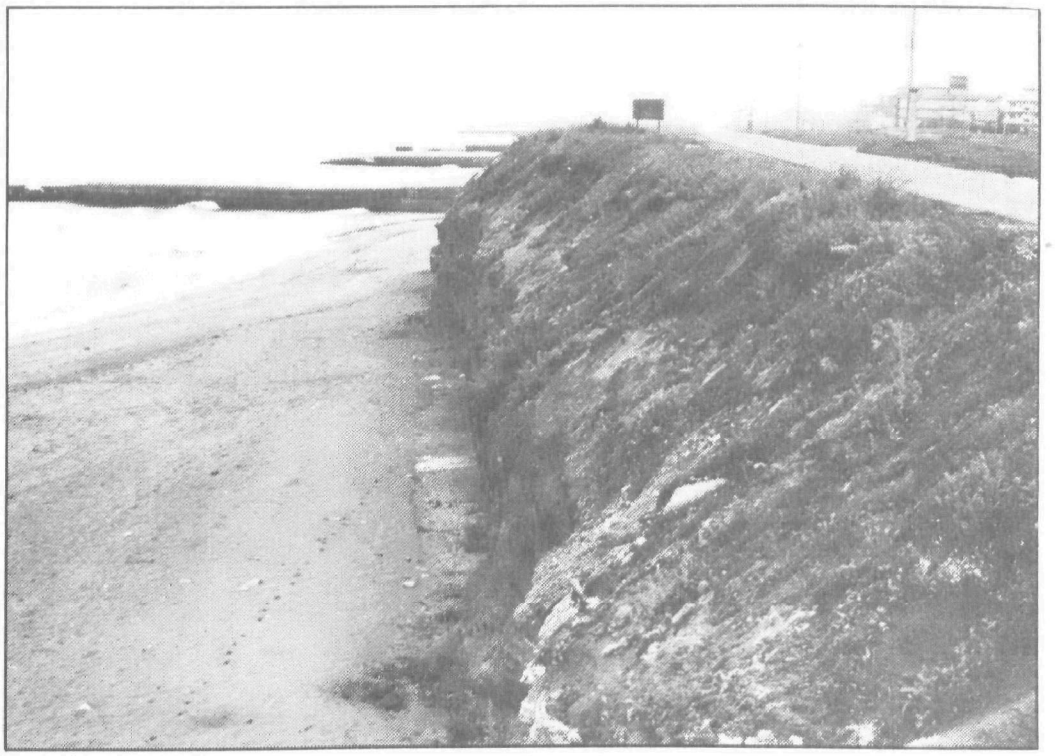

Figure 1. Near Mar del Plata, the Argentine coast is characterized by low bluffs (5-10 m high), which are generally comprised of highly erodable, unconsolidated materials. The coastal highway (main thruway) from Mar del Plata to Mar Chiquita is threatened by cliff recession, indicating an already severe beach erosion problem which will only be exacerbated with accelerated sea level rise.

Figure 2. At Mar Chiquita, salt marsh and lagoonal deposits are presently being eroded on the active beach face. This situation indicates a long-term and continuing trend of barrier recession, which is similar to that found on U.S. East and Gulf Coast barrier islands.

The state of Rio de Janeiro, as already mentioned, is largely characterized by the coastal mountain range intersecting the coast. However, small coastal barriers to either side of Rio proper will be greatly influenced by sea level rise (Muehe 1979; Figure 3). As these burgeoning coastal communities derive their potable water from the groundwater table at shallow depths, sea level rise will diminish the size of this freshwater lens through time. (Even without such a rise, it seems likely that the ensuing overpopulation of these fragile coastal environments will virtually ruin the potable water supply by waste discharge directly into barrier substrate.)

The sandy beaches of Rio and Niteroi along Guanabara Bay are all artificial, having been created by beach fill (Figure 4). Although the wave climate of this sheltered embayment is low, sea level rise will cause shore erosion as has been documented in similar environmental settings along the U.S. coast (e.g., Galveston Bay, Texas; Leatherman 1984).

The outer, open ocean beaches of Copacabana and Ipanema are more subject to rapid retreat. The world famous Copacabana Beach was nourished in the early 1970s by Dutch engineers who pumped offshore sand onto the beaches. Unfortunately, the grain size of the introduced material was slightly larger than the native sand so that the beaches have become noticeably steeper since nourishment (Julio Gongalez, personal communication 1985). This beach profile alteration actually reduced the usable intertidal foreshore beach (apart from the widening of the dry backshore beach region). In addition, larger waves now break directly on the beach face, which makes even the shallow water zone dangerous for small children. Copacabana Beach is already quite narrow and heavily utilized (Figure 5) so that another beach fill project will be required soon. Beaches are clearly a national priority in Brazil so that as sea level rises and the beaches recede, money will be allocated to maintain this international tourist area if necessary, at the expense of other public needs.

New high-rise residential developments are in the suburbs to the west of Rio along the Atlantic Ocean barriers. Here high-rise construction of condominiums is proceeding at a rapid pace (Figure 6) despite the apparent shore retreat. This type of building along an already eroding, low shoreline is reminiscent of the Miami Beach, Florida, development in the 1950s and more recently the high-rise construction at Ocean City, Maryland, in the 1970s (Figure 7; Leatherman 1981, 1986). Parallels can easily be drawn among the construction practices, lack of governmental control and planning, present hazardous situation for the development, and the impending problems with accelerated sea level rise. At Miami Beach and Ocean City, large-scale beach nourishment projects costing $65 million and $30 million, respectively, have already been conducted or will be shortly undertaken. The high-rise buildings along the barrier shorelines of the swanky Rio suburbs will also soon be in the same predicament, and one can assume that political muscle and power will be applied so that public funds are used to protect private investment.

CONCLUSIONS

South America has a diverse coastline, but similar conditions and problems exist in both American hemispheres especially along the Atlantic Coast. While large portions of the coastal zone have not been mapped in detail and frequently only general descriptions exist, the present erosional

Figure 3. Rapid urbanization is occurring along this coastal barrier, just to the east of Rio. The populace draws their water from the near-surface (unconfined) ground water table. As sea level rises, this low barrier will be subject to increased flooding and reduced supplies of potable water due to contraction of the fresh water lens.

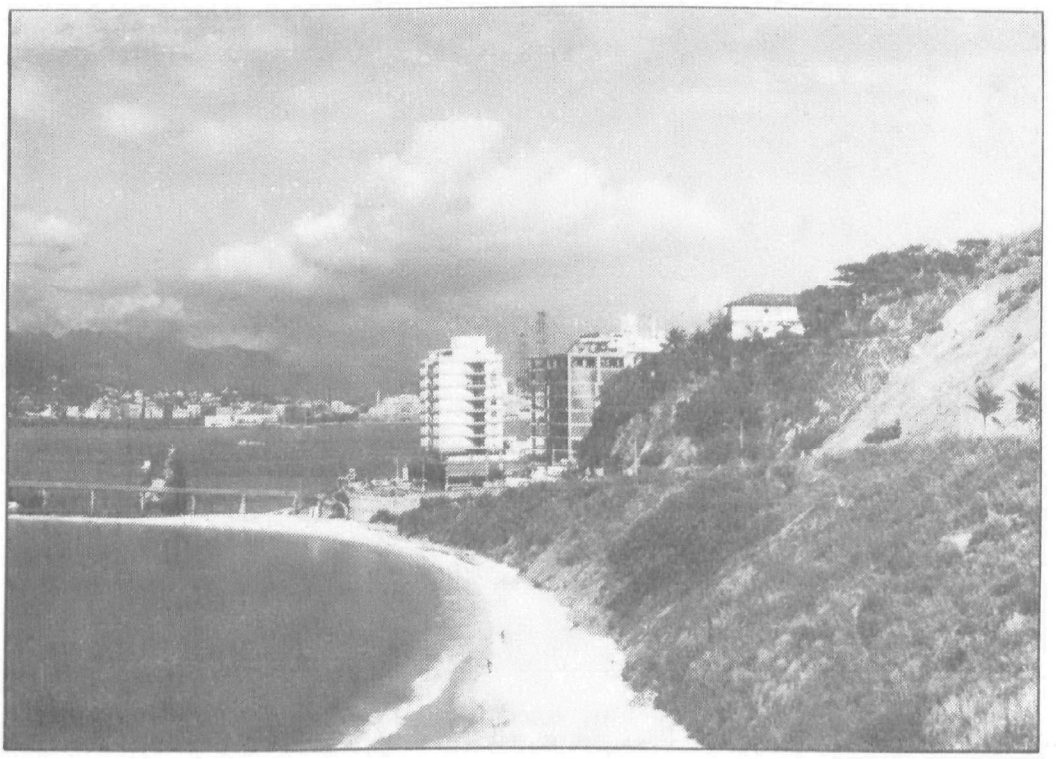

Figure 4. The Rio de Janeiro area lacks any true coastal plain. Historical erosion and cliff instability are evident across Guanabara Bay in Niteroi. The beaches in this area are all artificial in that sand has been manually emplaced from dredging operations offshore. Although the wave climate is low in the sheltered bay, increased sea level rise will cause beach erosion and eventually reactivate cliff retreat in the absence of any mitigating measures.

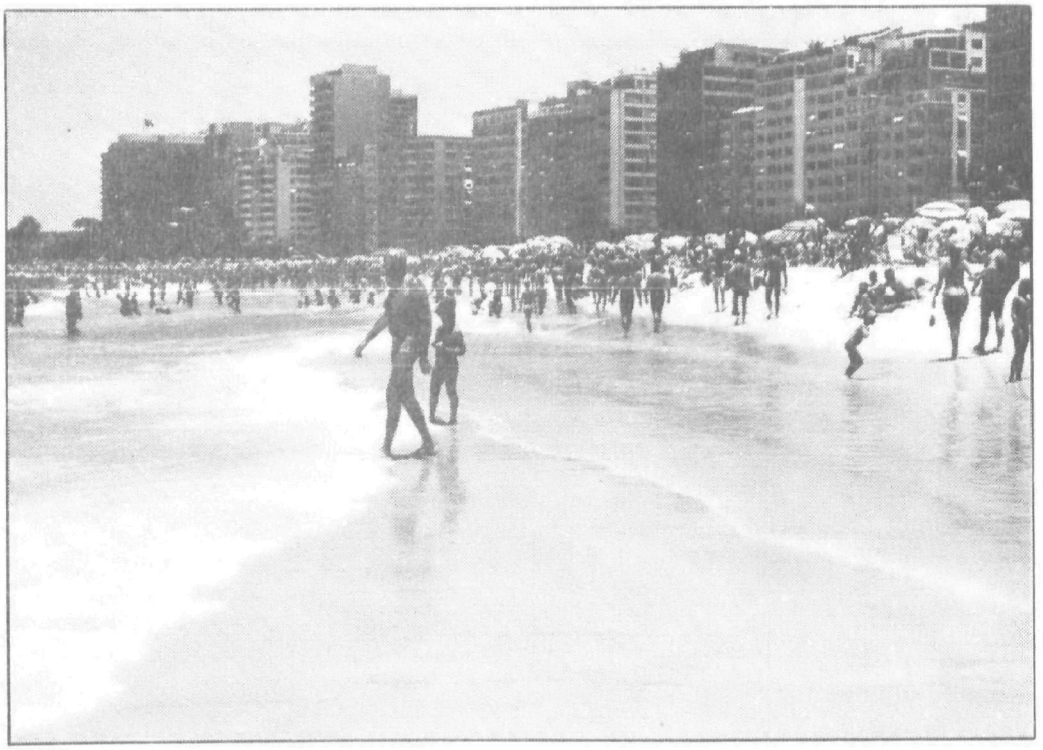

Figure 5. Copacabana Beach in Rio is perhaps the most famous beach in the world. This beach was nourished in the early 1970s with offshore sands. The beaches are already overcrowded by U.S. standards, and another beach fill project will be necessary in the near future.

Figure 6. To the west of Rio is a major suburban development occupied by the relatively wealthy Brazilians. Unfortunately, there is little to no planning, and high-rise condominiums are being constructed along the waters edge. Shore recession rates are not available, but the presence of a wave-cut scarp along a high energy coast indicates ongoing beach erosion and the potential for major problems in the future for this urbanizing coastal barrier.

Figure 7. Ocean City, Maryland, is overbuilt with high-rise condominiums located along the eroding beach strand.

trend along populated, sandy coastal areas is obvious, and we can expect increasing, critical problems with accelerated sea level rise. In summary, the major problems will be experienced at the coastal resort and population centers (e.g., Rio de Janeiro, Brazil, and Mar del Plata, Argentina) due to beach erosion and cliff retreat. Coastal wetlands, particularly mangroves, will be virtually eliminated in these coastal areas due to overpopulation and crowding as well as to loss of suitable intertidal areas with continued sea level rise.

ACKNOWLEDGMENTS

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Potential Effects of Sea Level Rise on the Coasts of Australia, Africa, and Asia

Eric C. F. Bird
University of Melbourne
Melbourne, Australia

INTRODUCTION

Recent studies (e.g., Barth and Titus 1984) have indicated the possibility that human-induced global climatic changes will result in a rise of sea level: it is thought that atmospheric warming will lead to a reduction in glaciers and ice sheets and a consequent addition of water volume to the oceans, as well as to thermal expansion of ocean water. Hoffman (1984) estimated a rise of 0.24-1.17 m (0.78-3.8 3 ft) by 2050, and 0.56-3.45 m (1.83-3.83 ft) by 2100. According to these predictions, sea level will stand 1 m (3.3 ft) higher than it is now between 2045 (high scenario) and 2140 (conservative scenario).

Factors that complicate the prediction of actual changes on particular sectors of the world's coastline include tectonic uplift or subsidence of the land margin, the effects of the additional water load, which may hydro-isostatically depress the submerged land, and the spatial variability of ocean surface levels, which make it unlikely that the rise of sea level will be equivalent around the world's coastlines, even on sectors where the land margin remains stable.

This paper is concerned with the potential geomorphological, ecological, and socio-economic consequences of a rise of mean sea level, relative to the coastal land margin, of the order of one meter within the next century, and refers particularly to the coastlines of Australia, Africa, and Asia (Bird and Schwartz 1985).

A mean sea level rise of 1 m (3.3 ft) implies that the mean high spring tide limit will rise a similar amount, subject to any modification of tidal amplitude due to the deepening of nearshore waters in relation to coastal configuration. As a first approximation, the forecast coastline may be determined by surveying a contour 1 m (3.3 ft) above high spring tide line, but allowance must then be made for the effects of erosion or deposition as

submergence proceeds. Submergence will result in coastline recession, except where the coast consists of a vertical cliff, or where deposition of sediment continues at a sufficient rate to maintain or prograde the coast. Progradation may continue in the vicinity of the mouths of major sediment-yielding rivers which have built large deltas, such as the Ganges, the Irrawaddy, and the Mekong in Asia, but erosion is already prevalent on some deltas, notably the Nile and Volta deltas in Africa.

EFFECTS OF SUBMERGENCE

The general effects of coastal submergence may be listed as follows:

- On cliffed coasts submergence is likely to accelerate coastline recession, except on outcrops of hard rock formations, where the high and low tide lines will simply move up the cliff face. Existing shore platforms and abrasion ramps will disappear beneath the sea.

- The shores of deltas and coastal plains will retreat, except where they are maintained by coastal sedimentation.

- Beaches will be narrowed, and beach erosion will become much more extensive and severe than it is now.

- Inlets, embayments, and estuaries will be enlarged and deepened, and increasing salinity penetration will cause a regression of coastal ecosystems: where possible, mangrove and salt marsh communities will move back into terrain presently occupied by freshwater vegetation.

- Coastal lagoons will also become larger and deeper, but the enclosing barriers may transgress landward on to them. If the barriers are submerged, or destroyed by erosion, the lagoons will become coastal inlets or embayments.

- Low-lying areas on coastal plains, such as sebkhas (saline depressions now subject to occasional marine flooding) on arid coasts, will be flooded to form permanent lagoons.

- Upward growth of coral and associated organisms will be stimulated on fringing biogenic reefs, keeping pace with the marine transgression or lagging somewhat behind it (Neumann and Macintyre 1985).

- Erosion, structural damage, and marine flooding caused by storm surges or tsunamis will intensify because of the greater heights of waves arriving through deepening coastal waters.

- Water tables will rise in coastal regions, and soil and water salinity will be augmented.

If the sea level rise continues, the sea will eventually reoccupy levels it held in the Late Pleistocene (e.g., the 3-m and 7-m emerged coastlines in southeastern Australia), reviving raised beaches and rejuvenating Pleistocene bluffs as active cliffs.

It should be noted that many existing coastal features have developed during a period of relatively stable sea level. Over the past 6000 years, the sea has remained at or close to its present level on much of the Australian, African, and Asian coastline, in contrast with the slow marine transgression recorded on parts of the Atlantic coast of North America, and the secular emergence resulting from postglacial isostatic rebound in Scandinavia and northern Canada (Bloom 1977). The Holocene sea level "stillstand" has been marked by the development of broad shore platforms on many cliffed coasts, of beach-ridge plains, prograded barriers, deltas, and depositional terraces formed under mangroves and salt marshes. Such features will not immediately redevelop at higher levels as the sea rises: they will evolve only gradually, after a new sea level stillstand has become established. Such a stillstand requires the attainment of a new balance between global atmospheric temperatures and ice volumes, which could occur at any level up to 60 m, the estimated height of the ocean surface if all the world's glaciers and ice sheets were to melt (Donn, Farrand, and Ewing 1962).

On the coasts of Australia, Africa, and Asia the most dramatic changes in a century of rising sea level are likely to be on beaches, around coastal lagoons, and in mangrove ecosystems. These will now be considered further.

SEA LEVEL RISE AND BEACH EROSION

Studies by the International Geographical Union's Commission on the Coastal Environment have demonstrated that there is already a prevalence of erosion on sandy beaches: more than 70% of the world's sandy coastline has shown net erosion over the past few decades, and less than 10% net progradation; the remaining 20%-30% have remained stable, or shown no measurable change within this period (Bird 1985). Beach erosion is partly due to a sea level rise of the order of 1.2 mm/yr (0.05 in/yr) (i.e., about one-eighth the rate of sea level rise forecast for the next century) recorded on tide gauges around the world's coastline since the beginning of the present century (Gornitz et al. 1982; Pirazzoli 1984). However, this is only one of fourteen factors identified by the Commission as initiating or accelerating beach erosion (Table 1). A sea level rise of 1 m (3.3 ft) during the forthcoming century will certainly become the major factor causing recession of sandy beaches, but most of the other factors will continue to operate. An exception may be found locally where beaches that were nourished with sediment derived from nearby cliffs actually receive an increased sediment supply because sea level rise has accelerated cliff erosion. On the other hand the supply of fluvial sediment to beaches will diminish, as greater proportions are retained within submerging river mouth areas.

Because there are so many variables, it is difficult to forecast the extent of erosion or deposition that will accompany submergence by a rising sea (Leatherman 1984). Bruun (1962) devised the rule that beaches in equilibrium with the processes at work on them will respond to a sea level rise by being cut back and lowered until a new equilibrium profile is established. It is possible to estimate the extent of recession necessary to accomplish this under the conditions specified by Bruun (Figure 1), but in practice many beach systems are complicated by gains and losses of sediment from offshore, alongshore and hinterland sources (Figure 2), and prediction of the response to sea level rise then becomes much more difficult. A beach could be maintained during a period of sea level rise if it were supplied with sufficient

Table 1. Factors That Favor Initiation or Acceleration of Beach Erosion

1. Diminution of fluvial sand supply to the coast, as a result of reduced runoff and sediment yield from a river catchment (e.g., because of reduced rainfall, or dam construction leading to sand entrapment in reservoirs, or successful soil conservation works).

2. Reduction in sand supply from eroding cliffs and shore outcrops (e.g., because of diminished runoff, a decline in the strength and frequency of wave attack, or the building of sea walls to halt cliff recession).

3. Reduction of sand supply to the shore where dunes that had been moving from inland are stabilized, either by natural vegetation colonization or by conservation works, or where the sand supply from this source has run out.

4. Diminution of sand supply washed in by waves and currents from the adjacent sea floor, either because the sand supply has run out, or because the transverse profile has attained a form that no longer permits such shoreward drifting.

5. Reduction in sand supply from alongshore sources as the result of interception (e.g., by a constructed breakwater).

6. Increased losses of sand from the beach to the backshore and hinterland areas by landward drifting of dunes, notably where backshore dunes have lost their retaining vegetation cover and drifted inland, lowering the terrain immediately behind the beach and thus reducing the volume of sand to be removed to achieve coastline recession.

7. Removal of sand from the beach by quarrying, and losses of sand from intensively used recreational beaches.

8. Increased wave attack resulting from the deepening of nearshore water (e.g., where a shoal has drifted away, where seagrass vegetation has disappeared, or where dredging has taken place).

9. Submergence and increased wave attack as the result of a rise of sea level relative to the land.

10. Increased wave attack due to a climatic change yielding a higher frequency, duration, or severity of storms in coastal waters.

11. Diminution in the volume of beach material as the result of weathering, solution, or attrition of beach sand grains leading to a lowering of the beach face and a consequent increase of wave attack on the backshore.

12. Increased beach erosion resulting from a rise in the water table, due to increased rainfall or local drainage modification, rendering the beach sand wet and more readily eroded.

13. Increased losses of sand alongshore as a result of a change in the angle of incidence of waves (e.g., as the result of shoal or reef growth, or of breakwater construction).

14. Intensification of wave attack as the result of lowering of the beach face on an adjacent sector (e.g., as the result of reflection scour induced by sea wall construction).

SOURCE: Bird (1985)

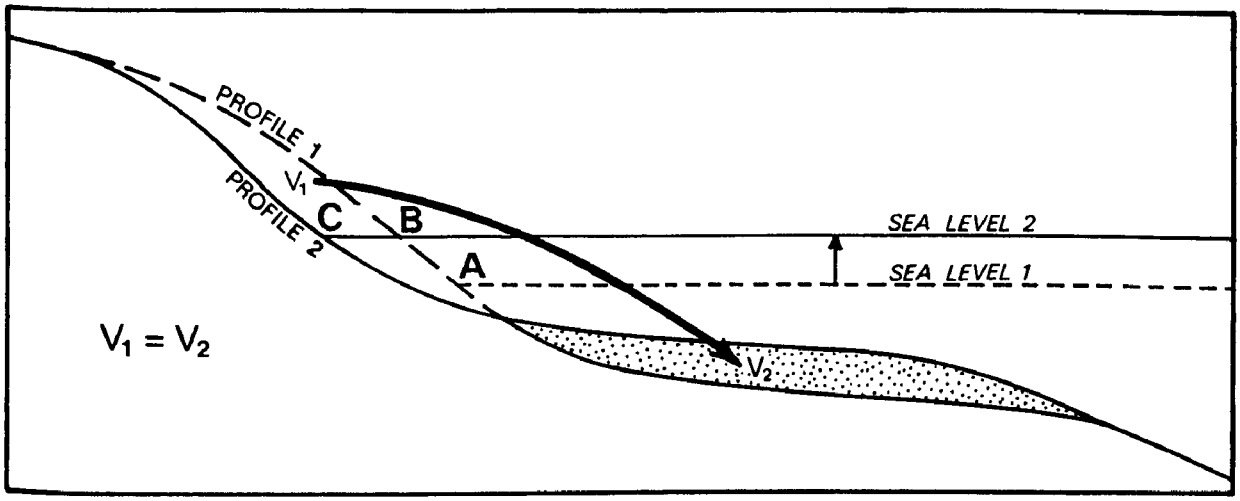

Figure 1. The Bruun Rule states that a beach that has attained equilibrium with coastal processes (Profile 1) will respond to a rise in sea level by losing sand from the upper part of the profile and gaining it in the nearshore area until a new equilibrium (Profile 2) is established. The coastline will thus retreat from A to B as the direct result of the sea level rise, and from B to C as a result of the transference of sand seaward. It is possible to predict the extent of coastline recession where the conditions proposed by Bruun apply, but it should be noted that other factors (see Table 1) also influence the changes that will occur on a beach as a result of a sea level rise.

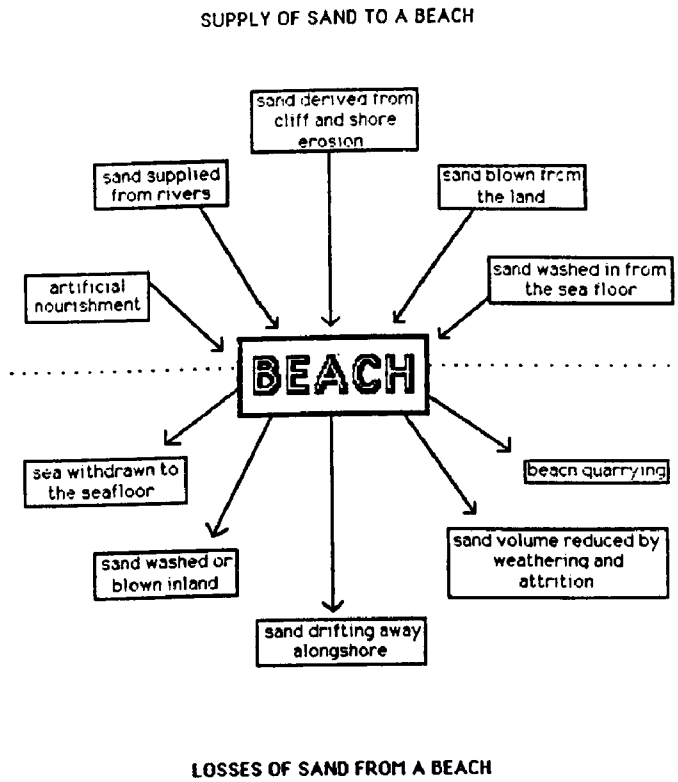

Figure 2. The various ways in which sand is supplied to, and removed from a beach.

quantities of sediment from nearby rivers, melting glaciers or spilling dunes. Erosion of a beach undergoing marine submergence would also be reduced if at the same time the coastal environment became calmer and drier, or if swash-dominant wave regimes replaced drift-dominant wave regimes (i.e., if losses by longshore drifting are reduced) as a result of changes in coastal configuration that accompany a sea level rise.

A great deal of additional site-specific research is therefore needed to determine the extent of beach erosion that will result from a sea level rise of the order of 1 m (3.3 ft) over the next century.

EFFECTS OF SEA LEVEL RISE ON COASTAL LAGOONS

Coastal lagoons, formed where inlets, estuaries, or embayments have been partly or wholly sealed off from the sea by the formation of depositional spits, barrier islands, and barriers, are numerous on the coasts of Australia, Africa, and parts of Asia. Typically they show salinity gradients from fresh river inflow through brackish to sea water, and are important to coastal fisheries, especially as breeding and feeding areas. In Asia, especially in India and Sri Lanka, some have been extensively converted into brackish-water fish ponds (e.g., the lagoons south of Madras), while others have been modified by increased freshwater outflow resulting from development of irrigated rice fields in their immediate hinterlands, e.g., Kalametiya Lagoon, Sri Lanka (see Mahinda Silva 1986).

A sea level rise of 1 m (3.3 ft) over the next century is likely to increase marine influences in such lagoons by deepening and widening their tidal inlets. At the same time the depositional spits and barriers that enclose them will be trimmed back on their seaward shores and possibly breached locally: as sand is washed and blown across them, they will transgress landward (Bird 1983). In turn, the lagoons will become deeper and (unless deposition offsets this) larger in area, inundating marginal lands, and initiating or intensifying erosion on their shores. Where enclosing barriers are submerged or removed by erosion, lagoons will open out as marine inlets or embayments.

Some of the likely consequences of sea level rise can be deduced from studies of changes in coastal lagoons where sea water inflow has increased as the result of the opening or enlargement of a tidal entrance, as in the Gippsland Lakes in southeastern Australia, where the cutting of an artificial entrance in 1889 resulted in previously freshwater lakes becoming brackish estuarine lagoons, with die-back of freshwater vegetation fringes and their replacement by salt marsh, the displacement of freshwater biota by estuarine and marine species, and the onset of extensive shoreline erosion (Bird 1978). Similar changes have followed the opening or widening of tidal entrances to other coastal lagoons, notably the Ebrie Lagoon on the Ivory Coast and Lake St. Lucia in South Africa. A sea level rise would have similar effects, and would accentuate changes in already-estuarine lagoons such as the Gippsland Lakes. By contrast, the Murray-mouth lagoons in South Australia were brackish until 1940, when natural tidal entrances were sealed by barrages, and they have since developed into freshwater lakes, with associated ecological changes that are the reverse of those seen in the Gippsland Lakes. Where coastal lagoons have thus been artificially separated from the marine environment, they will only be maintained in their present condition by raising the enclosed barrages to prevent the rising sea from reinvading.

SEA LEVEL RISE AND MANGROVE ECOSYSTEMS

Mangrove-fringed coastlines have become much less extensive in Australia, Africa, and Asia in recent decades because of the impacts of land reclamation, fishpond construction, mining, and waste disposal, but where they persist they typically stand in front of zones of salt marsh and freshwater vegetation (fen, scrub, or swamp forest). In many cases there has been coastal progradation accompanied by the advance of the mangroves (often arranged in species zones), with salt marsh and freshwater communities following in succession as sedimentation builds up the substrate to appropriate levels, forming an intertidal depositional terrace.

A sea level rise will reverse this, unless sedimentation continues at a sufficient rate to maintain or prograde the coastline. Submergence will kill the seaward mangroves and initiate erosion of the previously prograded terrace. As the coastline retreats the mangrove zone will migrate landward to displace the salt marsh, which in turn will invade the freshwater hinterland. Mangroves regenerate quickly in areas that have been cleared then abandoned, and it is likely that they will spread back on the suitable hinterland habitats as the sea rises, but where the hinterland is steep or rugged the mangrove zone may be extinguished by submergence.

On the Asian coast the land immediately behind the mangroves is commonly used intensively for fish ponds or rice fields, and it is these that would be colonized by the regressing mangroves, if local people permit. In drier areas, as in northern Australia, mangroves are backed by bare, hypersaline plains, and in these areas a sea level rise will result in the colonization of presently unvegetated tracts by mangroves as the coastline retreats.

HUMAN RESPONSES TO COASTAL SUBMERGENCE AND EROSION

Secular coastal submergence rates of as much as a meter per century have not been documented in historical times. Goudie (1977) quoted Vasilev's (1969) report of submergence of parts of the Black Sea coast at rates of 30-52.5 cm (11.8-20.5 in) per century; Tjia (1970) recorded up to 30 cm (11.8 in)/century from parts of Indonesia, and Veenstra (1970), 10-20 cm (4-8 in)/century from the southern shores of the North Sea. Sudden submergence has occurred locally as the result of earthquakes, as on Homer Spit, Alaska, parts of which sank nearly 2 m (6.6 ft) in the 1964 earthquake, around Tumaco, Colombia, which subsided up to 1.6 m (5.2 ft) in the 1979 earthquake, and in the Rann of Kutch, Pakistan, which has been subject to recurrent tectonic subsidence (Bird 1985), but such events have been highly localized, and their effects are not necessarily indicative of the changes that would accompany a more gradual but sustained global sea level rise.

A more rapid rise occurred in prehistoric times. About 18,000 years ago, at the end of the Last Glacial cold period, sea level stood about 140 m (460 ft) lower than it does now. Global warming then produced a rapid sea level rise, the Flandrian Transgression, which brought the sea up close to its present level about 6000 years ago, at an average rate of 1.16 m (3.8 ft)/century. It was probably an oscillatory rise, phases of more rapid submergence alternating with phases of slower submergence or episodes of emergence (Fairbridge 1961; Bloom 1977). Primitive societies that occupied emerged shelf areas were forced to retreat as this transgression proceeded.

Thus, the Australian Aborigines became separated from their Tasmanian counterparts with the submergence of Bass Strait between 13,500 and 12,000 years ago and were cut off from Papua New Guinea by the submergence of Torres Strait 8,000 to 6,500 years ago (Bird 1986). Unfortunately, we have no record of their perceptions and reactions to a sea level rise proceeding at a rate similar to that expected over the coming century.

The ways in which modern coastal societies will respond to a relatively rapid rise in sea level will vary considerably with political and economic factors. Within the regions here considered, the response in developed countries such as Australia, South Africa, Japan, and Singapore will differ from that of less developed countries in tropical Africa and Asia. The former will have the organization, technology, and resources to counter the effects of a sea level rise, whereas the latter will in general have to choose between evacuation and adaptation to their changing coastal environments (Figure 3).

On coastlines close to urban and industrial centers it is likely that a sea level rise of about 1 m over the next century will stimulate massive expenditure on structures designed to prevent submergence and erosion. It is very likely that where land has recently been reclaimed from the sea for use by large coastal populations (as in Singapore, Hong Kong, and Tokyo Bay) strenuous efforts will be made to retain it, using techniques familiar from the history of the Netherlands coast. Where eroding beaches are valued for recreation or tourism, as in Australia close to the state capitals and other seaside towns and at coastal resorts in Africa and Asia, it is likely that they will be maintained by expensive beach renourishment programs of the kind already used in some of these areas.

Away from such highly developed centers, especially on the coastlines of less wealthy countries, there may have to be evacuation and abandonment of coastal fringes as submergence and erosion proceed, and modification of developed land and water uses as the water table rises and soil and water salinity increase. Efforts will certainly be made to prevent the sea from inundating farmland. The Yilan Plain in northeast Taiwan is an already-subsiding coastal area where dykes have been built to protect an intensively used lowland from marine invasion (Hsu 1985). But as submergence proceeds there is a strong possibility, already in evidence in parts of the Philippines, of increasing the use of nearshore waters for mariculture and the occupation of shallow areas by people who live on boats and who may eventually occupy floating villages and towns.

In Asia, brackish-water fish ponds have been constructed extensively on the fringes of deltas and coastal plains, sometimes just behind the mangrove fringe, sometimes replacing it (Figure 4). On the deltaic north coast of Java, fishponds are constructed on mud deposited at river mouths by floodwaters directly after the floods disperse, and before mangroves are able to colonize (Bird and Ongkosongo 1980). On prograding deltas and coastal plains, where such fish ponds become gradually farther from the coast, and less easy to supply with sea water, they are progressively converted into rice fields irrigated with fresh water from rivers. The effects of sea level rise in such situations can be judged with reference to sectors where the coastline

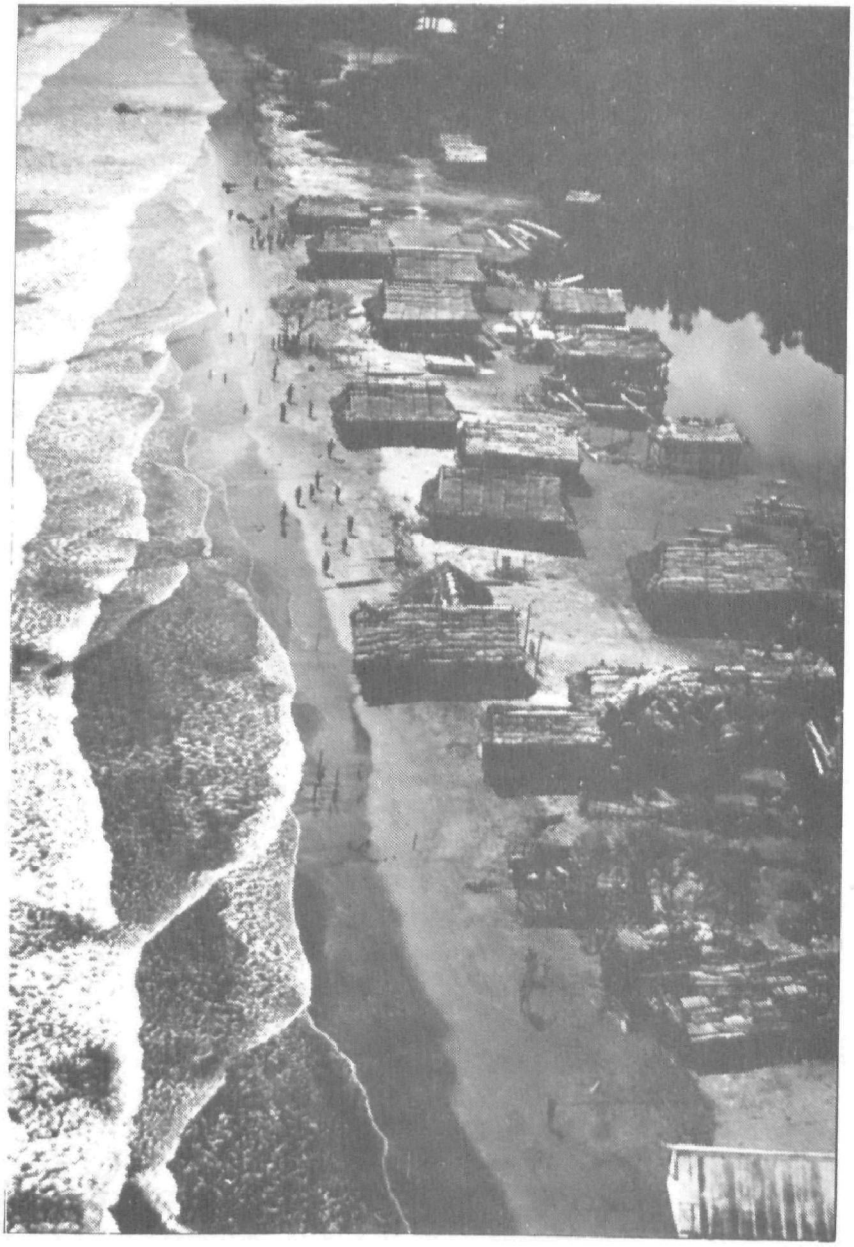

Figure 3. Village on the narrow sand barrier which borders the subsiding northern shore of the Sepik Delta, New Guinea. As submergence proceeds the barrier is migrating intermittently landward as the result of occasional storm overwash. The village has been repeatedly rebuilt on the retreating barrier. Photo: Eric Bird.

Figure 4. Intensive use of the coastal fringe (brackish-water fish ponds) and shallow nearshore areas (shellfish farms) in Manila Bay, Phillipines. Photo: Eric Bird

is eroding (usually because the river mouth has been diverted, naturally or artificially, to some other outlet) and fish ponds are being destroyed (Figure 5). In such areas, the landward spread of salt water has prompted the conversion of ricefields back to brackish-water fish ponds. Such changes raise socio-economic and political problems, for people who live on eroding sectors are losing land and resources, whereas those on accreting sectors are gaining them, and it is difficult to organize equitable redistributions.

A sea level rise of 1 m (3.3 ft) over the next century will thus cause major problems on the intensively utilized and densely populated Asian coastal plains--producing coastline recession of up to several kilometers, displacing coastal villages, and depriving many people of their land and resources. On the low-lying coast of the Bight of Bangkok (Figure 6), for example, the mangrove fringe has been largely cleared, the seaward parts being converted into brackish-water fish and shrimp ponds and salt pans, while landward, canals have been built to bring fresh water to irrigate the rice fields (Figure 7). Tide range there is up to 2.3 m (7.6 ft) and a sea level rise of a meter on this gently sloping coastal plain could submerge the whole of the previous mangrove area and an additional zone up to 5 km (3.2 mi) inland (Figure 8). The existing fishponds, shrimp ponds, and salt pans are likely to be destroyed by marine erosion, but the local people will

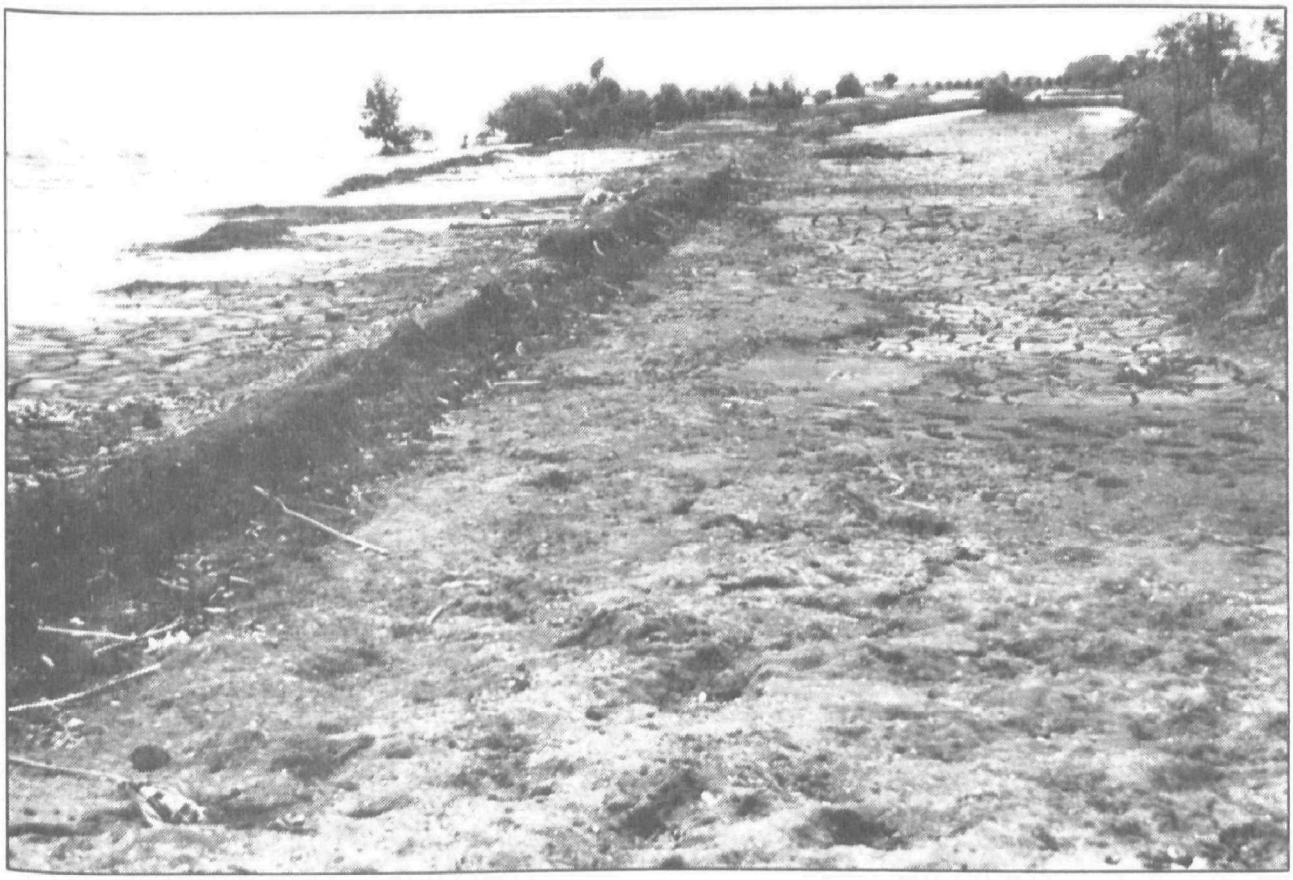

Figure 5. Brackish-water fish ponds on the coastline of the Citarum Delta, northern Java, being destroyed by marine erosion, which has developed as a sequel to the diversion of the mouth of the river that formerly supplied sediment to prograde this sector. Similar erosion is likely to occur on low-lying coasts as the result of the sea level rise expected during the next century. Photo: Eric Bird

probably try to hold the coastline along the banks of the Tuang Canal. As submergence proceeds, some of the existing rice fields will probably then be converted into brackish-water fish ponds, and a new canal will have to be built inland to maintain freshwater irrigation of surviving rice fields.

There seems little chance that funds will be available for the construction of sea walls of Dutch dimensions necessary to prevent submergence and erosion of such low-lying coastlines; instead, it is likely that some coastal people will develop mariculture more intensively, and thus make greater use of the submerging terrain and shallow nearshore areas. There will be problems of sea tenure over the submerging lands (Ruddle and Johannes 1985).

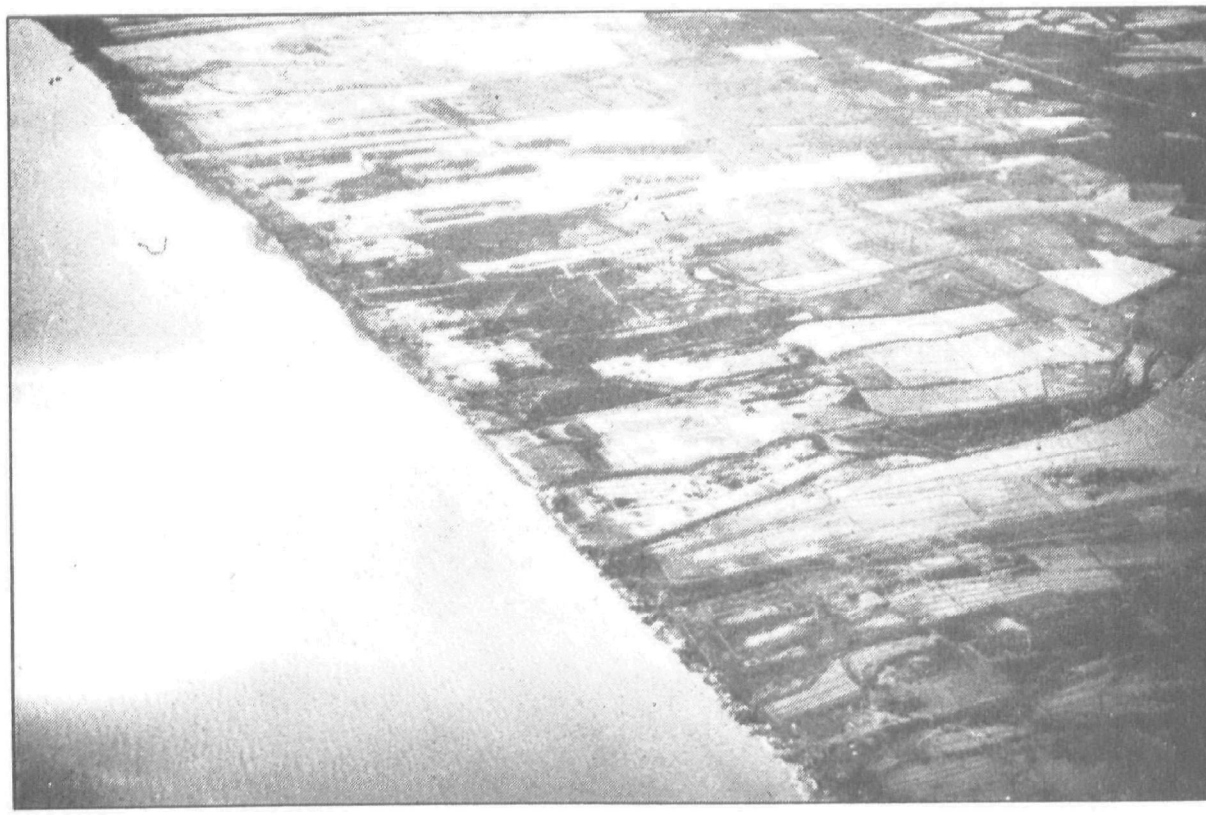

Figure 6. Coastal plain behind the Bight of Bangkok, Thailand, showing fish ponds and some uncleared mangrove remnants behind a narrow mangrove fringe. Photo: Eric Bird

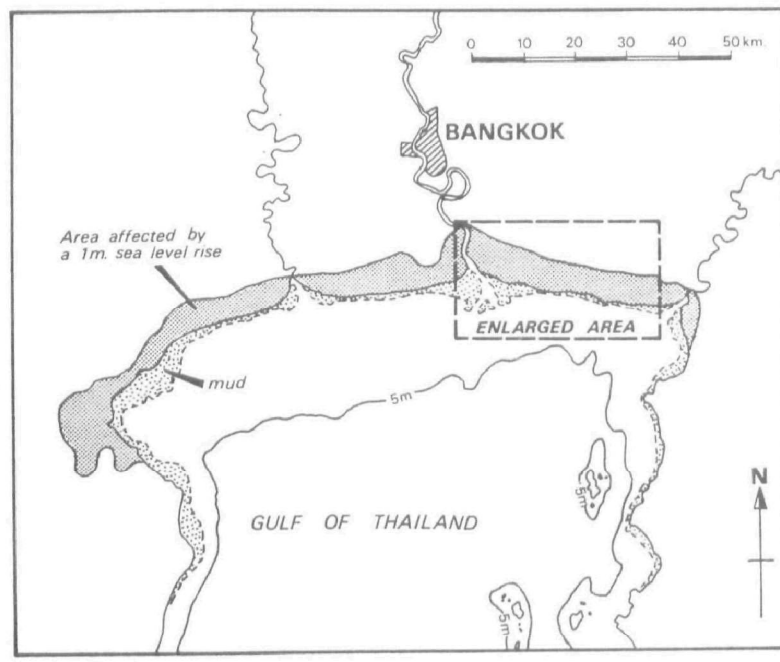

Figure 7. Probable extent of submergence on the low-lying coast at the head of the Gulf of Thailand if sea level rises 1 m (3.3 ft).

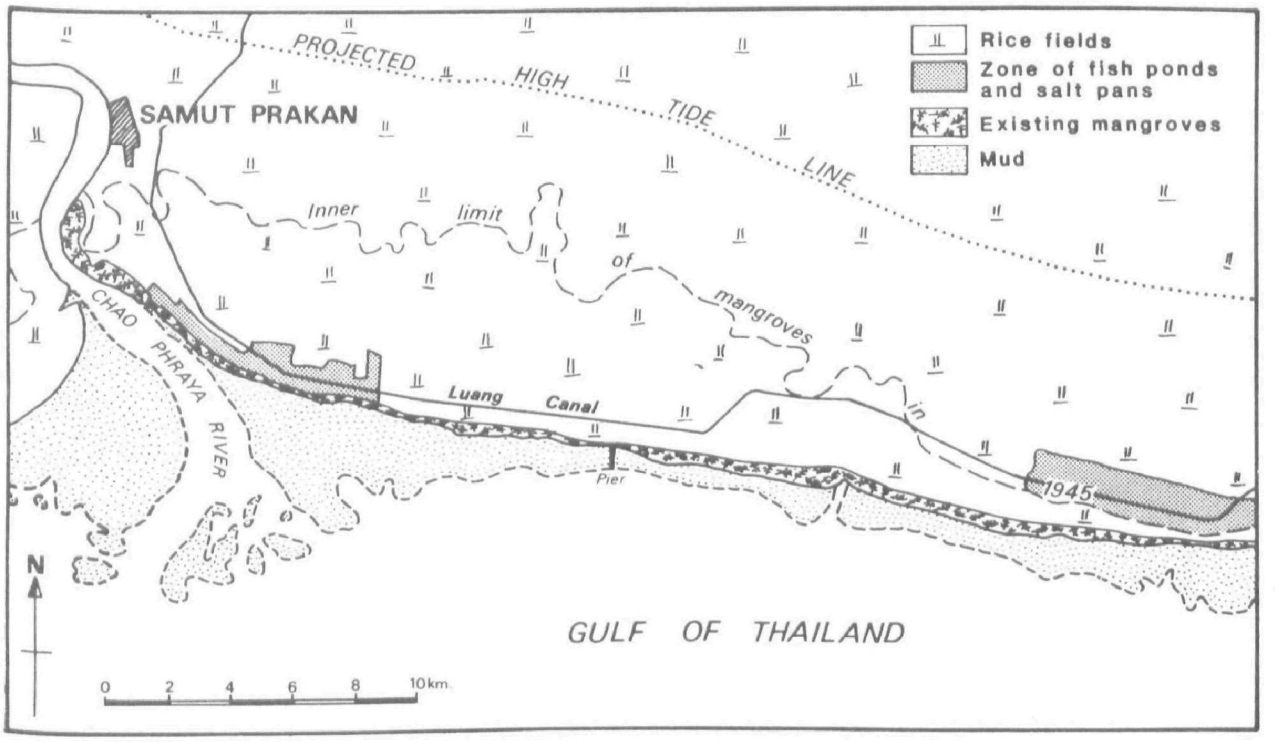

Figure 8. Part of the low-lying coastline south of Bangkok, Thailand, showing the natural coastline in 1945 (inner limit of mangroves), the present features (including areas reclaimed for fish ponds and rice cultivation), and the predicted coastline after a sea level rise of one meter, assuming no countermeasures are taken.

CONCLUSION

The effects of a sea level rise can be deduced theoretically, or inferred from studies of coastlines where submergence is already in progress, as in southeast England (e.g., the Thames estuary), the Netherlands (e.g., the Rhine Delta), northeast Italy (e.g., Venice and Ravenna), parts of the Gulf coast of the United States (e.g., Galveston), and Taipei, Taiwan. Alternatively, some of the effects may be deduced from studies of retreating coastlines where the recession is due partly or wholly to factors other than active submergence, as on parts of the deltaic coastline of northern Java. There is a need for site-specific predictive studies of the physical and ecological consequences of a sea level rise on various types of coastline, especially those that are low-lying, densely populated, and intensively utilized.

The human response to sea level rise may be countermeasures (where resources and technology are capable) evacuation, and adaptation to the changing coastal environment. With the prospect of a continuing sea level rise, some countries may decide to enclose and reclaim embayments, such as Port Phillip Bay (Figure 9) and Botany Bay in Australia, and Tokyo Bay and parts of the Inland Sea in Japan, on the grounds that the cost of protecting a shortened, artificial coastline can be justified by increased economic yields from the land gained. But on the coasts of less-developed countries, the most likely outcome is an intensification of use and occupance of nearshore sea areas.

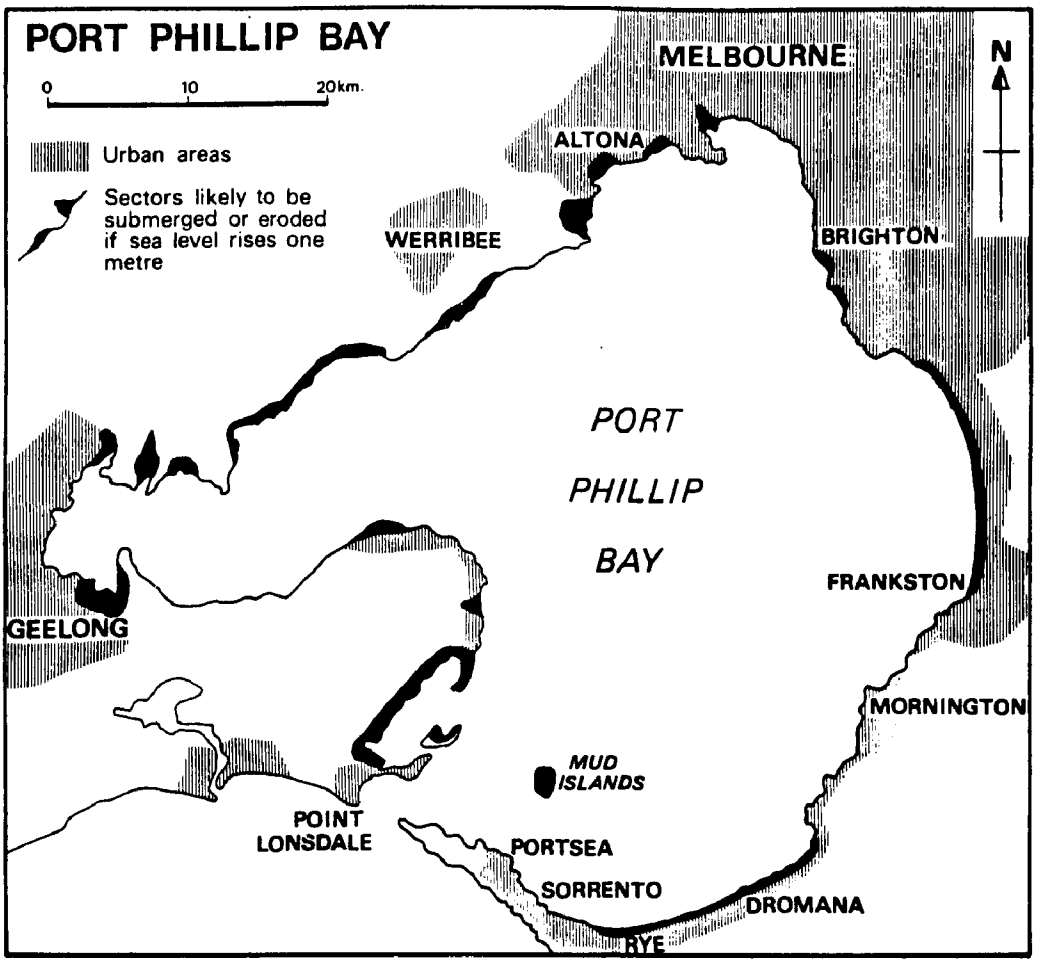

Figure 9. Port Phillip Bay, southeastern Australia, showing sectors likely to be submerged or eroded if sea level rises 1 m (3.3 ft). If the sea continues to rise, a possible response would be to build a dam across the outlet at Point Lonsdale, with canals to the ports of Melbourne and Greelong, and to reclaim the rest of the bay in the manner of the Dutch polders.

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Worldwide Impact of Sea Level Rise on Shorelines

Per Bruun
Chairman (Ret) Technical University of Norway
Hilton Head, South Carolina USA

INTRODUCTION

Sea level is rising around the world. As Hansen (Volume 1) and others point out, anthropogenic emissions may result in a climatic warming through the next few centuries, which could overcompensate the natural cooling that might otherwise be expected. As Thomas (this volume) notes, the warming might be a threat to the continued existence of the Greenland and the West Antarctic ice sheets.

This paper discusses evidence from tidal gauges and archeology that sea level has been rising in the past centuries. Next, it describes methods for assessing erosion caused by sea level rise. It then describes how people have held back the sea in the past, focusing on the low countries of Europe. Finally, it describes the options available to society for responding to shoreline changes resulting from projected sea level rise.

HISTORIC EVIDENCES OF SEA LEVEL RISE

Tide level recordings tell us of sea level movements over the last 200 years. For longer-term developments, we must seek the evidence of such rises in, for example, increased flooding of low coastal areas, drowning of valleys and shore features, including some ancient manmade features, and density currents penetrating further upstream. The findings are not always easy to interpret. Tectonic movements, glacial rebounds, consolidation of softer materials in the ground and re-balancing of land masses due to offshore sedimentation have interfered with the relative movement of land and sea. The many authors who have written about above-mentioned phenomena come from a variety of disciplines, including geology, geography, engineering, and archeology, to name a few. Other evidence of sea level rise comes from historic records of past construction activities.

Recordings of the events were solely descriptive rather than by instruments, although surveys have been made to state the actual situation. An impressive geophysical review was given by Fairbridge (1961) who referred to works by Marmar (1948), Stommel (1960), and Guilcher (1958). Others include Milliman and Emery (1968) and Emery (1980).

Important reviews of tide level fluctuation are given by U.S. Dept. of Commerce (1983) for the United States' shores. The recent contribution by Barth and Titus (1984) was the first to examine future conditions.

The following text presents a few examples of these reviews, some of them tracked down by the author and not known before (see Bruun 1985).

Early Harbor Works

The Port of Alexandria in Egypt was founded by Alexander the Great, who destroyed the ports at Tyre and Sidon. Alexander built the port by connecting through reclamation the island of Pharos (the scene, centuries earlier, of the great harbor works, which had by then mostly disappeared) with the mainland. This formed two harbors protected by the island, in which basins were formed by the construction of walls in the form (on plan) of semicircles, the northeastern basin having an outer mole protecting the single central entrance channel. This was a form of layout that was later adopted by both Greeks and Romans.

The first mention of a lighthouse for the benefit of shipping is that built upon a rock off the northeast of the island of Pharos. This lighthouse appears to have been of considerable height and was circular in plan, tapering to the top.

Of the Greek ports, perhaps the most interesting are those of Piraeus, Zea and Munychia, Phodes, and Cnidus. All these were natural bays protected on the seaward sides by moles or breakwaters. In the Mediterranean, where there is practically no rise or fall in water level--and the earlier Greeks had apparently not evolved any means of drying out the sites by cofferdams--these structures were all founded upon beds of tipped impervious material, which were built up until they reached the surface or thereabouts, when they were leveled to receive the masonry that formed the superstructures.

The period of the Roman Empire provides considerably more information in regard to the construction of many harbors that were built on the coasts of Italy and Sicily, both from the accounts written by historians and from remains of the actual works. These works were much more substantial than anything previously existing, both in design and in the means and methods of construction employed. For example, in Italy, as distinct from Greece, natural bays that could readily be formed into harbors were scarce, and the character of the works was therefore somewhat different. Moreover, Roman cement was in general use, which contributed not a little to stability and lasting qualities; again, methods of constructing underwater works were evolved, many of which were founded on piles driven into the sea-bed, for all Roman moles and breakwaters were constructed of masonry founded at sea-bed level. Many moles were of arched formation, probably to avoid the siltation that in some places would be induced by solid walls; and to reduce foundation work and masonry in exposed situations, double arcades were formed some

distance apart, with the arches staggered to break the force of waves but still allow the passage of water. Cellae-covered recesses for ships of war, which protected the vessels from the sun and inclement weather, were a feature of many Roman ports, but vessels used for purely commercial purposes were berthed at marginal quays or moles.

For all these ancient ports, the piers and wharves today are covered by 2-3 meters of water. However, because the structures have deteriorated, this does not provide quantitatively firm figures for the amount of sea level rise occurring in the last 1,500-3,000 years.

Viking Ports

We know little about port development during the centuries following the downfall of the Roman Empire. Sea voyages and trade undoubtedly continued. Ports were river based; quays or piers hardly existed or were uncommon. The big seafarers for several centuries were the Vikings, whose large fleets enabled them to invade England, France, Ireland, Spain, and the Baltic countries all the way down to Constantinople (Istanbul). Next they crossed the Atlantic Ocean to Iceland, Greenland, and Vineland (North America). We know about their powers from historic accounts of what they accomplished. But navies require naval bases for operation. We have found them during recent decades of excavations.

From archeological discoveries in Denmark and in the southern part of Sweden we know that the Vikings built large forts at rivers and in fiords. Their vessels were probably moored, or they may have been beached, but we have also found large pile walls, for example, at Hedeby, South Jutland, demonstrating that their vessels, whether built for commerce or for war, used piers for loading or unloading. Sometimes they also built large submerged walls or dams from sunken ships, or from piles across a navigation channel to stop enemies from penetrating into their harbors. A magnificent example of the latter is in Roskilde Fiord on the Island of Zealand in Denmark.

The remains of these 1,000- to 1,500-year-old Viking structures do not provide direct data on elevations, but some of them were built in a way that indicates that the water table must have been lower than it is today. The conclusion of the Danish National Museum regarding water tables is that sea level about 1,000 years ago must have been 1 to 1.5 m below present sea level.

Sedimentalogical Evidence

Coastal geomorphologists observe the elevation of beach ridges and strandlines. In emerged condition they provide evidence of a higher sea level (e.g., as may be seen in Denmark where strandlines are found in up to about 60 to 70 meters elevation) generated by the postglacial arctic waters. After melting of the ice cap, the ground experienced a rebound effect, which was much faster than the sea level rise. That this situation still continues was revealed by Svante Arhenius' famous drilling of holes in vertical rock walls on the Swedish west coast outside Gothenburg. The holes were drilled in 1890 and are now found about 0.6 m above present mean sea level (MSL). (Svante Arhenius is also known for coining the term "greenhouse effect.")

On the Skagen Spit, the northernmost tip of Jutland, the elevation of old beach ridges elevated by the glacial rebound decreases to the north as deposits get younger. One of these changes in elevation occurs rather abruptly, revealing a slowdown in the relative movement of land and sea about 2,500 years ago, demonstrating a rise in sea level elsewhere.

Two examples of sedimentation provide indirect confirmation of the mechanics of the sea/land interaction process. At Penang, West Malaysia, rivers discharge known quantities of sediments on the estuary bottom. If the area of the estuary bottom (↓500 km^2) is multiplied by a sea level rise of 0.002 m/yr one arrives at 1 million m^3, which corresponds to the annual river discharge of sediments. This is consistent with the observation that water depths have not changed in the last 200 years.

The situation on the 140-km pocket shore on the South Coast of Iceland between Porlakshofn and Dyrholaey is described by Bruun (1986). The discharge of river sediments of sand size is 4.5 million m^3/year. This quantity is balanced by deposits of 0.0035 m/yr (which corresponds to the recorded sea level rise in the Port of Reykjavik) on the 140-km long, 9,000-m wide platform, of which 2,000 m is beach area, extending to a 50-m to 60-m depth where there is a steepening of the offshore bottom leaving the impression of a deposit boundary slope. Grain size distributions confirm the existence of an equilibrium condition. A forth horizontal rock platform is found at a 100-m depth, possibly an abrasion platform from a lower sea level during an extended glacial period.

Tidal Gauges

As described by Hicks (1985):

> Tidal datums are the fundamental base from which most coastal and marine boundaries are determined. They are also the fundamental references for sounding and depiction of the shoreline on all nautical charts. As such, they are intrinsic to the activities of coastal engineering, surveying, hydrography, and photogrammetry. The most important tidal datums are defined, amplified, and their specific uses listed in abbreviated outline form. The definitions are in terms of the procedures used in their computation.
>
> As "tide authority" (in the international and legal sense) of the United States of America, the National Ocean Service (NOS) of the National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Commerce, has statutory responsibility for tidal measurements, analyses, predictions, and datum determinations. Responsibility for tidal datums included the development and any subsequent modifications of the methods of computation.
>
> The method used for the computation of a tidal datum is specified in the official definition of that datum. The purposes of these "method definitions" are to:
>
> - Ensure uniformity of computation among oceanographers

- Ensure uniformity of computation among the various tidal regimes of the U.S.

- Provide for comparisons with foreign datums

- Enable outside scientific verification of results through duplication

- provide precise terminology for judicial and legislative acceptance in cases involving coastal and marine boundaries.

Hicks gives twelve references of recordings of sea levels. Tide level recordings, however, have been undertaken on a larger scale for some decades only. Exceptions are the Dutch and British recordings, which date back a few centuries; however, the accuracy of those tidal observations is questionable. In Holland, the influence of sea level rise is reinforced by subsidence due to the soft underground caused by the large Rhine, Maas, and Scheldt rivers.

In the United States the trend of relative sea level rise is fairly well documented by surveys on all shores (Hicks 1980; Lisle 1982; U.S. Dept. of Commerce 1983; Nummedal 1983, for the Louisiana Coast, are among the most important contributions). Sea level rise during the latest decades ranges from 1 to 4 mm/yr depending upon the location. The subsidence in Louisiana is about 10 mm/yr. On the East Coast the rise is 2-3.5 mm/yr, on the Gulf, 2-3 mm/yr, and on the Pacific, about 2 mm/yr. Rises for east and west coasts of Canada are similar. Germany has kept good records of the rises on the North Sea coast (Siefert 1984), as may be seen from Table 1. The conclusion of the Siefert paper reads as follows:

> The knowledge of the probable development of the water level on the German North Sea coast--in general on all flat coasts --is of greatest importance for coastal engineering. In Germany an increase of MThw (mean high water) of 25 cm per century has been taken as a basis for dimensioning of coastal protection constructions (e.g. dikes or storm surge barrages). If instead one had to reckon with a rise of MThw of 2 m or more in the next 100 years and with at least the same increase of the storm surge levels, all coastal protection works would be ineffective. It is doubtful that an elevation of the dikes for such a water level rise would be possible everywhere. As one can conclude from the development of MThw at all locations on the German North Sea coast for the last 400 years in connection with the development of temperature in Central England, an increase of 2 m or more would be thinkable in the case of an increase of the temperature of about 4°C. The increase of temperature is assumed to be 1°C since the culminating-point of the "Little Ice Age". In the same period MThw rose about 1 m.
>
> Therefore it is necessary to intensify investigations in order to predict the probable development of the global sea level as well as that of certain coastal sections for the

next 100 years as exactly as possible. Three routes of research are deemed necessary:

1) One has to analyze all the factors responsible for the development of water level in the ocean and on the coasts as exactly as possible. This demands an extensive and close co-operation of the different scientific disciplines of climatology, meteorology, oceanology, glaciology, geodesy and coastal engineering. This co-operation has to be international. Coastal engineers should contact such projects as the International Climate Research Program and the Project No. 200 of the International Geological Correlation Program (Sea-Level Correlation and Applications). The results of these projects are of greatest practical importance for coastal engineering.

Table 1. Trends in Sea Level Along the German North Sea Coast

		Mean High Water		Mean Low Water	
		till 1955	1873-1955	1956-1983	1956-1983
		1	2	2	4
Emden	(1857)	0.25	0.23	0.54	-0.33
Wilhelmshaven	(1873)	0.23	0.23	0.37	-0.15
Cuxhaven	(1843)	0.25	0.24	0.51	-0.21
Busum	(1871)	0.22	0.21	0.62	-0.25
Husum	(1870)	0.30	0.28	0.63	-0.09
Dagebull	(1873)	0.28	0.28	0.65	-0.32

Slope "b" of the regression lines y = a + bx of mean high water in three different periods and of mean low water in the last period.

From these figures it appears that high tides apparently have risen from 2 to 6 mm/yr, while low tides have dropped 1-3 mm/yr; therefore, tidal ranges have increased. The large differences occur during the 1956-1983 period when the means of high and low tide levels have increased 2-5 mm/yr.

In Denmark the rebound from the glacial period was believed to dominate until recently. The latest decades, however, show that relative sea level is rising in the entire country, being highest (1-2 mm/yr) in the southwest part, but close to 0 at the northernmost part of Jutland. At the tip of Jutland, the Skagen Spit, the apparent 3-mm rise may be related to the consolidation of thick layers of silt upon which the spit grew out by littoral drift deposits in water depths of about 200 m in "the Norwegian trench."

In Norway it appears that the Oslo fiord area of granite and old lavas may still be rising in comparison with sea level. The rest of the Norwegian coast up to North Cape seems to be in a neutral situation, but at some places sea level is slightly rising compared to land despite the fact that glaciers were roaming here only about 10,000 years ago. Movements range from a 1-2

mm/yr sea level rise in the northern part to a 3-4 mm/yr land level rise (compared to sea level) in the Oslo fiord areas.

In Sweden, glacial rebound is still very predominant, as shown in Figure 1. The southern shore of Sweden, however, now experiences a sea level rise. The situation in Iceland is described by the already-mentioned recordings in Reykjavik, which show a rise of 3.5 mm/yr.

In Holland and Belgium, sea level is rising 2-3 mm/yr (Table 2). The general situation in northwest Europe is seen in Figure 1. The glacial rebound in Fenno-Scandinavia is still active, but not along most of the shores.

Table 2. Average Rate of Rise of Relative Mean Sea Level (MSL), and Mean High Water Level (HW), Mean Low Water Level (LW) and Mean Tidal Difference (TD) in cm per Century in Holland and Belgium

Station	MSL	HW	LW	TD	period used
Oostende		17	5	12	1925-1980
Flushing	22	33	19	13	1900-1980
Terneuzen		40	18	22	1900-1980
Hansweert		40	10	30	1900-1980
Bath		44	16	28	1900-1980
Zierikzee	17	26	5	21	1900-1980
Hook of Holland	19	22	16	6	1900-1980
IJmuiden	21	24	18	6	1900-1980
Den Helder	16	15	7	8	1933-1980
Harlingen	16	27	10	17	1933-1980
Delfzijl	16	21	7	14	1900-1900

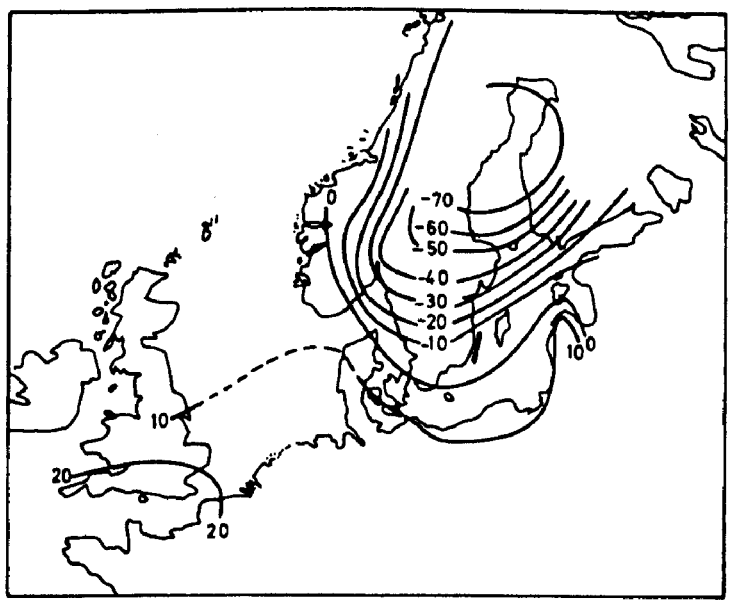


Figure 1. Changes in Relation to Sea Level (cm per year)

It has not been possible to secure data from the USSR. In Japan, sea level has been observed (e.g., in the Osaka Bay) and is of the order of magnitude of 2 mm/yr. On the Northern Island, settling takes place to a considerable extent due to the extraction of gas and water. In China the rise in sea level has been noticed mainly because of the increasing problems of saltwater intrusion in the rivers.

In summary, sea level is rising worldwide at a rate of from 2 to 4 mm annually in the areas we have discussed. However, it appears to be stable in a number of places, such as in the vicinity of coral reefs in the Pacific and Australia. As a result, most authors estimate the eustatic rate of rise at 1 to 1.5 mm/yr. There is some indication of an increase in the rise, but the evidence is not too clear at this point.

THE IMPACT OF SEA LEVEL RISE ON SHORELINES

Erosion

It has long been known that high tides, particularly storm tides, can be very destructive. The influence of the eustatic rise of sea level on shore stability was "rediscovered" in the early 1960s.

The Bruun Rule of erosion (Bruun 1962), so named by American coastal geomorphologists (Schwartz 1967, 1968, 1980), concerns a long-term budget of onshore/offshore movement of material. The rule is based on the assumption of a closed material balance system between (1) the beach and nearshore and (2) the offshore bottom profile. This topic is dealt with extensively in theory (Hallermeier 1972; Allison 1980; Bruun 1980) and through observations in the field (Bruun 1954a,b, 1962, 1980; Dubois 1976; Fisher 1980; Hands 1980). The "rule" has sometimes been used rather indiscriminately without realizing its limitations. One should always remember that it is basically two-dimensional, but it is almost always applied three-dimensionally.

The theory has now been tested extensively in the field (e.g., by Schwartz 1967; DuBois 1976; Fisher 1980; Hands 1980; and others). Its overall validity seems unquestionable when boundary conditions are well defined, but this is not always the case. Its mathematics has been proven for two-dimensional conditions (Allison 1980, 1981). The difficulty lies in clear definitions of boundaries in relation to the composition of the materials of which the shores are built up, usually sand particles decreasing in size as distance offshore increases, until silt- and perhaps clay-sized particles finally prevail. Such fine materials may originate from erosion of the shore, but may also originate from rivers or from deserts and volcanoes as windblown dust (Bruun 1980; Hands 1980).

As explained above, the theory of the influence of sea level rise on erosion is proposed as being two-dimensional, but nature is three-dimensional. This in turn means that in practice one must consider a certain uninterrupted length offshore, when the material transport is contained in a "box", xyz, where x is the distance offshore from a defined point on the shoreline, y, the length of the box along the shore, and z, the depth from a defined water table. The numerical material balance in and out of two x-z sections y meters apart is initially assumed to be zero. If there is no balance between the two quantities, this must be considered in the total material balance equations. There are two boundary y-z sections, one located

on the beach or in the dunes, the other at a certain water depth, which separates the "nearshore drift" from the "offshore drift" in the x-direction. On the beach, the effect of wind-drift may then have to be added. It is usually negligible, but it may in some cases present a non-negligible quantity. The outer y-z boundary is more difficult to define, because there is no clear distinction between the limit of exchange between beach and offshore drifts of material. In practice these limits are "fading-out."

Often the term "wave base" is used for material agitation on the bottom. Recent research by Hands (1980) and Hallermeier (1972) attempts to present rational methods for calculation of the limits of active agitation of the sand bottom and the long-term erosion rates based on long-term rises of sea level. The short-term "seasonal" limit may be close to depth 2Hb, where Hb is the height of the highest breaking waves. The "wave base" is thereby related to the capacity or limit of the wave action in agitating the bottom material "actively," which in a statistical sense depends upon the time interval considered (Hallermeier 1972). A "five-year wave base" obviously may not be the same as a "fifty-year base."

In addition to this, there is the problem of diffusion of material along the bottom and other boundary layer phenomena (Bruun 1980). The original theory (Bruun 1962), however, is based on a quantitative two-dimensional balance between the beach and the nearshore and offshore bottom and there will be a certain transition area between "nearshore" and "offshore" adjustments to a change in sea level. If the physical forces do not change in the nearshore area, the equilibrium-balance condition apparently will be maintained. But the situation may be different in the offshore area, where forces and supplies of materials are very different from those governing the nearshore area. No equilibrium balance situation needs to exist in the offshore area, where currents are offshore-originated. Bottom sediments in movement are clay and silt, occasionally fine sand where currents are strong enough to carry the material. Current-generated ripple marks have been found at very great depths (e.g., at 5,000 ft (1,500 m) on the Blake Plateau), which include indications of scour due to current movement over shells.

Depending upon the grain size, the "base" may extend to shallower or deeper water. This refers to open sea coasts, where sediments of silt and clay size may be carried long distances in suspension before being deposited. In defining the area of exchange between nearshore and offshore drifts, one therefore has to consider the grain sizes and materials of certain characteristics available on the shore. The finest parts of this material, which may stay in suspension for long periods, therefore have to be included in the materials balance equations. This refers to a certain depth beyond which fines may still be transported to much deeper water for deposition (Bruun 1980; Hands 1980).

The ultimate limit for movement characterized by threshold velocities is discussed by Bruun (1985, 1986) based on research by Losada and Desire (1985). The results from Iceland mentioned by Bruun (1986) point in the direction of ultimate depth

$$d_1 \approx 3.5 \text{ Hs}$$

where Hs then refers to wave heights occurring once, or over a certain number of hours, every 1, 10, 20, 50, 100, and 500 years.

Bruun (1962, 1983) points out that his two-dimensional theory depends upon a "closing depth" for exchange of material between the offshore bottom and the shore. It must also be adjusted for grain sizes that will eventually wind up far offshore due to their small size and consequent slow settling velocities (i.e., silts and clays). For three-dimensional applications, major adjustments may become necessary, particularly when features like tidal inlets, canyons, and other "sinks" of materials enter the balance picture. The report by Titus et al. (1985) on the erosion at Ocean City, Maryland, is remarkable because it emphasizes the great importance of sea level rise on a long unabstructural shore.

A quantification of erosion caused by the rise in sea level is attempted by Bruun and Schartz (1985). Sea level rise may contribute from 10% to 100% to the total erosion or from 1 to 6 m^3/m yr. If erosion is not caused by natural or artificial inlets, breakwaters, groins, or sea walls, the sea level rise is the only explanation for the occurring erosion. Figures 2-5 are examples of erosion where sea level rise has been the major contributor. Examples were taken from Queensland in Australia, Dajeng Bay in northeast China, Kerala in southwest India, and Kamchatka in the USSR. Shoreline recessions are of the order of 0.3 m/yr. If sea level rises 1.5 m by the year 2100, shoreline recession will be about 150 meters. For the lower bay lagoon, estuary, and other tidelands such development may approach the catastrophic. Huge areas in Bangladesh, Brazil, China, Egypt, Iraq, Iran, India, Lagos, Nigeria, and areas on the U.S. East and Gulf coasts will be flooded.

Erosion of shores is a worldwide phenomenon. Shores always attempt to adjust their condition to the impact of the acting forces, thereby establishing an "equilibrium condition." But why do they then <u>continue to erode</u>? There is no other explanation than that sea level is rising.

The author has observed erosion in many countries all over the world. Table 3 gives a record of his experiences, listing six different reasons for erosion, three "natural" and three "man-induced." Sea level rise is listed as a reason in all cases, either because no other reason could be given for the erosion of uninterrupted shorelines of extended length or that sea level was known to be rising and consequently erosion must result.

Another "natural" reason is subsidence caused by the consolidation of soft materials, such as that which occurs in Holland; the Po-estuary in Italy; part of India; Louisiana, USA; and elsewhere. Subsidence could, however, also be caused by the extraction of oil and/or gas as it occurs in Japan (Hokaido) and California (Long Beach). Some areas may experience large- or small-scale tectonic movements related to fault lines.

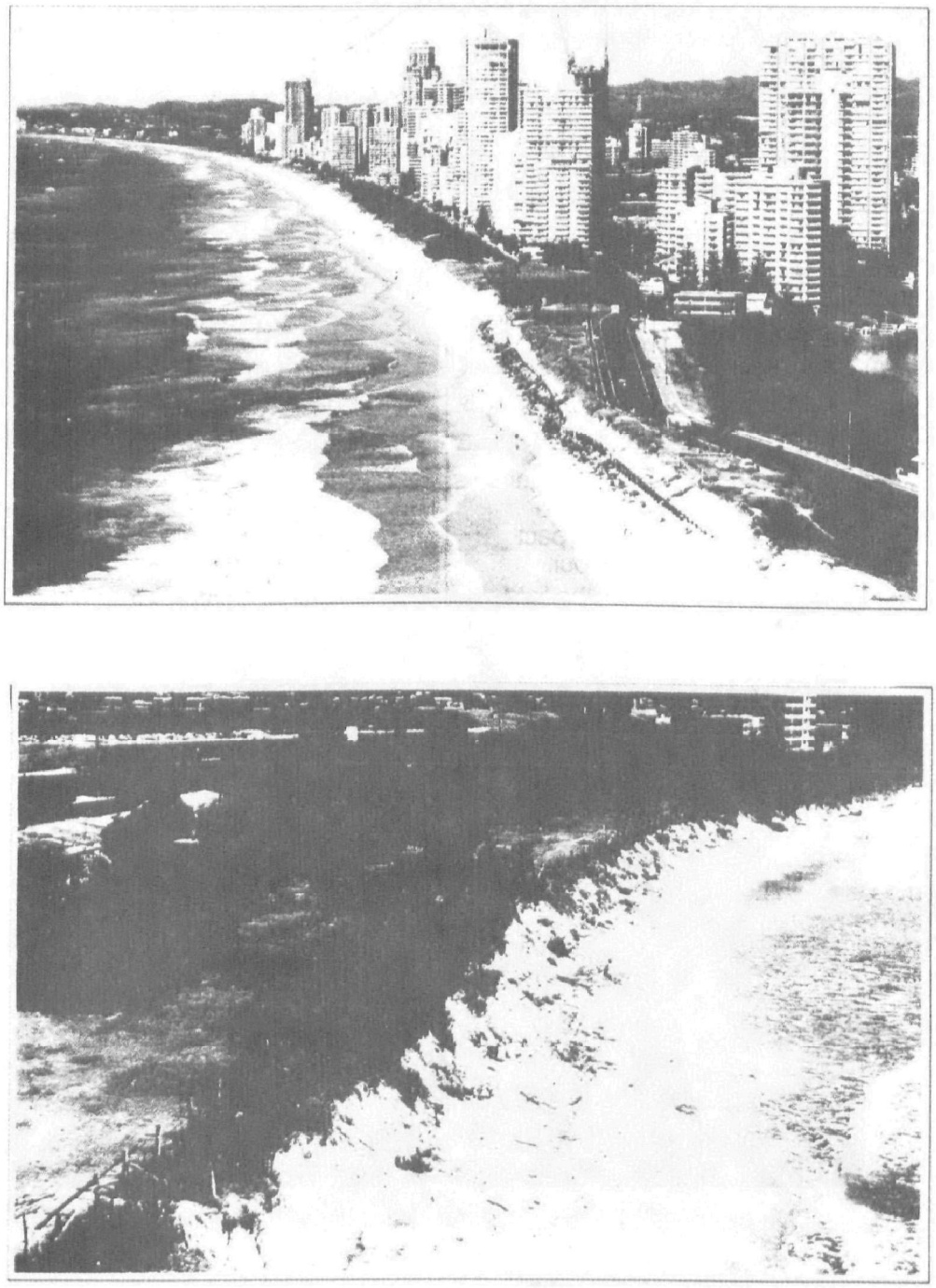


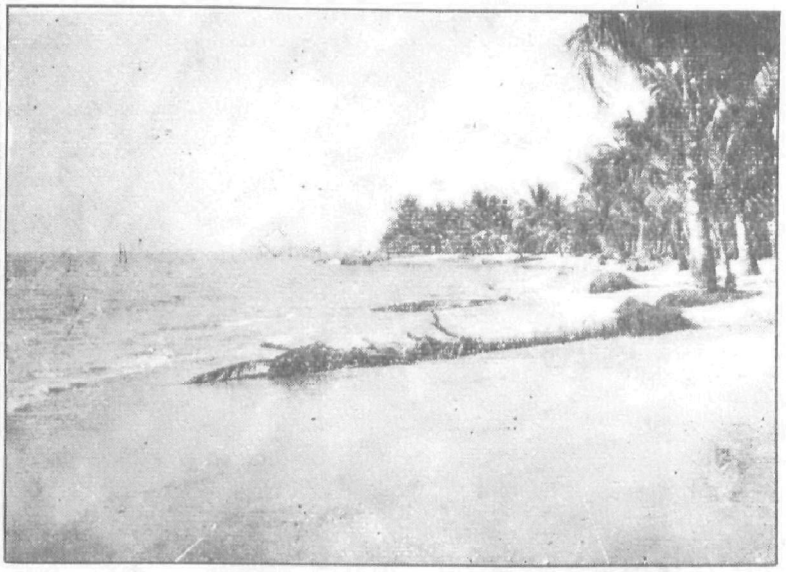
Figure 2. Erosion in Queensland, Gold Coast, Australia (1985)

Figure 3. Erosion at Dajeng Bay, China
Courtesy: Tinjang University (1984)

(a) Photograph showing beach erosion at Punnapra, Kerala during the Monsoon of 1967.

(b) Photograph showing how the coconut trees were being uprooted at Punnapra, Kerala due to beach erosion (1967).

(c) Photograph showing erosion problem at a beach at Trivandrum, Kerala during the Monsoon of 1976.



(d) Photograph showing the uprooted coconut trees at Vypeen, Kerala due to the terminal effect of a seawall.

Figure 4. Erosion on the Southeast Coast of India, Kerala State
Source: NIO, GOA, 1983

Figure 5. Erosion in the USSR, Kamsjatka (1962)

Table 3. Overview of Causes of Erosion Worldwide

Country	NATURAL			MAN-INDUCED		
	Sea Level Rise	Sub-sidence	Tidal Inlets	Navig. Channels	Man-made Structures	Mining
Algeria	x			x	x	
Argentina	x		x	x	x	
Australia	x		x	x		
Belgia	x		x	x	x	
Brazil	x		x	x	x	
Canada	x			x	x	
China	x	x		x	x	
Columbia	x		x	x		
Denmark	x		x	x	x	
Ecuador	x		x	x	x	
Egypt	x	x	x	x	x	
France	x		x	x	x	
Holland	x	x	x	x	x	
Iceland	x		x			
Ireland	x			x	x	
India	x	x	x	x	x	x
Iran	x		x	x		
Israel	x			x	x	
Italy	x	x	x	x	x	
Japan	x	x	x	x	x	
Lebanon	x			x	x	
Malaysia	x			x	x	x
Mexico	x		x	x	x	
Nigeria	x		x	x	x	
New Zealand	x		x		x	
Nicaragua	x		x	x		
Norway	x					
Pakistan	x		x	x		
Portugal	x		x	x	x	
Saudi Arabia	x			x	x	
Spain	x		x	x	x	
Sweden	x	anti		x	x	
Sri Lanka	x		x	x	x	
Tripoli	x			x	x	
Turkey	x			x	x	
UK	x		x	x	x	
USA	x	(x)	x	x	x	
USSR	x		x	x	x	
Venezuela	x		x	x	x	
West Germany	x	x	x	x	x	
Σ 40	40	7	28	37	33	2

The following are other causes of erosion:

- Tidal entrances interrupt the normal littoral longshore drift causing erosion because they discharge shore material in the bay and/or in the ocean. Tidal entrances accounted for 28 out of 40 cases in the 40 countries where erosion was observed by the author; some of these cases were very severe (Bruun 1978).

- Navigation channels, like the tidal entrances upon which they were often based, constitute littoral barriers to the normal drift by accumulating materials that otherwise would drift to downdrift shores thereby contributing to their stability.

- Manmade structures such as breakwaters, jetties, groins, and other shore-perpendicular structures are also barriers to the longshore drift and have also caused severe damages to downdrift shores. It can safely be said that the coastal protective groins have caused more erosion than accretion. According to the author's experience, manmade structures (listed in Table 3) are second only to sea level rise and head of natural tidal inlets as causes of erosion.

- Mining for heavy minerals has caused damages in several countries until the adverse effects were observed. Mining also includes extruction of sand, gravel, and stones. Such operations are now largely prohibited, but they still occur in countries where the problems they cause have not yet been realized.

Short-term erosion events of a severe or extreme nature usually catch the eye of the public. To evaluate occurrences of rapid dune erosion due to storm tides, like hurricanes and typhoons, the large-scale experiments by Vellinga (1983), Vellinga and Bruun (1984), Vellinga et al. (1985) and van de Graaf (1986) are important for assessing events of an extreme nature for which preparedness is warranted.

In summary, erosion due to sea level rise is obvious. Compared to other reasons, particularly the manmade, it is less severe, but as it occurs almost everywhere, it undoubtedly counts for the largest part of erosion worldwide. It is therefore very unfortunate that we may expect (during the next several decades) an accelerated rise in sea level.

Shoreline Recession

Shoreline recession can be expected on the ocean shore as a result of sea level rise. The actual shoreline recession depends upon the exposure, the offshore profile-steepness, and the character of the material that builds up the shore and the offshore bottom.

One may get a general impression of the rate of shoreline recession by examining the following data which are representative of recession rates for exposed shores like those of the Atlantic, the Pacific, and the Indian Oceans.

Rise per year	Shoreline Recession per year	
1 cm	1-1.5 m	(4-5 ft)
2 cm	2-3.0 m	(7-10 ft)
3 cm	3-4.5 m	(10-15 ft)
10 cm	10-15.0 m	(33-50 ft)

These numbers represent the volume of material lost to the sea or the amount needed to maintain a status quo with respect to erosion. The figures speak for themselves, giving an impression of the severity of the problem we are now facing.

COASTAL PROTECTION IN THE LOW COUNTRIES IN EUROPE AND IN ENGLAND

Erosion is a deficit in the material balance: We lose more than we gain. HOW OLD IS THE ART OF COASTAL PROTECTION? We do not know; probably very old. Adam and Eve escaped from the gardens of Paradise located on the island of Ceylon following their blunder in an apple orchard. They crossed the waters on "Adams Bridge," which was not only a "bridge" (reef) but a coastal protection for a major part of the most southern southeast coast of India (Bruun 1973).

Coastal protective works of major order probably first came into existence when man was forced to protect the land on which he lived to avoid the waters digging away the ground under his feet.

Although a great many training and irrigation walls, dams, or dikes were built in the Far and Middle East, coastal protection per se probably first developed in the low countries in Europe where rivers poured soft materials, mainly clay and silt, out in the ocean for settling. Consolidation was a slow process which made the land settle. In addition sea level was rising. To avoid loss of land by flooding and to protect themselves from drowning, the Frisians and the Dutch first built earth mounds. Diking started about the year 1,000 A.D. In the 13th century, the Dutch had accomplished major coastal protection and reclamation works, particularly in the Dordrecht area.

Dr. van Veen in his book The Art of a Nation (1962) writes:

> The earliest written records about the Frisians (or Coastal Dutch) describe them as water-men and mud-workers. The Romans found in the North of the country the artificial hillocks upon which the inhabitants, already called "Frisii," made a living. We shall follow their history, because written records are available about the early reclamation works they made. One and the same race, now called the Dutch, took, held and made the low country.
>
> Pliny, who saw these mound-dwelling tribes in the year 47 A.D. described them as a poor people. He apparently exaggerated when he wrote that they had no cattle at all. Or did he see some much-exposed mounds near the outer shores where the sea had swallowed every bit of marshland? At stormtide, Pliny said, the Frisians resembled groups of miserable shipwrecked sailors, marooned on the top of their self-made mounds in the

midst of a waste of water. It was impossible to say whether the country belonged to the land or to the sea. "They try to warm their frozen bowels by burning mud, dug with their hands of the earth and dried to some extent in the wind more than in the sun, which one hardly ever sees.

No doubt the mud Pliny refers to was the peat which was found in the "wolds," or swamps, some distance south of the clay marshes, where the artificial mounds had been made. In all they built 1,260 of these mounds in the northeastern part of the Netherlands, an area of a mere 60 x 12 miles. Further East there are more of them in East Friesland. The areas of the mounds themselves vary from 5 to 40 acres; they rise sometimes to a height of 30 feet above normal sea level. The contents of a single mound may be up to a million yards.

They built their mounds on the shores of the creeks in which the tide ebbed and flowed. In their scows they went (in their language in which the roots of so many English words can be found): "uth mitha ebbe, up mitha flood," out with the ebb, up with the flood. The tide bore them towards the peat regions, or perhaps to the woods still farther inland and then brought them back. Or they went out with the ebb in the morning towards the sea, where they gathered their food, and returned in the evening with the incoming tide.

The Coastal Dutch have now lived 24 centuries in their marshes and of these the first 20 or 21 were spent in peril. It was not until 1600 or 1700 that some reasonable security from flooding was achieved. During these long treacherous centuries the artificial mounds made their survival possible.

It was a work which might be compared with the building of the pyramids. The pyramid of Cheops has a content of 3,500,000 cubic yards, that of Chephren 3,000,000 and that of Mycenium 400,000 cubic yards. The amount of clay carried into the mounds of the northeastern part of the Netherlands can be estimated at 100,000,000 cubic yards.

In Egypt it was a great and very powerful nation which built the pyramids throughout a series of dynasties. The aim was to glorify the Pharaohs. With us it was a struggling people, very small in number and often decimated, patiently lifting their race above the dangers of the sea, creating large monuments, not in stone, but in native clay.

In this Lex Frisionum of 802 there is not yet any mention of seawalls, but the first attempts at dike building must have been made shortly afterwards. Frisian manuscripts still extant, dating from the early Middle Ages, deal chiefly with the following three points: First, the right of the people to freedom, all of them, "the bern and the unbern." Secondly, the "wild Norsemen" whose invasions took place roughly from 800 to 1000, and thirdly: the Zeeburgh or Seawall.

> This novel means of defence against the sea by means of a continuous clay wall was called a Burgh, or stronghold. The people were apparently very proud of this seaburgh, because they described it in poetical language as "the Golden Hop," the Golden Hoop.
>
> ...This is also the Right of the Land to make and maintain a Golden Hoop that lies all around our country where the salt sea swells both by day and by night.

The spade, the hand barrow, and the fork were the instruments used for diking, the fork presumably for the grass turfs which were used to heighten the dikes and make them stronger. Despite the tremendous efforts the sea was the strongest.

> This was due partly to our insufficient technical skill and partly to lack of co-operation. For a single night, Dec. 14th 1287, the officials and priests estimated that 50,000 people had been drowned in the coastal district between Stavoren and the Ems. This is a large number considering that this was the area where so many dwelling mounds could be used as places of refuge.

The advances and successes have been tied to a few names. Says van Veen:

> We often wondered who was the master engineer who created marvellous Great Holland Polder, south of Dordrecht, the work which had included the damming off of the tidal mouth of the river Maas, and the leading of that river into the Rhine. This proved to be William I. He had already finished that gigantic undertaking by 1213. The polder was destroyed in 1421 by the St. Elisabeth's flood, described in a former chapter. William was a man of great conceptions. He surrounded the entire area of Holland-Proper with strong dikes and made several canals intended to drain the vast moors. They also served as a splendid network of shipping canals. It is likely that he made the dikes around the Zeeland islands Walcheren and Schouwen too, and that he established the still-existing administrations for the upkeep of these islands. The other part of his clever and amazing reclamation and construction programme cannot be described here, but it is very clear that he knew the geography of his county by heart. No maps as yet existed!

The earliest reference to the art of accelerating the natural rate of accretion is the manuscript "Tractaet van Dijckagie" (Treatise on Dikebuilding), written by the Dutch dikemaster Andries Vierlingh between 1576 and 1579. Vierlingh discusses the construction of "cross-dams" on mudflats which are not yet dry at low water. In this connection he also advises that old ships should be sunk and earth dumped on the top of them so as to make artificial islands or flats which should hold back the silt and sand suspended in the water. These islands should subsequently be connected with low dams. Although this method has not been used commonly, it is known that shipwrecks have been used at numerous places to close dike breaches. These wrecks formed the basis for the fill material which was secured with mats or brushwood.

Vierlingh, however, was much against closing of dike breaches with shipwrecks due to the non-homogenity they created in the dike structure. Nevertheless, this method was widely used over a long period of time, not only in Holland but in the (at that time Danish) Schleswig-Holstein.

Vierlingh was found to be a real master of the dikes and waters, a man of great ability and spirit - one of the greatest of his kind. Luckily the greater part of his manuscript has survived. Its ancient picturesque style is a joy to every hydraulic engineer. This remarkable book already shows the special vocabulary of the Dutch diking people in all its present-day richness. In some ways it is even richer.

His advice is simple and sound. The leading thought is: Water will not be compelled by any 'fortse' (force), or it will return that fortse onto you.

This is the principle of streamlines. Sudden changes in curves or cross-sections must be avoided. It is the law of action and reaction. And truly, this fundamental law of hydraulics must be thoroughly absorbed by any one who wants to be a master of tidal rivers.

Andries Vierlingh was a genius. If we had followed his advice on streamlining, we would have been better off today. His protection was the streamlined dike. It offered storm tide protection but not necessarily erosion protection unless the dike was provided with a hard surface. And even so, erosion might continue below or in front of the hard surface due to the combined action of waves and currents. To push the currents away, current breakers or groins were then introduced. The hard surface on the dike was a revetment with a gentle slope reflecting little wave energy, and so it still is in Holland, where vertical walls have long been banned. The groin worked well in certain areas, where currents and waves carried considerable material as they still do on some parts of the Dutch coast and in Denmark (Bruun 1984). If not, they were of little importance or only of value as a kind of toe protection for the dike. Experiences elsewhere are, of course, similar.

PLANNING FOR SEA LEVEL RISE ON THE OCEAN SHORES

We must accept that sea level in all probability is going to accelerate its rise. Consequently, the beach and bottom profiles must adjust to a new situation. As a result erosion will occur. Titus (1984) characterizes the issue as follows:

> Ocean beach resorts in the United States have always faced erosion and storm damage. At first, these risks were accepted as inevitable. Development was generally sparse, and people often built relatively inexpensive cottages along the ocean that they could afford to lose. When the occasional severe storm destroyed these houses and eroded the beach, replacement structures were frequently built farther inland to maintain the original distance from the shore.

After World War II, beaches became more popular and were developed more densely than before. The resulting increases in real estate values enabled greater numbers of communities to justify expensive engineering solutions to maintain their shorelines. Frequently subsidized by the federal government, the practice of stabilizing shorelines replaced the previous custom of accepting erosion as inevitable.

The projected rise in sea level poses a fundamental question: how long should these communities hold back the sea? In the decades ahead, the costs of shoreline protection will rise dramatically and the relative efficiencies of various measures will change. But without such efforts, a 1 ft rise would erode most shorelines over 100 ft, threatening recreational use of both beaches and adjacent houses. Even under the low scenario, this could happen by 2025.

Although sea level is not expected to rise rapidly until after 2000, resort communities may have to consider its consequences much sooner. After the next major storm, in particular, homeowners whose properties are destroyed will decide whether and how to rebuild; and local governments will decide whether or not to let all of them rebuild, and which options are appropriate to address the storm-induced erosion. How well a community ultimately adapts to sea level rise will depend largely on the direction it takes when it reaches this crossroads.

Quantification of erosion due to sea level rise is of course difficult as the rise-induced erosion is mixed with other agents of erosion. Bruun and Schwartz (1985) made an attempt and show that beach erosion due to sea level rise may amount to about 15%-20% of the total erosion occurring on heavily eroding shores. The above-mentioned report by Titus et al. (1985) (for Ocean City, MD), however, demonstrates that sea level rise could become the major part of the erosion on extended shores far from tidal inlets or other "sinks." See also Everts (1985) and Bruun (1986c).

Beach Nourishment

Bruun (1973) after having stated that future coastal protection must include beach restoration and maintenance as well as storm tide protection by dunes or revetted dunes stated the following:

> In future coastal protection one must think large. It will therefore develop as a function of the combined political, administrative and technical structure. There will be little or no use for "one-man shows." Large groups and large areas will have to be accomodated - by large scale measures. Needs will be concentrated on protective and recreational projects and all combinations thereof. Pressure will increase by the need for recreational beaches. Protection will be achieved simultaneously. The question of which protective measure will be most practical under such circumstances may be answered by just looking at Tables 5-10 which clearly demonstrate that artificial nourishment with suitable material offers the best large-scale

protection. This, however, does not mean that it always suffices. It may need support from dikes and/or sea walls because of the possibility of storm surges or it may need groins to break scouring currents running close to shore. One main technical advantage associated with artificial nourishment is that it is "smooth" and "streamlined" and therefore not only has no adverse leeside effects, but, on the contrary, benefits adjoining shores by a gradual release of material. Other measures, particularly groins and offshore breakwaters, have definite adverse effects on neighbouring shores. The importance of streamlining is obvious.

What shall we then do? We shall improve our artificial nourishment technology. For that we need (a) suitable sand, as coarse as possible or coarser than the beach sand (but sand must not be so coarse that it generates a partly reflecting beach which could become dangerous to bathers); (b) the sand must be placed by equipment which is as efficient and economic as possible, (c) the sand shall be placed with the right profile (which means: so that we lose as little of it as possible). Although items (a) and (b) have long been recognized as appropriate, that is not the case with item (c).

Bruun (1986a) discusses in theory, as well as in protective equilibrium, profiles including geometries and grain sizes. Theoretical and practical results favor placement of material, not on the beach, but along the entire cross section, all at one time, with grains of various sizes placed "exactly" where they belong in the profile. It is unquestionable that this will cause higher stability and less material loss alongshore as well as offshore.

Table 4 (Bruun 1986a) describes an example of profile nourishment, by which three different grain sizes (distributions) are placed in three different depth ranges. This, of course, requires meticulous planning and supervision of the actual work in the field under construction.

Table 4. Profile Nourishment

Tide		Area		
		A: + 1, -1	B: -1, -3	C: -3, -5
High	Spring	C	C	-
	Mean	C	M	F
	Neap	C	M	F
Mean	Spring	C	M	F
	Mean	-	M	F
	Neap	-	M	F
Low	Spring	-	M	F
	Mean	-	-	F
	Neap	-	-	F

Three different grain sizes C (0.25mm), M (0.21mm), and F (0.18mm), are dumped at three tidal elevations (High, Mean, and Low) on three different bottom areas for the portion of the beach profile extending from 1-m above sea level to 5-m below sea level (A, B, and C) (Bruun 1986a).

How shall we accomplish profile nourishment? -- using equipment that is able to dump on the beach as well as to whatever depth the material shall be placed. This includes pipelines and hopper-dredges as well as split-hull barges (Bruun et al. 1985) Figure 6 shows the principle of "profile nourishment;" Figure 7 is a Danish example. As explained in Bruun (1986a) profile nourishment is highly economical compared to conventional beach nourishment due to the lesser costs in offshore dumping bid prices in Queensland.

Other Measures

For storm tide protection we need dikes of adequate elevation. At some places where the beach has narrowed excessively, dikes must have a hardened surface on the ocean side to resist wave attack and overflows by uprushes. But to keep the dike intact a beach stabilization is needed in front of the dike. If we are not able to stabilize the beach, we will have to move the dike back sooner or later and keep moving it back if shore recession continues. We have no other option.

In the large scale we apparently have to consider three different possibilities as shown in Figure 8:

- Stabilization of the shoreline: No further shoreline recession due to the existing land developments.
- Let nature take its course: Accept the erosion; establish a beach park area instead.
- Compromise: Establish set-back lines valid for a certain time period before reviewing them for further set-backs.

Stabilization. This is a common case, where stabilization is a must. Shorelines in Holland, parts of Denmark, the United Kingdom, and Germany will have to be closely monitored in case stabilization becomes necessary. Shore developments like townships and barriers protecting bays or lagoons do not allow further shoreline recession. Consequently, it is necessary to nourish the beach and to stabilize the dunes. This will be done for many shores in California and Florida as well as for other shores on the east coast of the United States.

Let nature take its course. This may be done where plenty of undeveloped land is found behind the shoreline, such as in the Outer Banks of North Carolina in the United States. The most practical way of handling such a situation is by constructing withdrawn dikes at considerable distances behind the shoreline and prohibiting any substantial development outside the withdrawn dike. This is already taking place on the Danish North Sea Coast, the Dutch Friesan Island, and on the Outer Banks. The wisdom of this strategy is obvious--such national and state parks have become very popular and more of these are probably going to be established.

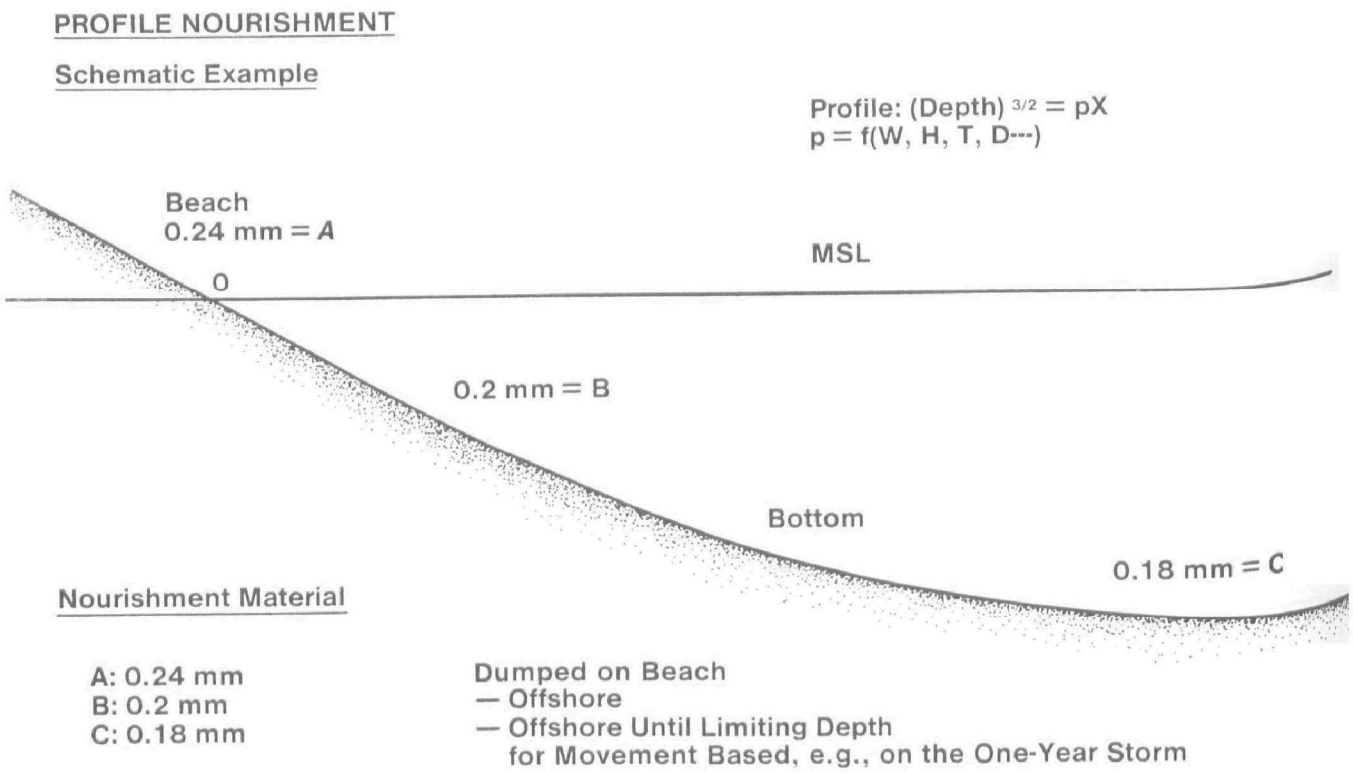


Figure 6. Profile Nourishment

Figure 7. Profile Nourishment on the Danish North Sea Coast
Source: Coastal Directorate, Lemvig 1985

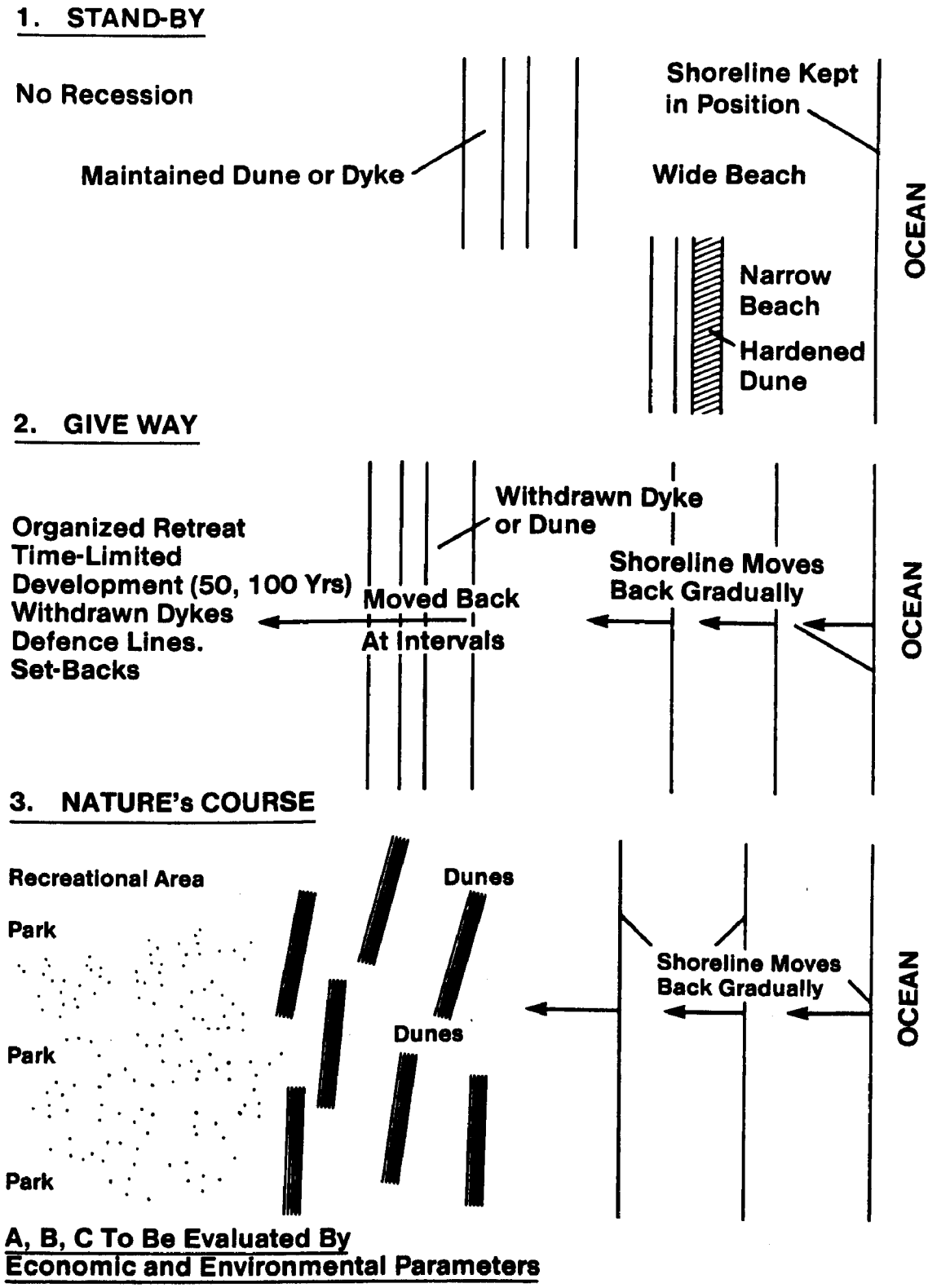


Figure 8. Long-Term Shore Management

Compromise. Establish a set-back line valid for a certain time-period (e.g., 50 or 100 years). Allow a controlled development. Houses can be built in such a way that they can easily be moved back.

While items (1) and (2) are straightforward, item (3) is more complicated because it must be anticipated that the lifetimes of parts of the development are time-limited. That would imply, for example, that buildings erected on the property after some time would be moved back to "safer locations." One may imagine the administrative difficulties involved in such an arrangement. One solution, of course would be to lease the coastal properties for limited periods of time (e.g., 20, 30, 50, or 100 years). The buildings erected on such property should then be designed in such a way that they could be moved landward to another location after a certain time period. Technically, this relocation would not be difficult; the problem would be to make new areas available for the reconstruction of such buildings, which are expendable after so many years.

Financing

Financing possibilities vary from country to country. In the United States the state governments are taking over more and more of the responsibility which earlier rested with the Federal Government. The Florida task force "Save our Beaches" suggests a 75% financial contribution by the state and a 25% local contribution. In the low countries in Europe, costs will be borne by the national government either entirely or with some matching funds from the local governments. The contributions by public funds range from 50% to 100%. In some latin countries, like Spain, the national and state governments will pay all costs of shoreline protection.

Developing countries in general have no provisions or possibilities for public funding. In some of these countries (e.g., large coastal areas in Bangladesh) the situation has become critical. Financing by UN-World Bank is a possibility being explored for Bangladesh.

CONCLUSION

- Sea level is rising. An accelerated rise would cause accelerating erosion of our coastal shorelines.
- Our ability to quantify the magnitude of the rise is steadily improving.
- We are (largely) able to predict the influence of sea level rise on shore stability.
- Proper coastal protective measures are available to mitigate the effects of erosion, wherever this is desirable.
- Future coastal protection will involve beach nourishment and storm tide protection by dikes and revetments, where needed, as well as the establishment of practical set-back lines.
- Progress is being made, scientifically and technically, to improve available nourishment procedures and equipment.

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Predicting the Effects of Sea Level Rise on Coastal Wetlands

Richard A. Park, Thomas V. Armentano, and
C. Leslie Cloonan
Holcomb Research Institute
Butler University
Indianapolis, Indiana USA

INTRODUCTION

Accelerated sea level rise brought about by global warming may have a profound effect on coastal wetland distribution (Titus, this volume). Wetlands, including salt-, brackish-, and freshwater marshes and, in subtropical and tropical regions, mangrove swamps, typically occupy low-energy, protected coastlines in estuaries, bays, and lagoons. Consequently, in the United States only 10% to 20% of the Pacific coast is suitable for wetland development because of the high-energy, rocky shoreline, whereas about 70% of the shoreline of the Atlantic and Gulf coasts is suitable because of the extensive estuaries and gently sloping coasts with lagoons behind barrier islands (Emery and Uchupi 1972).

Wetlands are important to the ecology and economy of coastal areas for several reasons. Their biological productivity is equal to or exceeds that of any other natural or agricultural system. For example, a Georgia salt marsh has, on average, an annual yield of 8 tons/acre (1700 g/m^2) of organic matter (Teal 1962) and a Florida mangrove swamp, 4 tons/acre (880 g/m^2) (Mann 1972). In comparison, the best wheat field yields 7 tons/acre (1570 g/m^2) and offshore coastal waters yield 1 to 1½ tons/acre (220 to 340 g/m^2) of organic material.

About half of marsh productivity is available to marsh animals and coastal fisheries (Teal and Teal 1969). Furthermore, salt marshes serve as nursery grounds for over half the species of commercially significant fishes in the southeastern United States (Thurman 1983), as rookeries for many water fowl, and as refuges for a variety of mammals (Teal and Teal 1969).

Wetlands also remove pollutants, including nitrogen, phosphorus, heavy metals, and radioisotopes, from sewage effluent and ground- and surface water (Pope and Gosselink 1973). Equally important, they store floodwater and provide protection from coastal storms and high tides (Lugo and Brinson

1978). Based on these functions, it has been estimated that marshes provide an annual return equivalent to $5,500/acre (Thurman 1983) and mangrove swamps, a return of $990/acre (Lugo and Brinson 1978).

These valuable systems could be diminished and lost with accelerated sea level rise, whereas slow sea level rise favors development and expansion of wetlands. In fact, during the past 4,000 years when the sea level has risen an average of 1 mm/yr, 0.04 in/yr (Emery and Uchupi 1972), wetlands have kept pace, and in many areas, actually increased significantly due to sediment entrapment and peat formation (Davis 1985). However, vertical accretion of wetlands has not been observed to occur at a rate comparable to the accelerated sea level rise projected for the next century by Hoffman (1984). Therefore, future inundation and erosion of wetlands has been projected (Barth and Titus 1984).

Based on available data, wetlands along undeveloped coastlines lacking protective engineering structures are expected to migrate readily onto adjacent lowlands, especially in areas less than 3.5 m (10 ft) in elevation. However, because most coastal lowlands have steeper slopes than present-day wetlands, the areas of wetlands lost may exceed areas gained, causing a net reduction in wetlands. Furthermore, many coastlines, especially those which are or will be developed commercially, probably will be protected by dikes and levees. These structures will preclude migration of the wetlands, and large-scale loss of wetlands has been projected (Titus, in press).

In order to assess the potential loss and migration of wetlands, detailed case studies were conducted in South Carolina and in New Jersey (Kana, Baca, and Williams 1986; Kana et al., in press), and a more general map and simulation analysis was conducted on fifty-seven sites along the contiguous coasts of the United States (Park, Armentano, and Cloonan 1986; Armentano, Park, and Cloonan, in press). This paper reviews these studies and suggests possible effects on marshes and mangrove swamps representative of a variety of coastal situations under a scenario of high sea level rise and protection of developed areas.

DETAILED CASE STUDIES

Charleston, South Carolina, Area

Twelve wetland transects provided the database for considering the effects of sea level rise on the harbor of Charleston, South Carolina (Kana, Baca, and Williams 1986). Figure 1 shows a composite of these transects. Shoreline changes were assumed to depend on slope, with gentle slopes experiencing considerable horizontal shoreline displacement and steep slopes, relatively little. Artificial or engineered shorelines were recognized as impediments to shifts in shoreline position until a threshold sea level was exceeded. Detailed maps were prepared based on topographic quadrangles that were digitized and displayed in computer-generated form. A good database on historical shoreline trends was available to help project future responses to sea level rise.

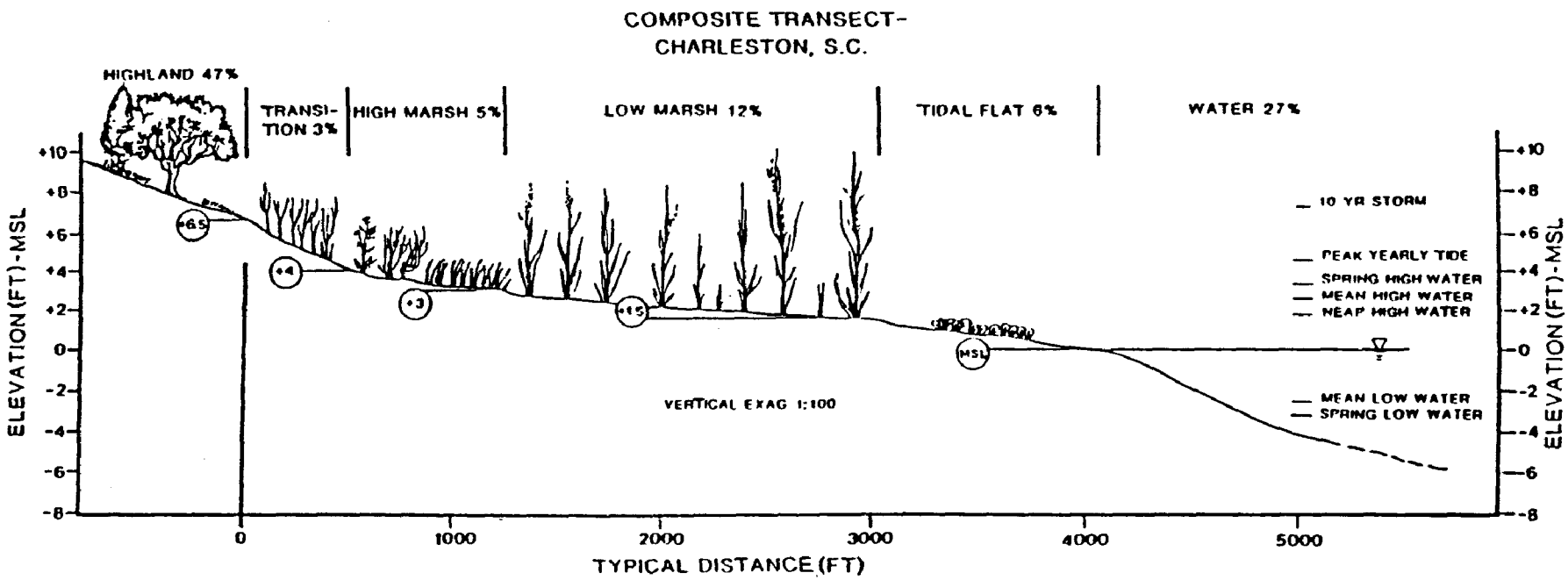


Figure 1. Composite Transect of Charleston, South Carolina, Marsh
Source: Kana, Baca, and Williams 1986

A previous study showed that over the past 40 years the Charleston shoreline has accreted relative to sea level, which is similar to shoreline responses throughout most of the Atlantic coast. For purposes of the present study, a vertical marsh accretion rate of 5 mm/yr was employed. Landward migration of tidal flats, low marsh, high marsh, and transitional wetland-upland vegetation, was considered as a response to sea level rise. Dikes, bulkheads, and other protective structures, however, would act as barriers to marsh migration onto uplands. Under such a scenario, wetland distribution through 2075 will depend on the potential for wetlands to maintain vertical sediment elevation relative to specified sea level rise rates, assuming a constant sedimentation rate throughout all marsh environments, and on the capacity for horizontal migration as rising seas encroach on the critical elevational range for each marsh type.

Results of the scenario analyses indicate that by the year 2075 significant marsh loss would occur under all scenarios (Figure 2). Even without additional protective structures, 70% of high marsh and 40%-84% of low marsh would be lost under moderate and high scenarios. Total wetland loss (excluding tidal flats but including transition marsh) would range from 43%-73% without additional protection, under moderate and high scenarios. Under specified construction of protective devices for certain sites, losses would rise to 51%-92% of 1980 marsh area. Nearly all of Sullivans Island, a seaward barrier island, would experience significant erosion and shoreline movement. In the high scenarios (a rise of 1.6 m, or 5.2 ft, by 2025), few additional changes would occur except for shifts up to 225 m (740 ft) inland of the shoreline parts of the mainland. Despite the extensive losses projected for the Charleston area, the relatively wide tidal range (1.6 m, or 5.2 ft) suggests less wetland vulnerability to rising seas.

Tuckerton, New Jersey, Area

This site, consisting of two marsh areas with a 0.6-1.0 m (2.0-3.3 ft) tidal range, was evaluated as representative of a microtidal back-barrier wetland area that is more typical of the Atlantic coast (Kana et al., in press). Six subenvironments were distinguished at Tuckerton, ranging from open sea to highland (Figure 3). Field surveys determined exact boundaries of subenvironments.

The Kana et al. model projects the replacement of high marsh by low marsh under the low scenario (Figure 4). However, the aggregate change in salt marsh area is small; if transition marsh is included, wetland changes counterbalance, with essentially no net change.

With a high scenario sea level rise, significant land and wetland losses result (Figure 5). Salt marsh is reduced by 85%-90%, favoring open sea. Transition marsh would be significantly reduced at Tuckerton. The South Carolina and New Jersey sites differ in projected response to the moderate sea level rise scenario as a result of the predominance of low marsh at one and high marsh at the other. The low marsh is lost to tidal flats or open water, whereas the extensive high marsh in New Jersey would be converted to low marsh.

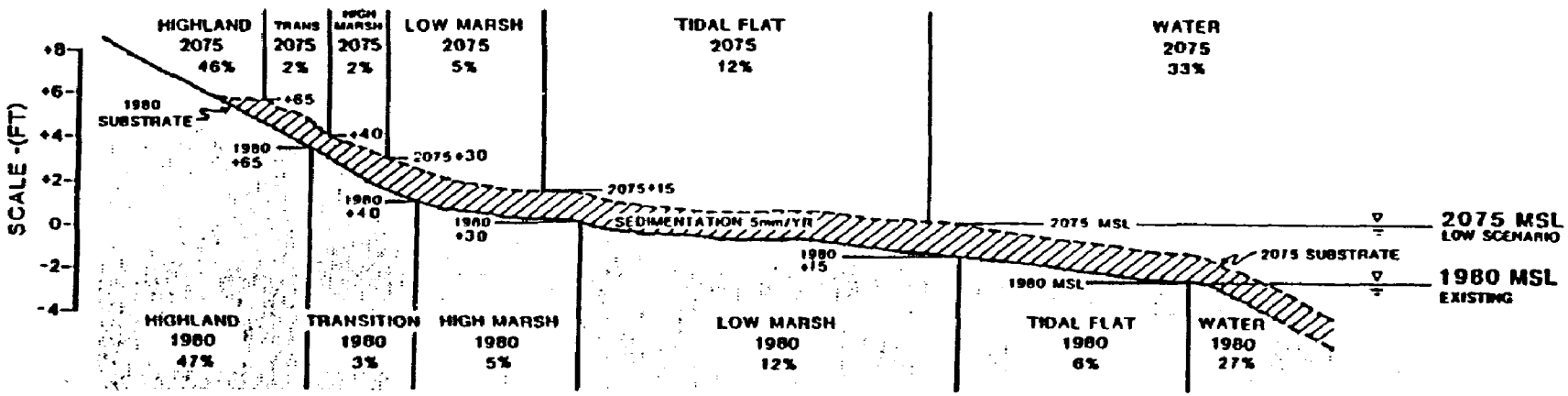


Figure 2. Conceptual Model of Low-Scenario Sea Level Rise in Charleston Marsh
Source: Kana, Baca, and Williams 1986

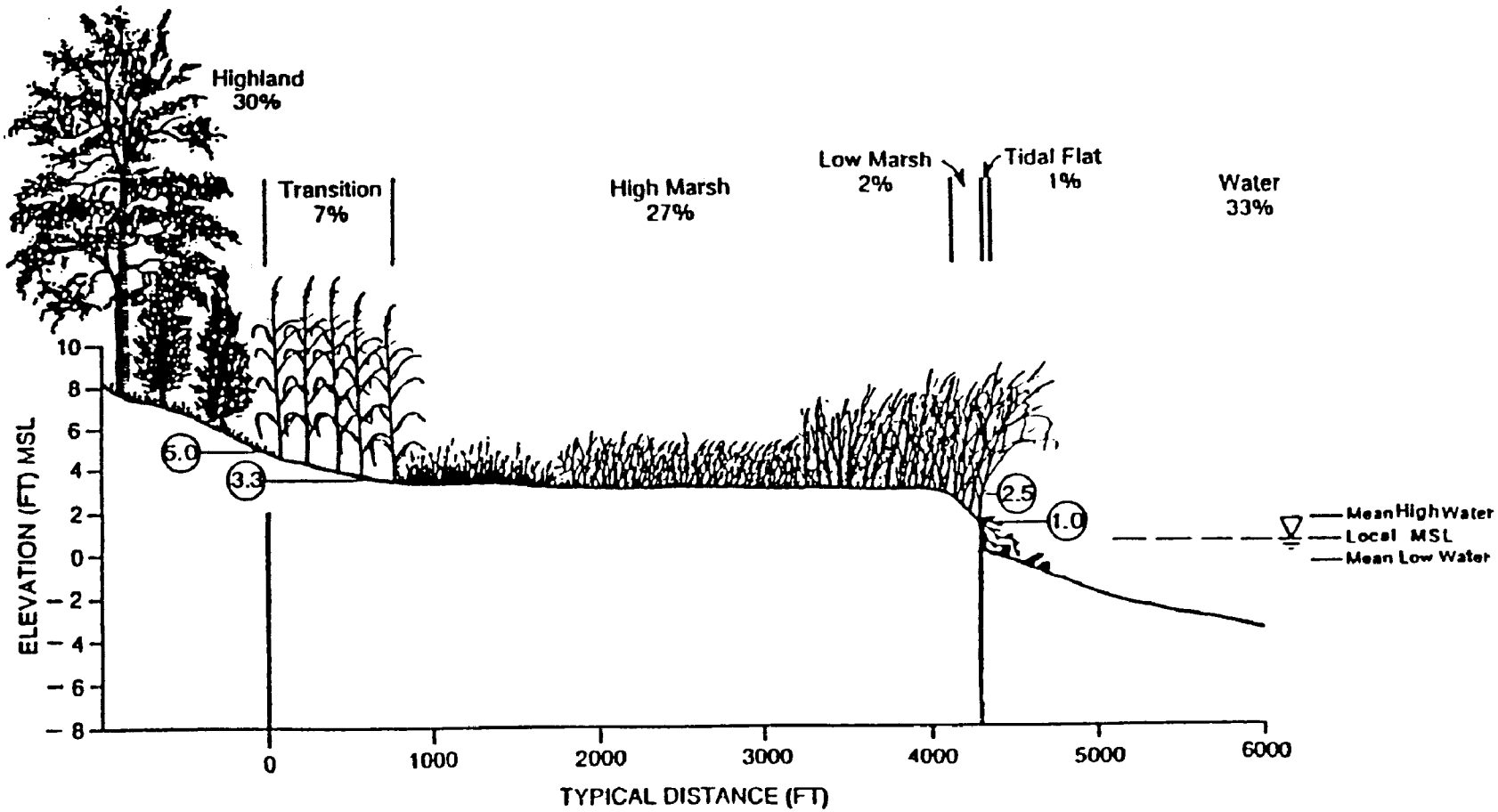


Figure 3. Composite Transect of Tuckerton, New Jersey, Marsh
Source Kana et al., in press

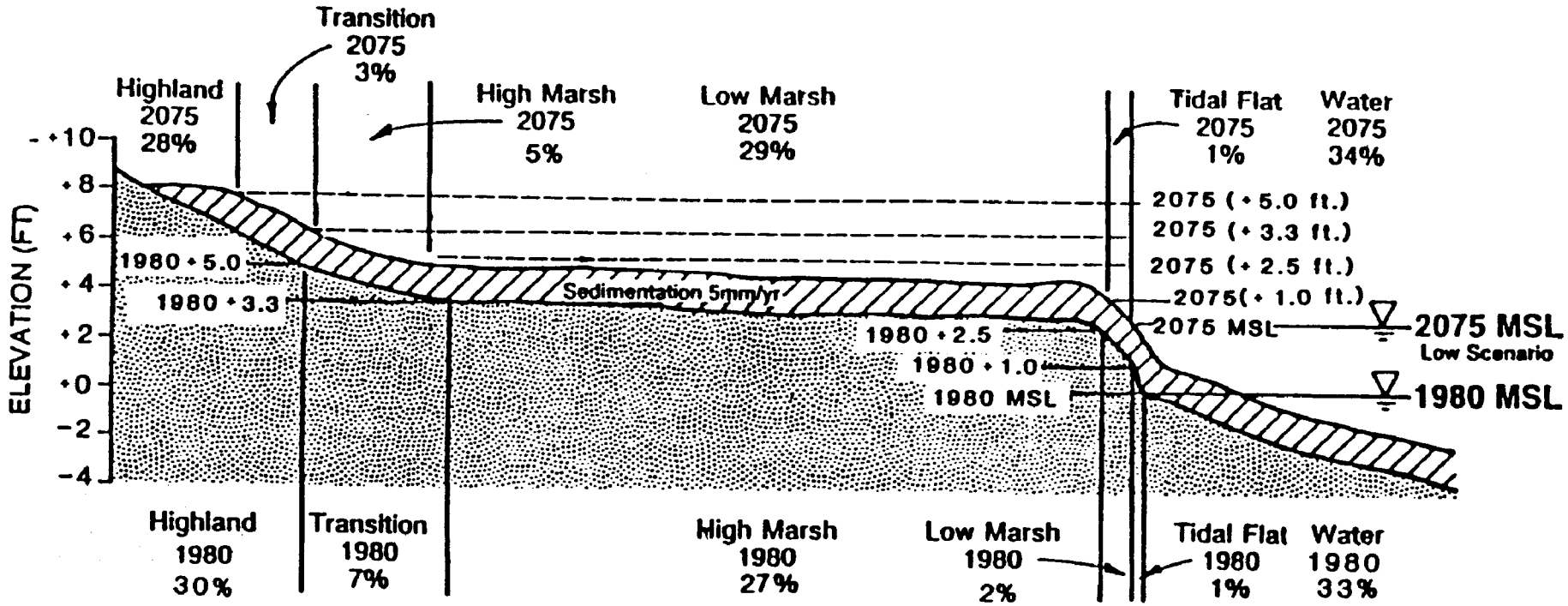


Figure 4. Conceptual Model of Low-Scenario Sea Level Rise in Tuckerton Marsh
Source: Kana et al., in press

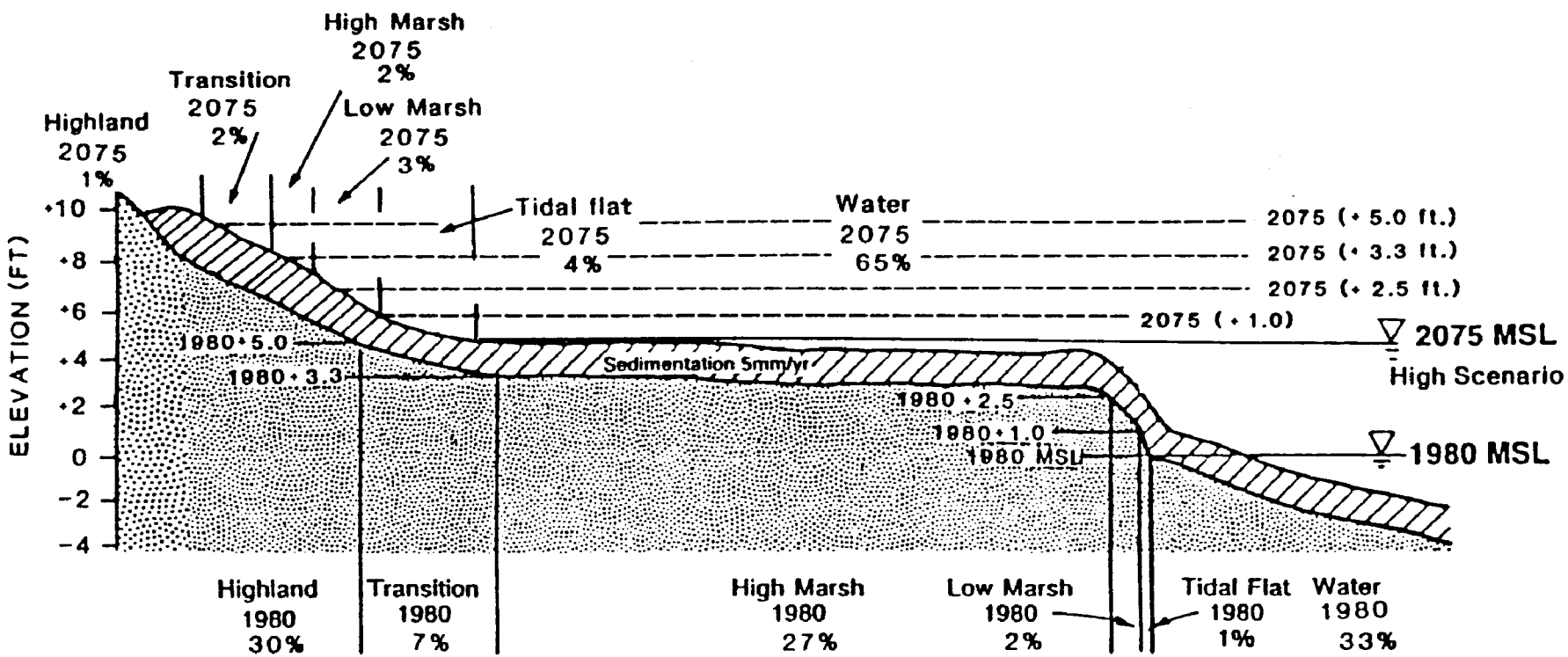


Figure 5. Conceptual Model of High-Scenario Sea Level Rise in Tuckerton Marsh
Source: Kana et al., in press

REGIONAL MODELING

To develop a regional-national analysis of U.S. coastal wetland responses to sea level rise, a general simulation model was developed, and model-supportive stratified sampling of the contiguous U.S. coastline was undertaken for nine regions (Armentano, Park, and Cloonan in press).

Data

A total of 183 7.5-minute USGS topographic quadrangles were used to characterize the fifty-seven sites depicted in Figure 6. The data were collected using the Universal Transverse Mercator grid so that each cell is 1 km^2 (100 hectares, or 247 acres). Of the sixteen categories of coastal types, each is based on the dominant category within the square-kilometer cell. They are summarized in Table 1. The mean elevation is based on the dominant category in the cell. Although this introduces an element of imprecision, if a large enough area is considered, the estimate is not biased. Tidal range for both open sea and sheltered areas is taken from the topographic maps, or, if necessary, from tide tables.

The presence of naturally sheltered areas (e.g., bays) is coded, as are major protective structures such as levees. Finally, the existence of significant residential and commercial development is noted. The extent of freshwater and brackish wetlands cannot be determined at the regional level from topographic maps.

Prior Models

A large number of models have been constructed for fresh- and saltwater wetlands (cf. Day et al. 1973; Wiegert et al. 1975; Costanza et al. 1983; Mitsch et al. 1982; Costanza and Sklar 1985). However, few of these models incorporate the spatial resolution desired in the present study. Two notable exceptions are recent papers by Browder, Bartley, and Davis (1985) and Sklar, Costanza, and Day (1985) on disintegration and habitat changes in the Louisiana coastal wetlands. No previous models provided both the spatial resolution and the generality required for studying the effects of sea level rise on a regional scale for the United States.

The SLAMM Model

Description. SLAMM (Sea Level Affecting Marshes Model) simulates the long-term change in coastal areas due to rising sea level. The smallest area simulated is a 7.5-minute quadrangle (1:24,000); the largest practical area is about the size of four 7.5-minute quadrangles. The assumptions and methodology are appropriate for application to entire coastlines.

SLAMM is intended to be used primarily as a diagnostic tool, providing scientists, resource planners, and decision makers with a basis for considering the impacts of future sea level rise on coastal systems, especially wetlands and barrier islands. As such, the model employs a reasonably straightforward but complex set of decision rules to predict the transfer of map cells from one category to another (Figure 7). These rules embody assumptions of

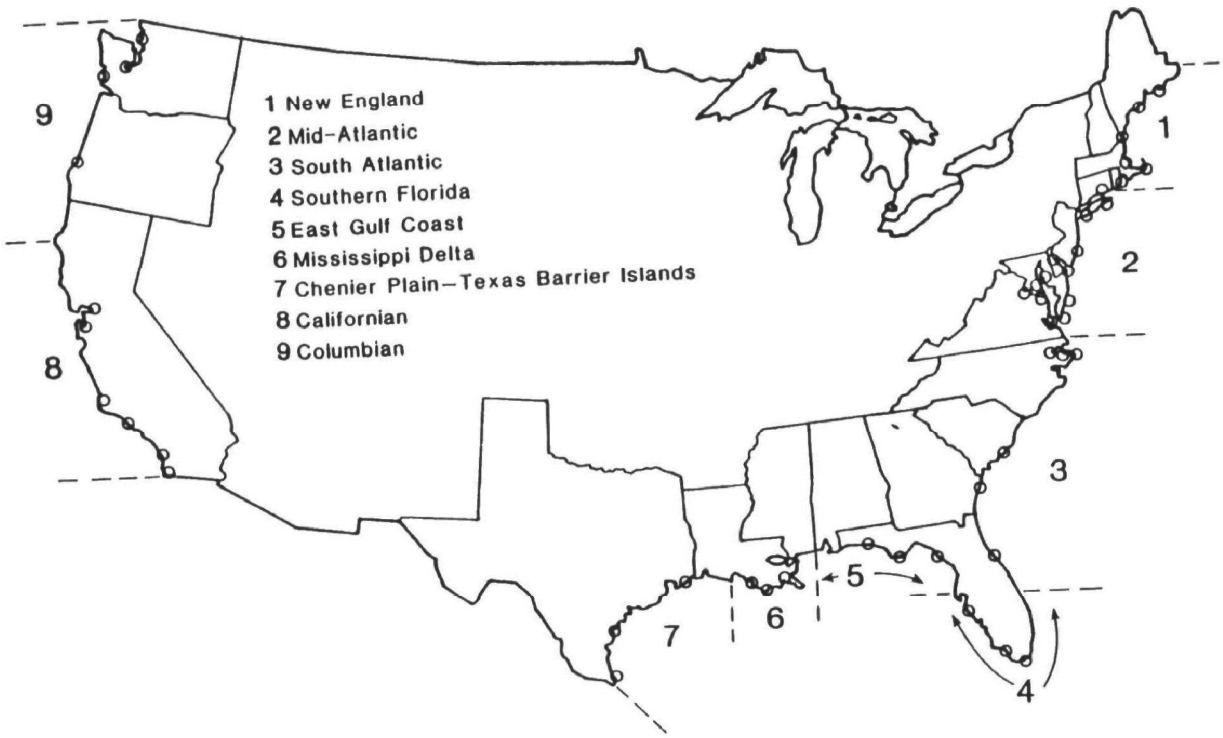


Figure 6. Location of Sample Sites and Coastal Regions Used in Modeling Wetlands
Source: Armentano et al., in press

Table 1. Coastal Land Categories

Category	Definition
Undeveloped Upland	Undeveloped upland land that is above 3.5 m elevation
Developed Upland	Upland that has significant line deleted development
Undeveloped Lowland	Land that is below 3.5 m elevation and above mean high water spring tide (MHW Spring)
Developed Lowland	Lowland that has significant residential or commercial development
Protected Lowland	Lowland that is protected from inundation by a dike or levee
High Dunes	Extensive, large sand dunes
Exposed Beach	Beach exposed to the open ocean
Sheltered Beach	Beach sheltered from the open ocean
Developed Exposed Beach	Exposed beach with significant residential or commercial development
Developed Sheltered Beach	Sheltered beach with significant residential or commercial development
Freshwater Marsh	Wetland composed of species intolerant of salt water
Salt Marsh	Wetland composed of herbaceous species that are tolerant of salt water
Mangrove Swamp	Wetland composed of mangrove trees
Tidal Flat	Muddy or rocky intertidal zone
Sheltered Water	Water that is protected from the open ocean
Open Water	Water that is not protected from the open ocean

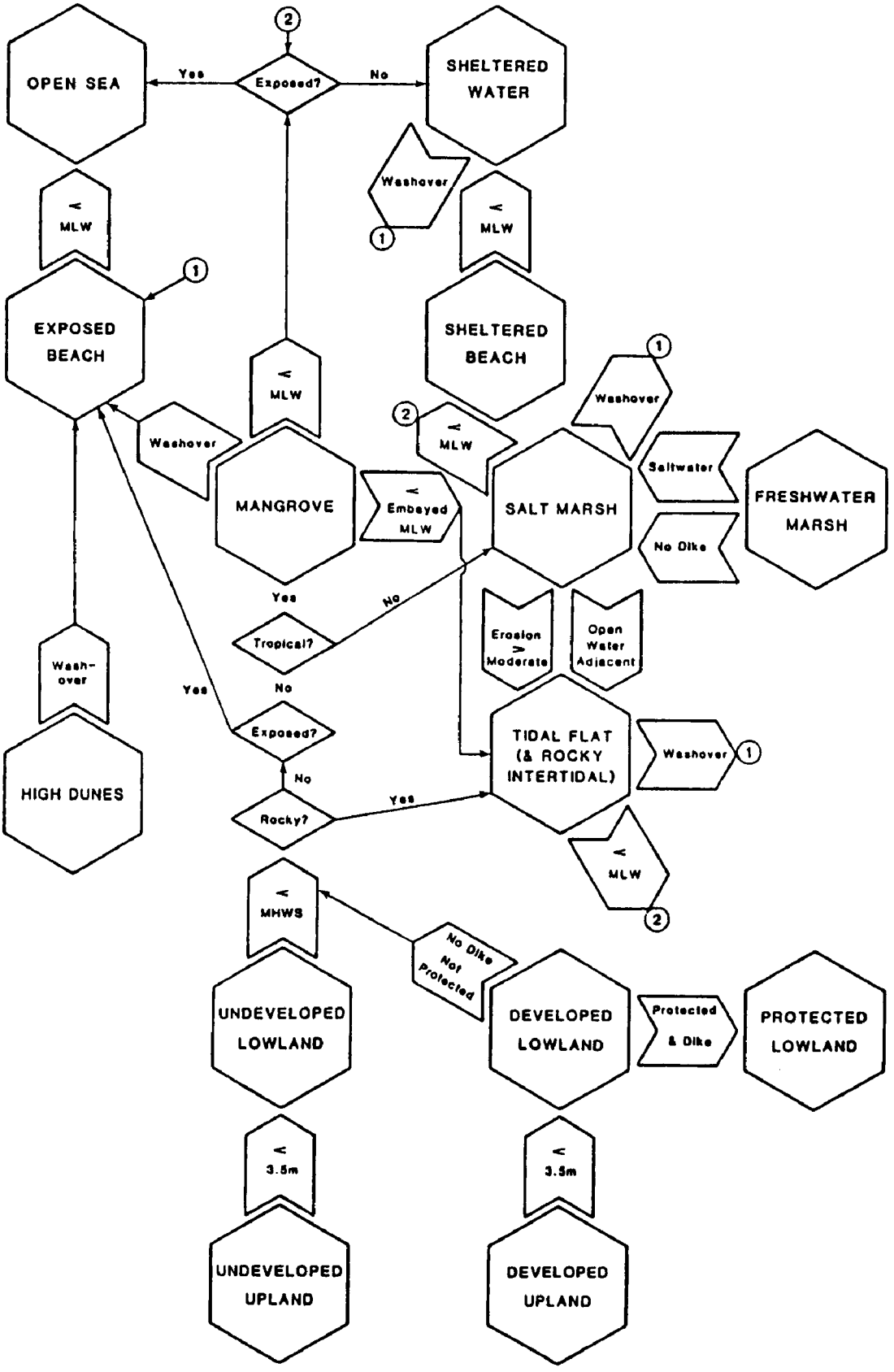


Figure 7. SLAMM Flow Chart Showing Transfers Among Categories
Source: Park et al., 1986.

linear, average responses and may not apply in detail for any particular area; however, they are suitable for policy development on a regional basis, providing an estimate of the magnitude of the problems and suggesting the nature of the regional policies needed to mitigate those problems. Because the model is intended to be applied to many different areas, the algorithms have been developed to require minimal input from the user.

Each cell category is represented by a pattern and a color, so that the primary output from the model is colored maps for user-specified yearly intervals for a given area and rate of sea level rise. Summary statistics for all categories are provided for 25-year intervals and for wetlands, for 5-year intervals, so that the progressive impact on coastal wetlands can be assessed. The model is implemented in Turbo Pascal for the IBM PC.

Assumptions and Simplifications. Because the model is intended to be used for regional analysis of long-term trends, several simplifying assumptions have been made that may not be appropriate for detailed analysis of local and short-term conditions:

- Each square-kilometer cell is represented by only one (dominant) category and by average elevation; this results in underrepresentation of pocket beaches, marshes, and narrow barrier beaches; furthermore, gradual changes seem to occur instantaneously when the threshold average elevation of the cell is reached.

- Continued residential and commercial development of coastal zones is ignored; only those areas developed when the maps were published are subject to protection; given current trends and policies, this may not be a reasonable assumption.

- Freshwater discharge is ignored in distinguishing freshwater wetlands from saltwater wetlands; this is most noticeable in the Florida Everglades, which are modeled as mangrove swamp due to their elevation near sea level.

- Sedimentation and accretion rates are related to the extent of existing wetlands; in most areas this results in a decrease in sedimentation as marshes disappear, coinciding with the decrease brought about by sediments "hanging up" further inland in the deepening estuaries; however, in areas where extensive lowlands are inundated and converted into wetlands, this algorithm will predict increased sedimentation--perhaps more than is reasonable.

- No distinction is made among East Coast, West Coast, and Gulf Coast marshes; the same algorithms are used for accretion, erosion, and position within the tidal range for all three regions; SLAMM also does not distinguish between mature and new marshes.

- No provision is made for changing vegetation due to global warming trends; in particular, mangroves will not be simulated in more northerly areas where they do not already occur.

- Cliff retreat is not modeled, nor is the increased supply of sediment to the coastal regime due to cliff erosion; this could affect areas such as Cape Cod, Massachusetts, and Oxnard, California.

- Actual bathymetry is not considered nor is the effect of changing bathymetry on wave energy; beach migration is permitted in sheltered water but not in open sea; this seems to be a reasonable simplification for essentially all areas.

- The change in erosion by tidal currents with changing morphometry and bathymetry is not modeled.

- Changes in storm tracks and in the erosive energy of storms concomitant with climatic change are not modeled.

Validation. SLAMM has been partially validated by comparison of results with those of the detailed study of the Tuckerton, New Jersey, area conducted by Kana et al. (1985). However, it must be recognized that true validation cannot be obtained because of the radically different approaches and scales being compared. In the detailed study the predicted major response at the New Jersey wetland site to a low-scenario sea level rise, as of the year 2075, is the replacement of high salt marsh with low salt marsh (Kana et al., in press). Also projected is the loss of over half the transition marsh in the Tuckerton area, but an increase of transition marsh in the Great Bay area. However, at both locations no change in overall wetland area is projected under the low scenario. The conversion of high salt marsh to low salt marsh would not be detected in our model; furthermore, because the distinction between salt marsh and freshwater marsh cannot be made in the input data but is based on imprecise elevation determinations, we prefer to consider total wetland changes. Adjustments to transitional marsh in the Kana et al. studies would occur within the framework of our general freshwater marsh category. The SLAMM model projects a 9% decline in total wetland area by 2075, growing rapidly to a 75% decline by the year 2100. For the common year of 2075, the New Jersey study projects no net change in the total marsh area, whereas ours projects a 9% decline. However, as late as 2045, SLAMM projects a 1.0% decline in wetland area, a figure not significantly different from one of no change, given the limits of both studies. Our simulation through the year 2100, however, suggests that the trend toward migration onto adjacent lowland would soon come to an end and that many of the gains would be lost.

Agreement is more pronounced under the high scenario. Kana et al. project an 84% decline in salt marshes of the Tuckerton area by 2075, compared with a loss of 75% by 2075 and a loss of 99% by 2080 in our study. Consequently, our conclusion with respect to salt marshes in the Tuckerton area is that the two methods, despite being dissimilar in many respects and covering different areas, represent reasonably well an unstable coastal situation which leads to either salt marsh gains or salt marsh losses, depending on rates of sea level rise.

Results

A major finding of the modeling study is that regional patterns of wetland distribution and the potential for loss or gain of wetlands with sea level rise during the next century depend on two principal factors: (1) the tidal range within which saltwater wetlands can occur; and (2) the extent of the lowest Pleistocene terrace (often found at approximately 1.5 m, or 5 ft, in elevation above present sea level along tectonically stable coasts).

Thus in New England, where there is virtually no low terrace, marshes occur in association with pocket beaches in small coves and behind small sand spits. Although the tidal range is high and thus favors maintenance of marshes, there is little lowland to be inundated and colonized by marshes. Consequently, after 2075, when sea level rise exceeds the present spring high tide level, present salt marshes will be lost with no compensating gain in new marsh area (Figure 8).

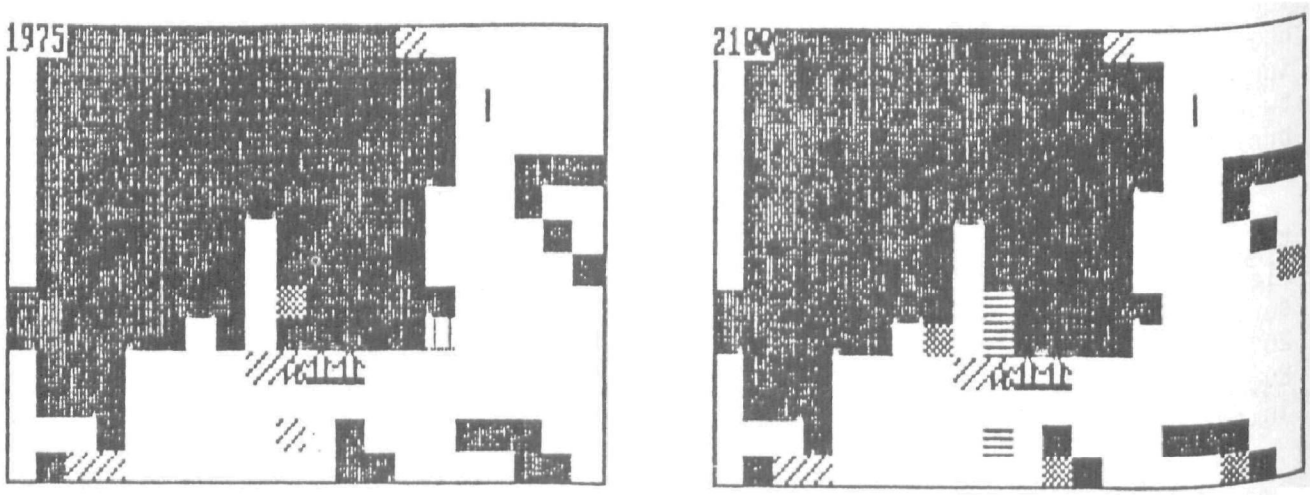
In contrast, from Long Island to southern Florida, coastal slopes are gentle, barrier beaches are common, and the low terrace is widespread. Tidal ranges are also moderately high. Therefore, wetlands are an important component of the coastal system. With the high scenario, most marsh areas will be inundated, such as those behind the Atlantic City barrier beach (Figure 9). However in a few areas, unless development of resort communities precludes inundation of the low terrace, some marshes will expand throughout much of the twenty-first century, decreasing only after the protective beach ridges are breached (Figure 10).

The Florida Keys and Everglades owe their existence to carbonate deposits that accumulated in shallow water during higher stands of sea level in the Pleistocene. As the Keys are inundated (in the absence of protective measures), a slight increase in mangrove swamps can be anticipated; but after 2075 the region will rapidly become open water (Figure 11). The southern Everglades will also disappear, but wetlands may actually increase where inland areas are inundated.

The Gulf Coast is also a region of low slopes and barrier coastlines; but, unlike the Atlantic, it has higher terraces along the coast and very low tidal ranges. Therefore, the marshes are more vulnerable to inundation and cannot migrate inland as readily as the marshes of the Atlantic Coast. With few exceptions, the Gulf Coast marshes will gradually disappear until the barrier islands are breached, at which time those marshes not protected by dikes will decline precipitously (Figure 12). A notable exception to this pattern is in the region of the Mississippi delta, where rapid subsidence is already overwhelming high sedimentation and accretion rates. In general, large-scale loss of marshes (far exceeding the current rate) can be expected in this region early in the next century (Figure 13).

Most of the West Coast is similar to New England: steep, rocky slopes predominate. Wetlands are of minor extent but occupy a wide tidal range, so that they can be expected to persist throughout most of the next century. The more extensive marshes in the tectonic lowlands of San Francisco Bay and the Washington coast will probably expand onto adjacent lowlands unless restricted by protective structures (Figure 14).

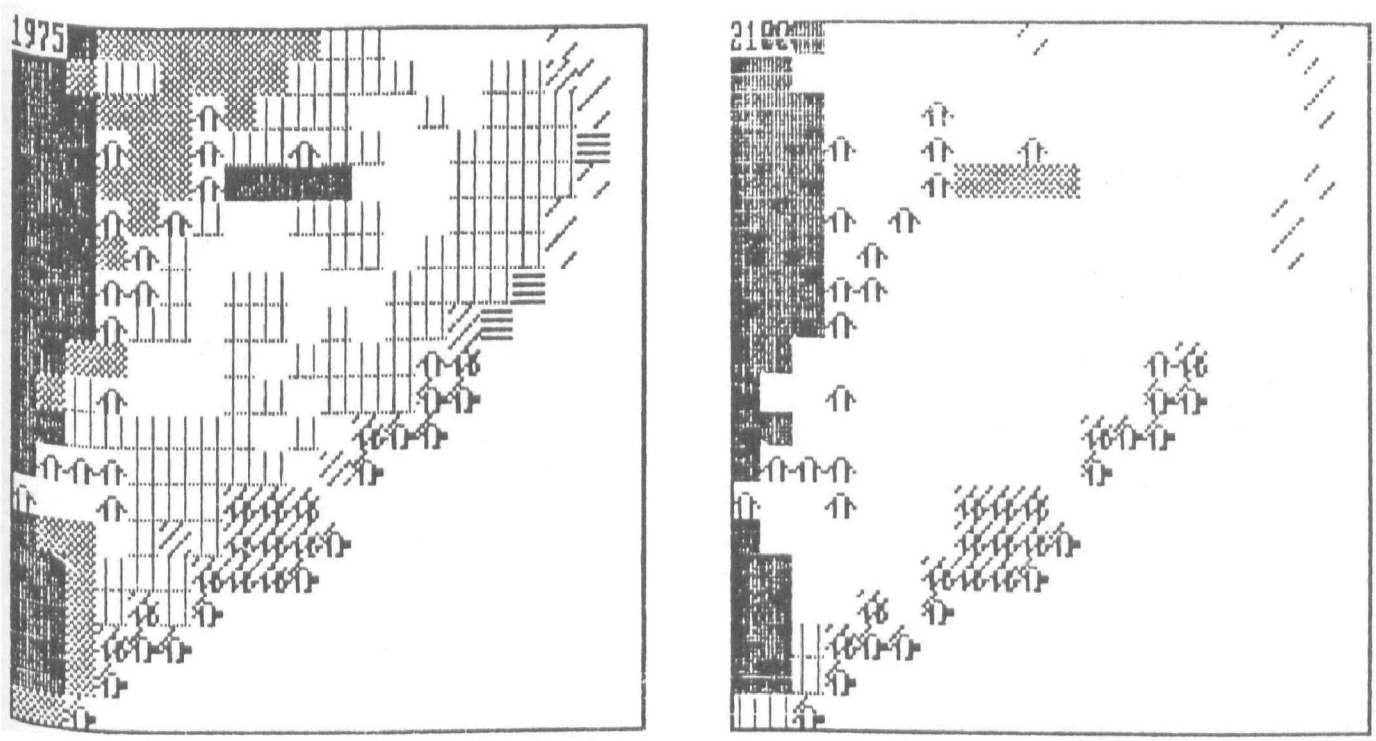
Aggregating the individual case studies provides, with one reservation, a convenient way to detect commonalities in wetland response trends throughout the diverse U.S. regions. Although the study sites were chosen to achieve a representative sample of wetland types without a priori bias as to expected responses, the case study sites were not randomly chosen nor was adequacy of sample size ensured. Therefore, the apparent patterns in any area cannot be interpreted as statistically valid estimates of region-wide responses to sea level rise. Instead, the aggregated data are best viewed as indicative of the class of responses likely to occur in coastal areas similar to the case study areas.



LEGEND

Undev. Upland		Dev. Upland	
UndevLowland		Dev. Lowland	
Prot. Lowland		High Dunes	
Exp. Beach		Shelt. Beach	
DevExp. Beach		Dev. Shelt. B.	
Fresh Marsh		Salt Marsh	
Mangrove		Tidal Flat	
Shelt. Water		Open Sea	
Dike or levee		Blank	

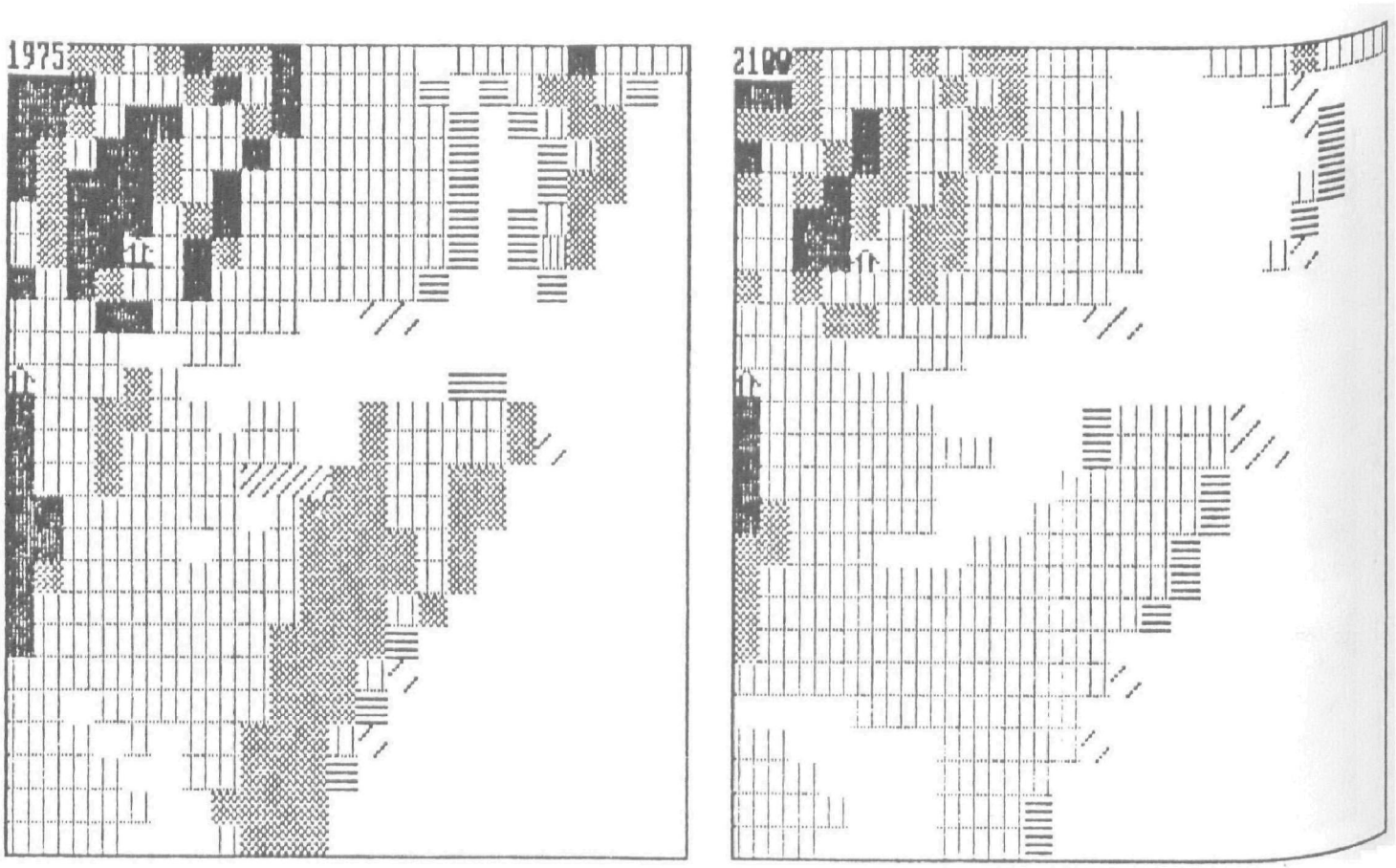
Figure 8. Small Marsh Is Lost at Jonesport, Maine, with High-Scenario Sea Level Rise.



LEGEND

Undev. Upland		Dev. Upland	
UndevLowland		Dev. Lowland	
Prot. Lowland		High Dunes	
Exp. Beach		Shelt. Beach	
DevExp. Beach		Dev. Shelt. B.	
Fresh Marsh		Salt Marsh	
Mangrove		Tidal Flat	
Shelt. Water		Open Sea	
Dike or levee		Blank	

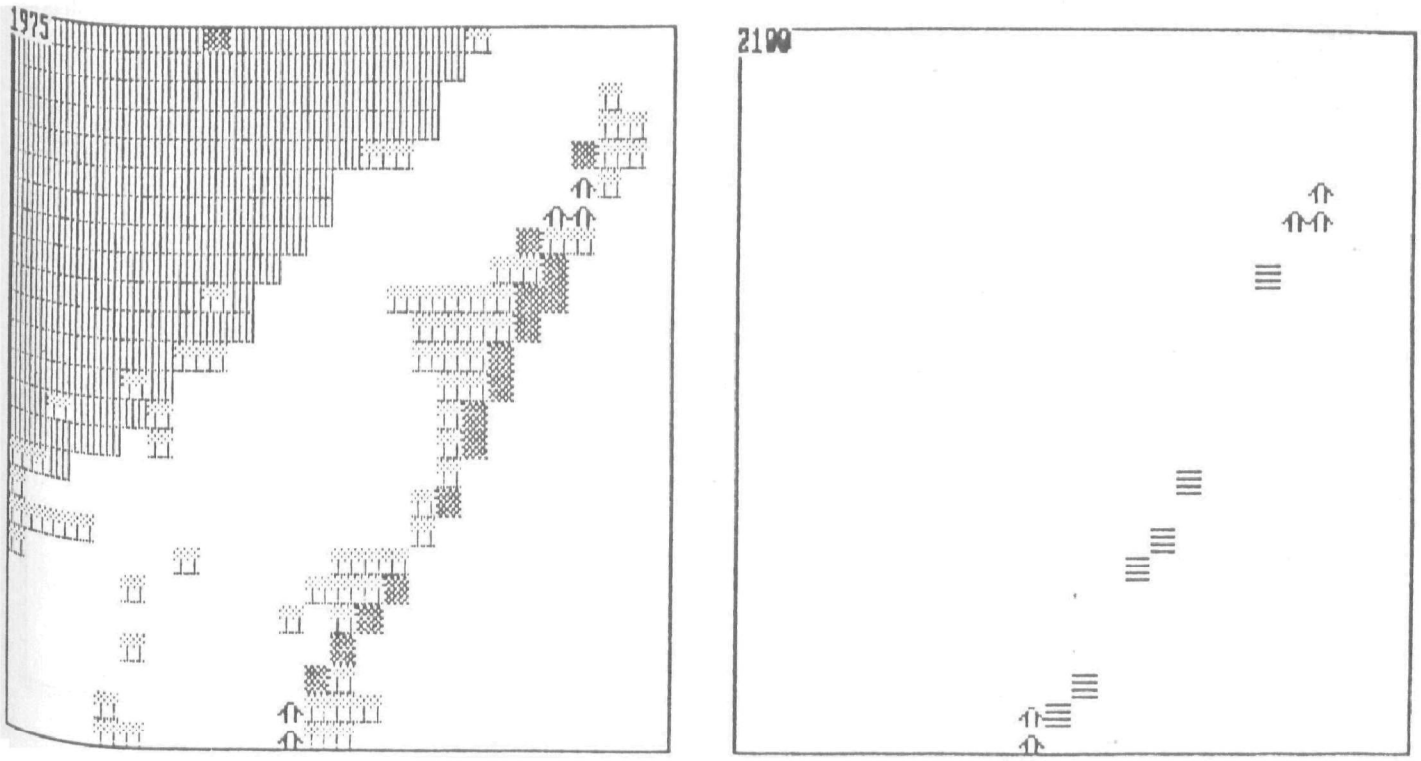
Figure 9. Extensive Back-Barrier Marsh Is Lost at Atlantic City, New Jersey, with High-Scenario Sea Level Rise



LEGEND

Undev. Upland		Dev. Upland	
UndevLowland		Dev. Lowland	
Prot. Lowland		High Dunes	
Exp. Beach		Shelt. Beach	
DevExp. Beach		Dev. Shelt. B.	
Fresh Marsh		Salt Marsh	
Mangrove		Tidal Flat	
Shelt. Water		Open Sea	
Dike or levee		Blank	

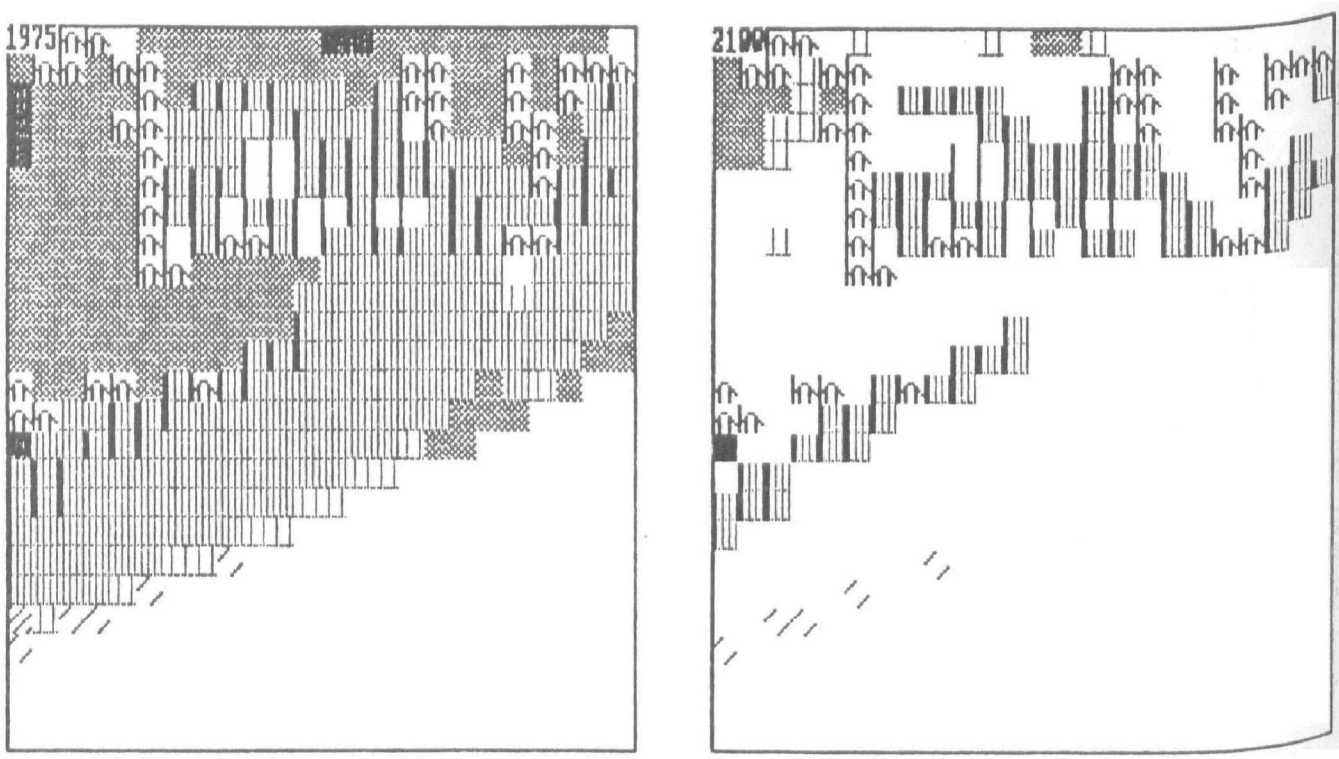
Figure 10. Marsh Persists by Migrating onto Adjacent Lowlands at Sapelo Island, Georgia, with High-Scenario Sea Level Rise



LEGEND

Undev. Upland		Dev. Upland	
UndevLowland		Dev. Lowland	
Prot. Lowland		High Dunes	
Exp. Beach		Shelt. Beach	
DevExp. Beach		Dev. Shelt. B.	
Fresh Marsh		Salt Marsh	
Mangrove		Tidal Flat	
Shelt. Water		Open Sea	
Dike or levee		Blank	

Figure 11. Everglades and Most of the Florida Keys Are Lost with High-Scenario Sea Level Rise



LEGEND

Undev. Upland		Dev. Upland	
UndevLowland		Dev. Lowland	
Prot. Lowland		High Dunes	
Exp. Beach		Shelt. Beach	
DevExp. Beach		Dev. Shelt. B.	
Fresh Marsh		Salt Marsh	
Mangrove		Tidal Flat	
Shelt. Water		Open Sea	
Dike or levee		Blank	

Figure 12. Marsh and Rice Fields Not Protected by Dikes West of Sabine Pass, Texas, Are Lost with High-Scenario Sea Level Rise (saltwater intrusion is not modeled)

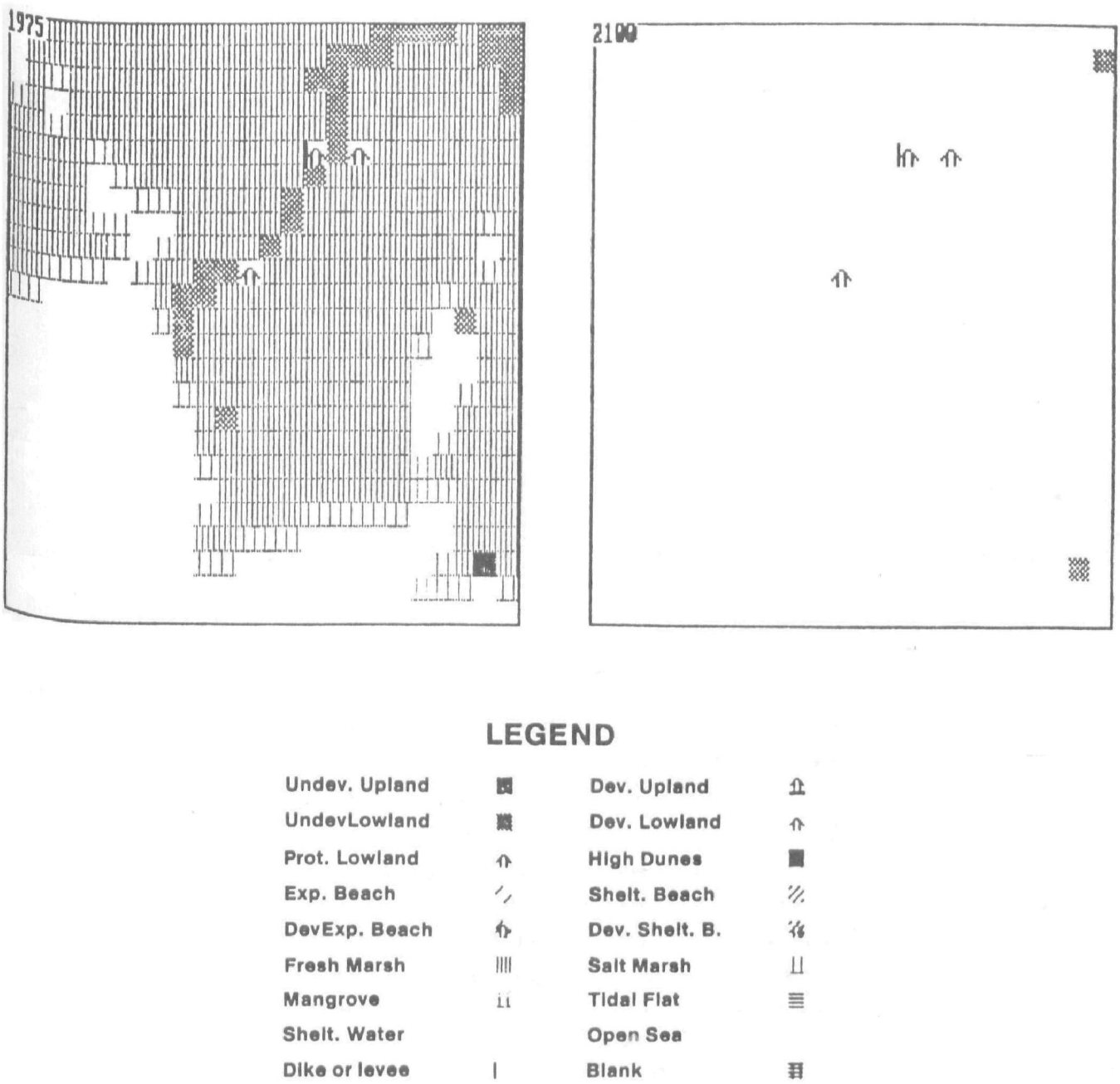
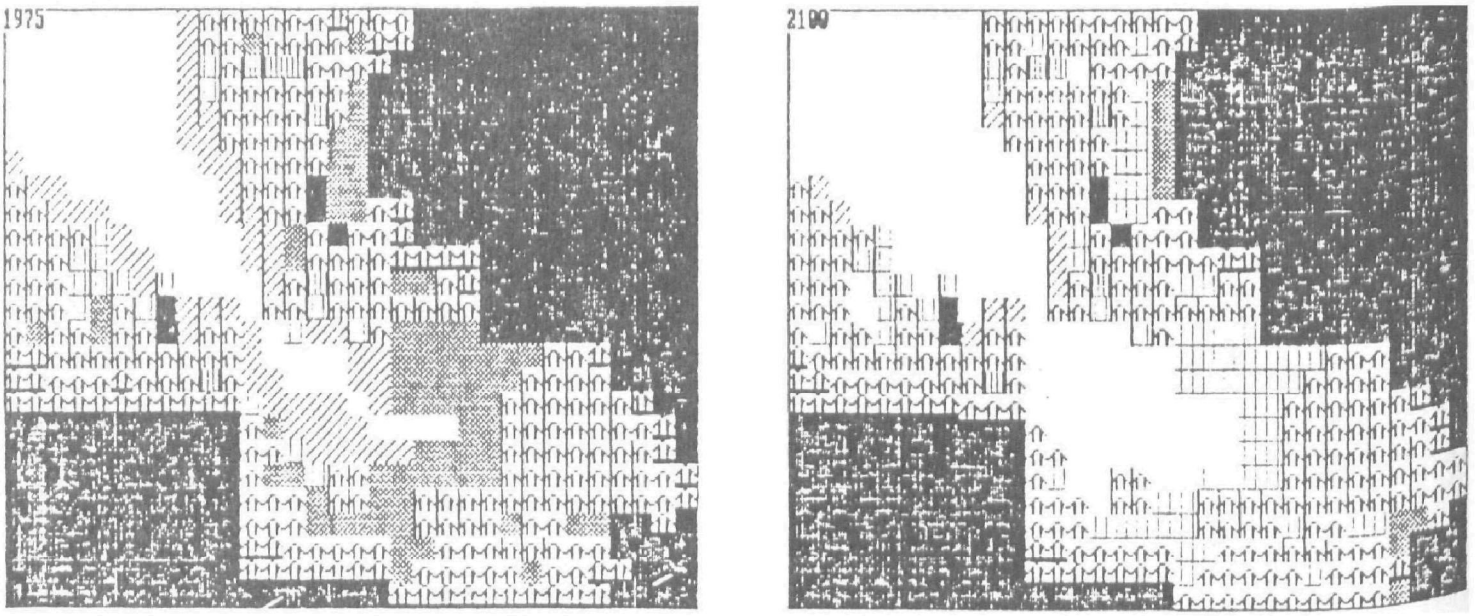


Figure 13. All the Lower Atchafalaya Delta in Louisiana Is Inundated with High-Scenario Sea Level Rise



LEGEND

Undev. Upland		Dev. Upland	
UndevLowland		Dev. Lowland	
Prot. Lowland		High Dunes	
Exp. Beach		Shelt. Beach	
DevExp. Beach		Dev. Shelt. B.	
Fresh Marsh		Salt Marsh	
Mangrove		Tidal Flat	
Shelt. Water		Open Sea	
Dike or levee		Blank	

Figure 14. The Salt Marshes of Southern San Francisco Bay, California, Expand into Unprotected, Undeveloped Lowlands with High-Scenario Sea Level Rise

Nationally, the fifty-seven sites selected for study include 485,000 ha (1,198,000 acres) of coastal wetlands. Under the high scenario, about 73% (354,000 ha, or 874,000 acres) of all wetlands considered were lost to rising seas by 2100. However, formation of new wetlands reduced the loss to 56% of the 1975 wetland area. Under the low scenario, about 40% (192,000 ha, or 474,000 acres) of the 1975 wetlands were inundated, but new wetlands extended over 85,100 ha (210,200 acres), leaving a net reduction by 2100 of 107,000 ha (264,300 acres) or 22% of the 1975 wetlands. The apparent national pattern is dominated by the Gulf Coast, especially the Mississippi Delta, and by the South Atlantic regions where the largest wetland areas are found.

In summary, some areas may exhibit an increase in wetlands if lowlands are permitted to be inundated by sea level rise; and in some areas existing wetlands may persist well into the the next century. Over extensive areas of the United States, however, catastrophic wetland losses will have occurred by 2100 if present practices of inadequately protecting existing wetlands are followed and if adjacent lowlands are not reserved for wetland migration.

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Increased Storms and Estuarine Salinity and Other Ecological Impacts of the Greenhouse Effect

Donald de Sylva
Rosenstiel School of Marine and Atmospheric Science
University of Miami
Miami, Florida USA

ABSTRACT

Increased concentrations of CO_2 and other trace gases, as well as the modification of the ozone layer by chlorofluorocarbons, should contribute to the atmospheric greenhouse effect and warming of the earth's surface. First, the principal effects of air temperature rise should result in an increase in relative humidity and changes in wind pressure systems which would reduce cooling sea breezes along coastal areas. Changes in global rainfall patterns may result in decreased rainfall in tropical and subtropical regions for drinking water, industry, and agriculture, and a reduced supply of freshwater flowing into brackish estuaries, which are nursery grounds for most recreational and commercial fisheries. The resulting increased salinity would induce salt-loving nuisance organisms--some of which are noxious or dangerous to human health--to move upstream. In the tropics, loss of coastal vegetation, principally mangroves, would reduce the protective advantage it affords beaches and waterfront property against normal wave action and cyclones. Pollutant-disposal effectiveness in estuaries would be reduced. Second, the principal effects of sea surface temperature (SST) rise will be to increase the frequency of tropical cyclones which may restore some expected loss in rainfall onto the land. The kinds of marine organisms and fisheries in the tropics will decrease in diversity and shift poleward, while tropical animals such as corals will become stressed and may perish, together with their value as recreational attractions and as protection against shoreline erosion. Pollutant effects in coastal ecosystems should be synergistically more severe at higher sea surface temperatures. Survival of exotic freshwater fishes, diseases, and aquatic parasites may increase. Finally the effects of sea-level rise may be limited biologically, including coral reef die-off, but coastal beach erosion would be severely exacerbated and would result in destruction of waterfront property, marinas, roads, and causeways as well as damage to coastal energy facilities, freshwater aquifer supplies, and coastal toxic waste facilities through saltwater corrosion of metal containers. A suggestion is made for aquatic organisms and their ecosystems

to be used as possible indicators of rising sea level and increasing water temperatures.

INTRODUCTION

The causes and effects of the "greenhouse effect" and associated sea level rise are well covered by Schneider and Chen (1980), Barth and Titus (1984), and the various papers of Volumes 1 and 4. This paper considers some marine ecological effects that apparently have not been considered, together with suggestions on how to use subtle changes in marine ecosystems as possible indicators of the greenhouse effect.

INCREASED STORMS

Rising air temperature resulting from an increase in atmospheric carbon dioxide (CO_2) and other greenhouse gases will increase sea surface temperatures (SST) (Wendland 1977; Manabe and Stouffer 1980). Warm water of at least 26.8°C (77°F) is needed to supply energy for generation of storms (Wendland 1977; Serra and Buendia 1976). These storms are known as typhoons in the western Pacific Ocean and as hurricanes in the Atlantic and eastern Pacific oceans. The El Nino/Southern Oscillation of 1982-83 in the eastern Pacific (Reed 1983; Rasmusson and Carpenter 1984; Mechoso, Kitoh, and Arakawa 1985; Gray 1984) resulted in a doubling of the average frequency of hurricanes from ten to twenty. Thus, low-lying coastal regions of the world, which are subjected to 6-7 billion U.S. dollars in damage each year, as well as 20,000 deaths worldwide (Anthes 1982), would be subjected to increased frequency and intensity of tropical cyclones, an increase in the duration of the cyclone season, and an increase in the surface water area of warmer sea surface temperature for cyclone generation. Storm surges caused by rising water resulting from landward movement of these huge storms would also increase in frequency, severity, and duration (Bruun 1962).

Two anticipated feedbacks from the greenhouse effect, which will also increase damage caused by cyclones, are associated with an expected rise in water temperature. Two natural buffers against storm destruction of coastal areas are coral reefs and mangrove forests. Increased coastal erosion from cyclones will result in increased water siltation, which reduces growth of corals or kills them (Adey 1978; Tomascik and Sander 1985). A Holocene barrier reef along the southeastern Florida shelf is believed to have died around 7,000 years ago as a result of erosion of the shelf soil cover and consequent smothering of coral (Lighty, MacIntyre, and Stuckenrath 1978). Furthermore, an increase in surface temperatures of only slightly above an ambient temperature of 30°C (86°F) will cause coral mortality (Jaap 1985; Glynn 1985; Lasker, Peters, and Coffroth 1984). A doubling of CO_2 could also lead to a decrease in ocean pH from 8.1 to about 7.8 (Bach 1980; Holm-Hansen 1982; Ausubel 1983), which would cause a dissolution of the calcium carbonate skeletons of which corals are made.

Mangroves and other vegetation will migrate landward with rising sea level, but such mitigation will be inhibited by manmade developments such as bulkheads, levees, and other structures (Titus, Henderson, and Teal 1984). Thus, the protective buffering effects of coral reefs and mangroves against cyclones will be reduced as a result of sea level rise and increased temperatures.

A third feedback of the greenhouse warming is an increase in evaporation and precipitation (Manabe and Stouffer 1980), which would lead to increases in relative humidity in the lower troposphere (Manabe and Wetherald 1975). This should result in greater electrical demand for air conditioning, and hence a greater release of CO_2 into the atmosphere in places where fossil fuels are used for electricity generation.

SEA LEVEL RISE AND EROSION, INUNDATION, AND SALINITY INTRUSION

Sea level rise should cause increased coastal erosion and shoreline inundation because of higher normal tide levels as well as increased temporary surge levels during storms (Sorensen, Weisman, and Lennon 1984). An acceleration of beach erosion in regions already eroding will occur and possibly cause a start in areas previously unaffected by erosion. This will happen because erosion from waves and currents can encroach further up the beach profile (Sorensen, Weisman, and Lennon 1984). Storm surges will be especially damaging from sea level rise in funnel-shaped bays and estuaries.

Saltwater intrusion will be experienced primarily in estuaries and aquifers (Parker 1955), especially along karst limestone coastlines (Bowen 1982), which are found in many of the low-lying countries of the world. As fresh water continues to be withdrawn for consumptive water uses and as human population centers continue to migrate toward the coast, the amount of fresh water used will increase accordingly. Rainfall will decrease, at least in the summer, and reduce the amount of fresh water entering estuaries (Manabe and Stouffer 1980). Saltwater intrusion in estuaries will cause more saline water to move further upstream, especially during droughts. Problems arising from saltwater intrusion into ground water include public health risks from higher concentrations of sodium chloride (a principal component of sea water), which is believed to exacerbate high blood pressure in humans (Braun and Florin 1963). Also important are increased costs of water treatment to remove salt from water for human consumption (Hull, Thatcher, and Tortoriello 1986), agricultural irrigation, manufacturing, and electricity generation (Bowen 1982; Titus and Barth 1984). Plumbing and machinery will also be damaged (Hull, Thatcher, and Tortoriello 1986). Hazardous waste sites in coastal areas, which contain metal drums, would be subject to damage because sea water is highly corrosive to metal (Flynn et al. 1984). All problems of saltwater intrusion caused by sea level rise will be heightened by projected increases in freshwater withdrawals for human use (Wilson 1982). It is important to note, for example, that the State of Florida apparently has no official plan to cope with sea level rise and saltwater intrusion (Tschinkel and Berquist 1986), although this is being given serious thought in at least the Delaware River Estuary (Hull and Titus 1986).

SEA LEVEL RISE AND ESTUARINE ECOLOGY

Estuaries are among the most highly productive ecosystems (Ketchum 1967; Odum 1971; Coutant 1981). They are characterized as areas where freshwater rivers flow into the sea and where tidal action brings about a mixing of salt water and fresh water (Odum 1971). Estuaries, salt marshes, mangrove swamps, and freshwater marshes are all considered important in providing food and protection for a variety of fishes, invertebrates, and birds.

The dominant effects which have been observed following damming, withdrawal, or diversion of freshwater flows are summarized as follows (Snedaker et al. 1977), recognizing, however, that such consequences will be greater or lesser depending upon the absolute reduction in the normal discharge:

- Nearshore waters become more saline.
- Mixing due to salinity differences is diminished.
- A salt-wedge may develop farther upstream in the discharge channel.
- Saltwater intrusion appears in coastal groundwater and surface water.
- The estuary is starved of essential nutrients of terrestrial origin.
- Benthic substrate tends to become anaerobic and heavy metals sequestered in the substrate are liberated; sulfur cycles become dominant.
- Particulate and soluble organic matter inputs are reduced and/or are flocculated and deposited nearshore rather than being dispersed.
- Certain fisheries are lost in their entirety for a variety of reasons, such as elevated salinity, reduction in food supply, and loss of a large area of low salinity.
- Euryhaline species lose dominance to stenohaline species and, in general, selection is for species adapted to the new conditions.
- Salt-tolerant mosquito and dipteran populations increase.
- Schistosomiasis becomes rampant.
- All negative effects are aggravated during low-flow periods.
- Saltmarshes and/or mangroves and seagrass beds deteriorate under constantly elevated salinity.
- Renourishment of sand/silt ceases; downstream shoals erode.
- Littoral drift patterns are altered as well as nearshore circulation.

As sea level rises, salt water will move farther into the estuary and prevent this freshwater outflow (Stone et al. 1978). These effects are complex and intertwined, as summarized by Snedaker, deSylva, and Cottrell (1977), and which are reviewed as follows:

Fresh water in estuaries is important as:

- Diluter of salt water. Lighter fresh water runs off land and into rivers, then toward the sea, while heavier salt water moves into the estuary. This forms a salt-wedge, which extends significant distances up the river channel (Pritchard 1967). A rise in sea level would extend the upstream movement of the salt wedge.

- Protector of fish, shrimp, oysters, and other biota. The temperature, salinity, food, substrate, and protection found in estuaries is balanced for a host of organisms to carry out their life cycles, and this optimum combination cannot be found in environments that are more saline or less saline (Odum and Heald 1975). Between 66% and 90% of the U.S. fisheries depend upon estuaries for their life cycle (Douglas and Stroud 1971). The dependence of fisheries upon estuaries has been documented for other parts of the world (e.g., MacNae 1968). Estuaries provide sites for reproduction and protection of young, moderate water temperatures, osmoregulation of the salt balance in marine organisms (Fontaine 1975), and an environment that is optimum for larval and juvenile fishes and invertebrates (Heald and Odum 1972).

One of the most important functions of estuaries, including the freshwater-dependent salt marshes and mangroves, is their contribution in providing organic and inorganic nutrients from the breakdown of their leaves, stems, and roots (Heald and Odum 1972). Adverse effects on estuarine productivity have been caused by diversion of fresh water away from marshlands (Carter et al. 1973). A decrease in the catch of fish and invertebrates in South Vietnam followed the nearly complete herbicidal defoliation of mangrove forests (deSylva and Michel 1974; deSylva 1975). Decreases in freshwater runoff caused by rising sea level would decrease the food resources or nutrients that form the basis of the food chain (Heald 1970; Reeve 1975).

Estuaries also offer protection to organisms by reducing predation and competition because the combined conditions of temperature, salinity, and turbidity, to name a few, cannot be tolerated by organisms normally found in offshore regions, but which are stenotopic and cannot adjust to the eurytopic conditions of the estuary (Green 1968).

The larvae of marine organisms that utilize the estuary for protection are able to carry out relatively long-distance horizontal movements toward more suitable habitats by selectively responding to either ebb or flood tide water characteristics (Hughes 1969). Changes in freshwater balance from estuaries due to increased salinity could thus affect the survival of pelagic larvae.

Estuaries also act as cutting and filling mechanisms. Rivers carry an estimated 30 billion metric tons per year of suspended material to the oceans (Turekian 1968). The best examples of this material, which is derived from erosion of the continental landscape, are found in areas where deltas are forming. These are regions where a river carries more sediment into a standing body of water than can be carried away by waves and currents. Here, the river velocity drops and the suspended sediments are deposited. Much of this deposition occurs at the river mouth as a sandbar deposit or as an alluvial plain, which eventually becomes a salt marsh or a mangrove swamp, which acts as a barrier to storms and surges to protect the land behind them (Warnke 1967). A rise in sea level would reduce the amount of sediment-laden runoff entering the coastal zone, thus reducing the protective nature of the sandbars. Salt marshes faced with rising sea level and a reduction in river-borne sediments could be converted to open-water habitats due to drowning (Orsen, Panageotou, and Leatherman 1985).

The reduction of freshwater inflow into estuarine systems and consequent increase in salinity has resulted in considerable changes in fisheries, currents, plankton, and benthos (Neiman 1974); has caused extensive changes in salt-marsh ecosystems (Hoese 1967); and has changed spawning migrations of economically important fishes (Massmann 1971). The latter phenomenon is believed to occur because many estuarine-dependent fishes, and probably invertebrates, respond to very slight gradients on brackish water, turbidity, or dissolved organic compounds to give them olfactory cues that trigger their migrations (Frolander 1964; Hoese 1967). A high correlation has also been shown between white shrimp catches and freshwater input into estuaries (Gunter and Edwards 1967). Salinity increases in estuaries due to sea level rise would diminish the freshwater runoff of estuaries and concomitantly reduce the various physio-chemical signals that organisms use to guide them into the estuaries.

An increase in estuarine salinity would favor the establishment of nuisance organisms, which normally are excluded from the estuary because of the low salinity. This effect would be exacerbated if sea surface temperatures were also to increase, because many of these nuisance organisms are tropical, and can become part of new coastal ecosystem shifts, which already has occurred as the result of warm-water discharges from electrical power stations (Krenkel and Parker 1969; deSylva 1969). Among these high-salinity organisms are the destructive mollusk Teredo (or shipworm), the crustacean Limnoria, and barnacles, which destroy wooden structures such as docks, pilings, and boats, causing extensive economic damage. Barnacles, which are scarcer in estuaries than in areas of higher salinity (Moore and Frue 1959), cause fouling of submerged objects, especially boat hulls, which must be periodically hauled and scraped (Ray 1959). (Barnacle-oyster communities may prove to be very good indicators of both sea level rise and increasing salinity in estuaries [Wanless 1982].)

Stingrays are bottom-feeding coastal fishes that can crush mollusks with their powerful jaws. In coastal areas, they cause extensive damage to clam beds. Their movement into estuaries as salinity increases would be associated with extensive damage to oyster beds. Similarly, oyster drills and oyster parasites, normally absent from estuaries because of their intolerance for low salinity, should increase their infestation of oyster beds. Sharks, which normally are not present in estuaries, which have low salinity levels, would be more likely to enter higher salinity estuaries, thus posing potential dangers to humans engaging in water sports.

Estuaries play an important function in dispersing pollutants. Normally, well-mixed estuaries with rapid flushing rates can dilute pollutants rather quickly (Pritchard 1967). However, reduced circulation from increased salinity due to sea level rise should diminish the ability of estuaries to perform this function.

It is clear, based upon the results of the National Symposium on Freshwater Flow to Estuaries (Cross and Williams 1981), that freshwater flow plays an intricate and complex role in the functioning of estuarine ecosystems. Rising sea level will surely decrease freshwater input into estuaries and reduce estuarine ecological and economic importance to mankind.

RESEARCH RECOMMENDATIONS

Meteorologists, physical oceanographers, atmospheric chemists, and geophysicists have tried to document the "greenhouse effect" and resulting climate change by attempting to detect statistically significant increases in air and water temperatures, glacial melting and retreat, and sea level rise. One problem seems to be that the variance fluctuates greatly about trends in the mean values, the so-called "signal-to-noise ratio." However, there appears to be little effort by biologists to use aquatic species or communities as biological indicators of rises in sea level and sea surface temperatures, or changes in dissolved gases or ionic concentrations. Sea level changes have long been known to be reflected in zonation of intertidal communities (Scholl and Stuiver 1967; Cubit 1985), while more recent evidence can be seen in a corresponding rise in the location of an oyster-barnacle community in a Coral Gables, Florida, coastal waterway between 1949 and 1981 of 15 cm (Wanless 1982).

Slight increases in water temperatures result in subtle changes in marine and freshwater organisms, which show physiological, behavioral, and ecological responses (Kinne 1984). Species and community shifts have thus been observed during long-term climate fluctuations on the U.S. Pacific coast (Hubbs 1948), over rather short periods due to El Nino (Gerard 1984; Glynn 1984), and over longer periods in the North Sea (Cushing 1978; Blacker 1957) and in North America (Dow 1969; Cushing and Dickson 1976). Short-term changes are seen as a result of thermal pollution, in which entire ecosystem shifts along a coastline can be documented as a result of warmer sea surface temperatures resulting from warm-water discharges from electrical power plants (Krenkel and Parker 1969; deSylva 1969; Kinne 1984).

It would seem that a golden opportunity is thus presented to marine and freshwater ecologists to benefit from the extensive literature on the relationships between aquatic organisms and increased temperatures to monitor the global experiment known as the "greenhouse effect."

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Rising Sea Level and Damming of Rivers: Possible Effects in Egypt and Bangladesh

James Broadus, John Milliman, Steven Edwards,
David Aubrey, and Frank Gable
Woods Hole Oceanographic Institution
Woods Hole, Massachusetts USA

INTRODUCTION

The projected worldwide rise of sea level during the next 100 years will be particularly hard-felt in deltaic areas where substantial areas are barely above sea level. Regional subsidence will increase the relative rate of sea level rise; and damming of large rivers could prevent sediment influx from compensating for regional subsidence, increasing coastal erosion. These effects will be felt most in developing countries, where the rivers are large, deltas extensive and inhabited, and proposed damming of large rivers may dramatically increase coastal erosion.

To help understand the potential consequences of sea level rise in the deltaic regions of the world, we have concentrated our attention on two areas that seem especially vulnerable: the Nile River delta in Egypt, which has already been dammed, and the delta of the complex Ganges-Brahmaputra-Meghna River system in Bangladesh, in which river damming has begun and is expected to increase during the next 15 years.

STUDY APPROACH

Our general approach for characterizing possible consequences of sea level rise in these two regions has been as follows: First, geological information has been employed to describe likely scenarios of shoreline change for scenarios of future dams and relative sea level for the next 100 years. These scenarios have then been used to describe the geographic areas within Egypt and Bangladesh that will be affected by landward transgression.

Next, demographic and economic information has been examined to portray the scale of economic activities within each nation that currently originate within the potentially affected areas.

Several limitations of this approach are immediately obvious. Geologically, we know little about the rates of subsidence in either the Nile or Bengal deltas, nor do we know the actual sediment flux from the Ganges-Brahmaputra River which flows into Bangladesh. The economic analysis reports current, not projected levels of economic activity within the two countries. Although techniques have been developed and employed elsewhere to measure the present monetary value of potential economic damages associated with physical scenarios for sea level rise (Barth and Titus 1984), we employ a more simplified way of describing the economic significance of future sea level rise. We have not yet attempted to describe the complex interactions of social processes that will come into play in response to rising sea level, such as the subtle social relationships identified by Warrick and Riebsame (1983).

Our approach employs a highly aggregated and very coarse scale of data to arrive at a rough characterization of the current scale of economic activities that are at stake as relative sea level rise encroaches on the areas of interest. It is extremely mechanical, intended only to portray the current scale of economic activities and population in potentially affected areas. It does not take into account future mitigation measures, nor adaptive responses, nor future changes in the distributions of economic activities and population. We suspect that our methods result in conservative approximations of the economic stakes, since we do not add future economic and population growth to our data on current conditions.

Deltaic regions may be particularly susceptible to disruptions from rising sea level because of the delicate balance achieved by deltas at the river/ocean interface through newly delivered sediment via river transport, local subsidence as deltas tend to sink, and the erosional forces of oceanic energy, waves, and storms. In this analysis, we focus on the net effect of subsidence and rising sea level, which consists of two primary elements: (a) global changes in sea level; and (b) local effects through subsidence or uplift. A third major influence that comes into play in river delta areas is the delivery of new sediments to nourish the delta itself. Subsidence can be thought of as that associated with tectonic movements and the more superficial subsidence resulting from compaction and dewatering of the soils that pile up to make the delta. Removal of sediments, as through upstream damming projects, reduces the ability of the delta to build itself seaward or to stabilize itself against the forces of subsidence and erosion.

Two other major influences are important for an analysis of potential effects of sea level rise on delta regions. The first is saltwater intrusion. As sea level rises the wedge of salt water that underlies the delta's fresh ground water is forced farther and farther inland, contaminating ground water used for drinking and agricultural purposes. A second major consideration, particularly in Bangladesh, is increased exposure to violent inundation by storm surges.

Two scenarios are examined here. The more optimistic scenario assumes a 1-m (3-ft) rise in relative sea level over the next 100 years (Hoffman, Keyes, and Titus 1983). This case can be thought of as a 50-cm (1.5-ft) rise in eustatic sea level combined with a 50-cm increase in local subsidence. The more pessimistic high case assumes a 3-m rise in relative sea level: the result of a 200 to 250-cm rise in eustatic sea level and a 50 to 100-cm local rise due to subsidence and reduced sediment delivery. Such reductions in

sediment delivery have already been experienced in Egypt, resulting in severe erosion in the delta there; and such effects could also be expected in Bangladesh in association with future water management projects such as dams and barrages upstream.

We now consider the nature of human activities taking place in two deltas.

EGYPT: THE NILE RIVER DELTA

The vital role of the Nile River in the nation's economy has been recorded for millenia. Herodotus wrote, "Egypt is the Nile and the Nile is Egypt." The population is densely clustered about the banks of the river and throughout the river's delta (Figure 1). Of the country's million square kilometer area, only about 35,000 square kilometers, or 3.5%, is cultivated and settled (Quarterly Economic Review of Egypt - 1985). This results in an estimated population density in 1985 of about 1,400 people for every square kilometer of arable land in the country. The deltaic area examined here extends from just west of the port city of Alexandria and eastward to Port Said at the northern entrance to the Suez Canal. Alexandria, exposed since antiquity to the forces of the sea and historically reached by a causeway extending to its walled enclosure, today contains about 3 million inhabitants. Port Said, at the eastern extremity of our study area, is the home of nearly one half million residents. The densely inhabitated delta between is devoted to intensive, multi-crop agriculture, and to urban and industrial uses (Figure 2).

Within this century, severe erosion has been documented on the delta coastline (Milliman 1986). Large reductions in the delivery of nourishing sediments to the delta began with the construction of the delta barrages in 1881. Additional diversion of Nile sediments resulted from the construction of the dam at Aswan in 1902 and its enlargement in 1934. Even so, approximately 80-100 million tons of sediment were delivered annually by the Nile to the delta before 1964. Closure of the high dam at Aswan in 1964, however, entirely eliminated sediment delivery to the delta. This loss of sediment, combined with tectonic subsidence on the order of 5-6 m every few thousand years, has resulted in spectacular erosion of the Nile delta. As can be seen in Figure 3, the delta's numerous former distributaries have been closed down by water management, irrigation, and land reclamation projects, so that the Nile's flow through the delta is channeled into only two major distributaries: the Rosetta on the west and the Damietta on the east. Many areas along the delta's coast have experienced annual erosion rates in excess of 1 m, between 1966 and 1974 (Figure 3), and locally, erosion has exceeded 100 m per year (Milliman 1985; Bird 1985; Inman, Aubrey, and Pawka 1976).

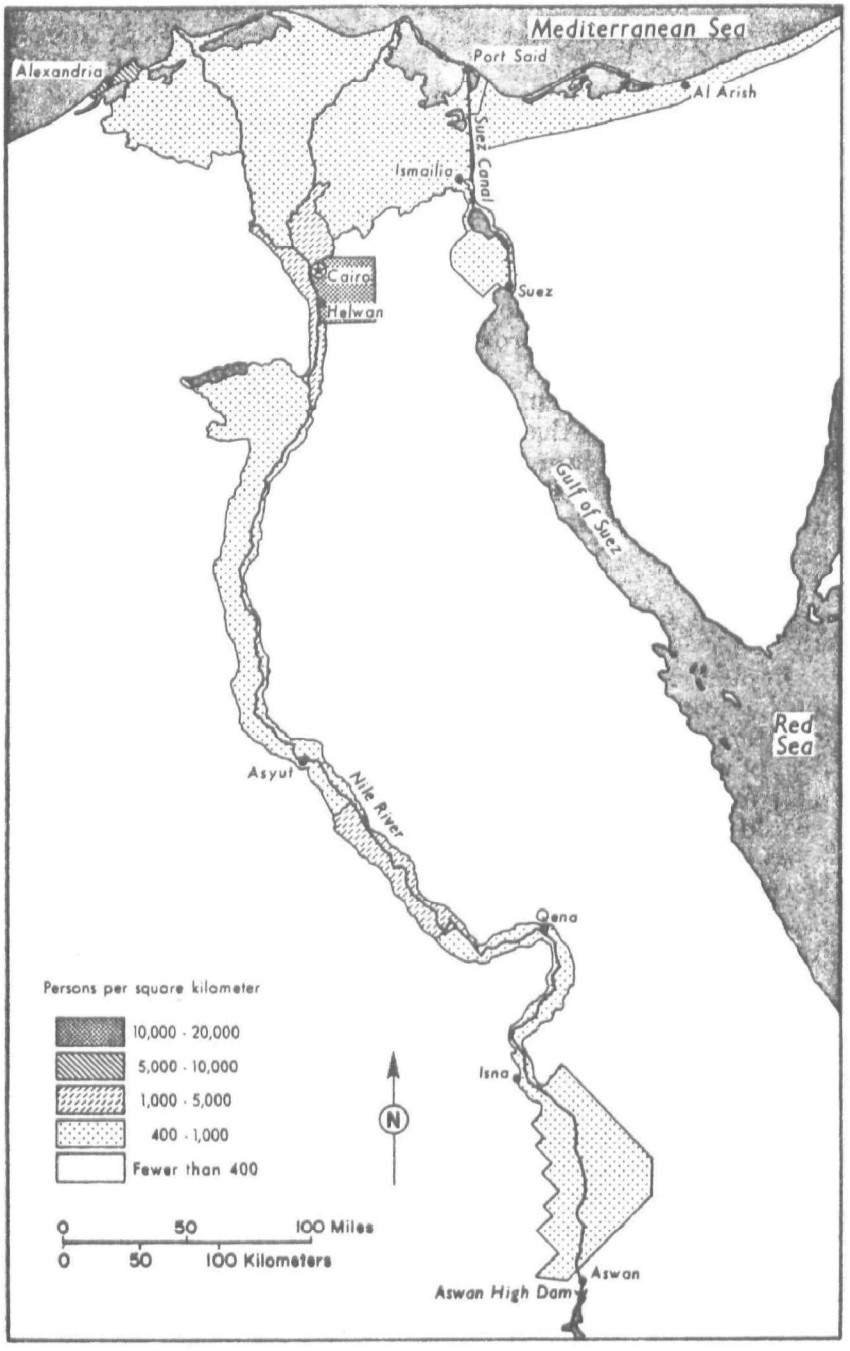

Figure 1. Population Density in Egypt 1982
Source: Central Agency for Public Mobilization and Statistics 1982

Figure 2. Nile Delta
Source: NASA

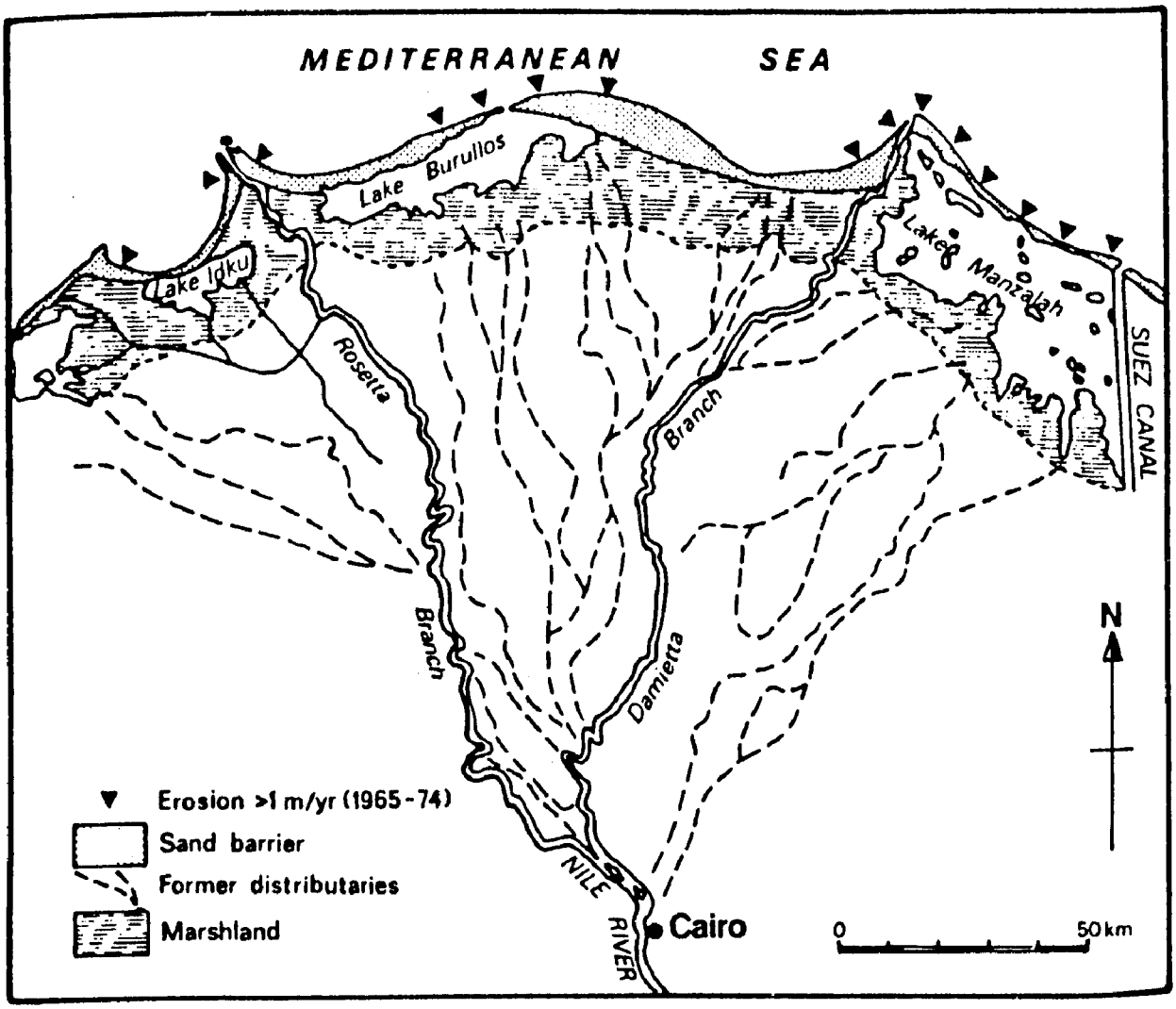

Figure 3. Coastal Erosion on the Nile Delta
Source: Bird 1985

Figure 4 illustrates the additional landward transgression that might result from a 1-m or a 3-m rise in relative sea level. The major existing natural defenses against such a retreat on the shore are the series of sand dunes along the delta's coast and the increasingly brackish lakes--Maryut, Idku, Burullos, and Manzalah--that lie behind them. These lakes are a major source of the nation's approximately 100,000 ton annual fish catch, 80% of which is freshwater fish. The area that might be inundated in the low scenario represents approximately 12%-15% of the nation's arable land and contains approximately 16% of the nation's estimated 49 million population, or almost 8 million people. The area that could be lost to the sea in the high scenario represents about 20% of the nation's arable land and is inhabited by over 10 million people, some 21% of Egypt's current population.

Assuming that agricultural output in the delta is distributed as arable area, and assuming that all other sectors of economic activity, as specified in Table 1, are distributed as population, we estimate that approximately 15% of Egypt's current gross domestic product (GDP) originates in the area likely to be affected by the 1-m increase in relative sea level. Similarly, approximately 20% of the nation's current GDP originates within the area likely to be affected by a 3-m increase in relative sea level. The magnitudes of economic activities comprising GDP that thus originate in the likely affected areas are disaggregated and reported in Table 1. It is worth noting here that large areas apparently targeted for priority development in land reclamation projects, both south of Lake Manzalah in the region of Port Said and around Lake Maryut in the region of Alexandria, lie within the area likely to be flooded by even a 1-m increase in relative sea level.

BANGLADESH: THE GANGES-BRAHMAPUTRA-MEGHNA DELTA

We turn now to the even more serious exposure that exists in Bangladesh (Figure 5). This densely populated nation of an estimated 93 million people covers an area of 143,000 square kilometers. Eighty percent of this area is made up of the complex Bengal delta system created by the Ganges, Brahmaputra, and Meghna Rivers. Together, the Ganges and the Brahmaputra currently deliver approximately 1.6 billion tons of sediment annually to the face of the delta (Milliman and Meade 1983). The seaward face of this delta extends some 650 km from the western boundary with India to the Chittagong Hill Tracts on the east.

The country's population is widely distributed, with heavy concentrations in the major city of Dhaka (population about 4 million), in the southwestern city of Khulna (population 800,000), and in the eastern port city of Chittagong (population about 1.5 million). Most of the remaining population is rurally dispersed and dependent on subsistence agriculture. Much of the population lives at the very edge of subsistence: it is estimated that 85% receive less than the 2,122 calories per day considered necessary for minimal subsistence (Jansen 1983). Per capita GNP is approximately $140, compared with that of Egypt, which is $670, and that of the United States, which is over $13,000. Under- and unemployment rates in Bangladesh are estimated in the 35-40% range, and population increase is in the range of 2.5%-3.0% per annum.

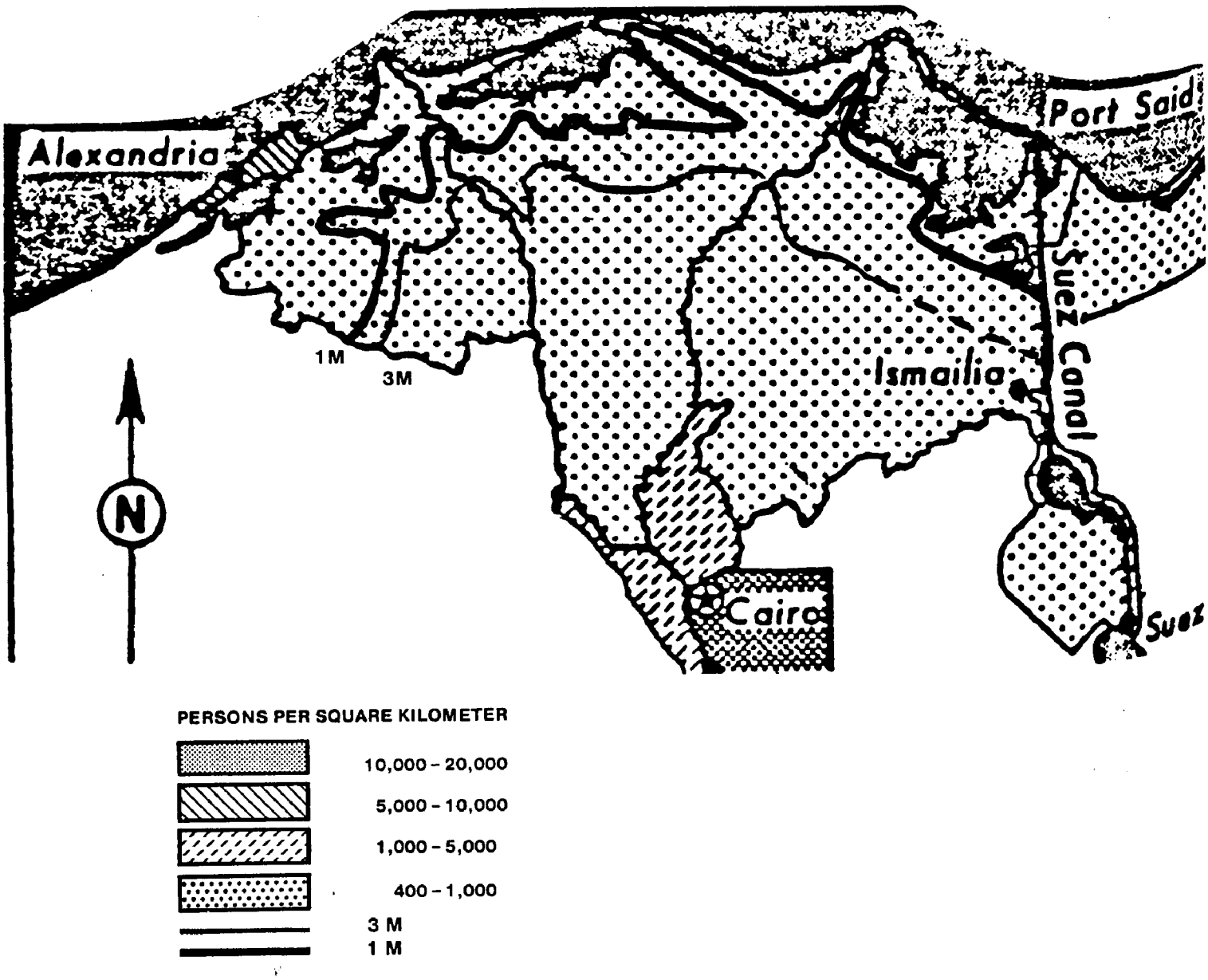

Figure 4. One-meter and three-meter transgression scenarios for relative sea level rise in the Nile Delta (detail from Figure 1).

(Note: Dashed segment in three-meter scenario projected in lieu of exact topographic detail.)

Table 1. Economic Activity and Population Originating in Affected Region: Egypt (1984-85)

Activity*	One-Meter Scenario	Three-Meter Scenario
Agriculture	631	1,052
Industry and Mining	674	885
Oil and Oil Products	785	1,030
Construction	237	311
Power, Water and Sanitation	41	54
Transportation, Storage, and Communications	258	338
Trade Services and Finance	916	1,202
Housing	95	125
Miscellaneous Services	804	1,056
GDP in Affected Region	4,441	6,053
Total GDP	29,872	29,872
Percent of GDP	15	20

*Values in millions of Egyptian pounds in 1984/85. ($1 U.S. = 1.23/pounds in 1983)

Total Estimated Population	48.6 million	48.6 million
Estimated Population in Affected Region	8 million	10 million
Percent Population in Affected Region	16	21

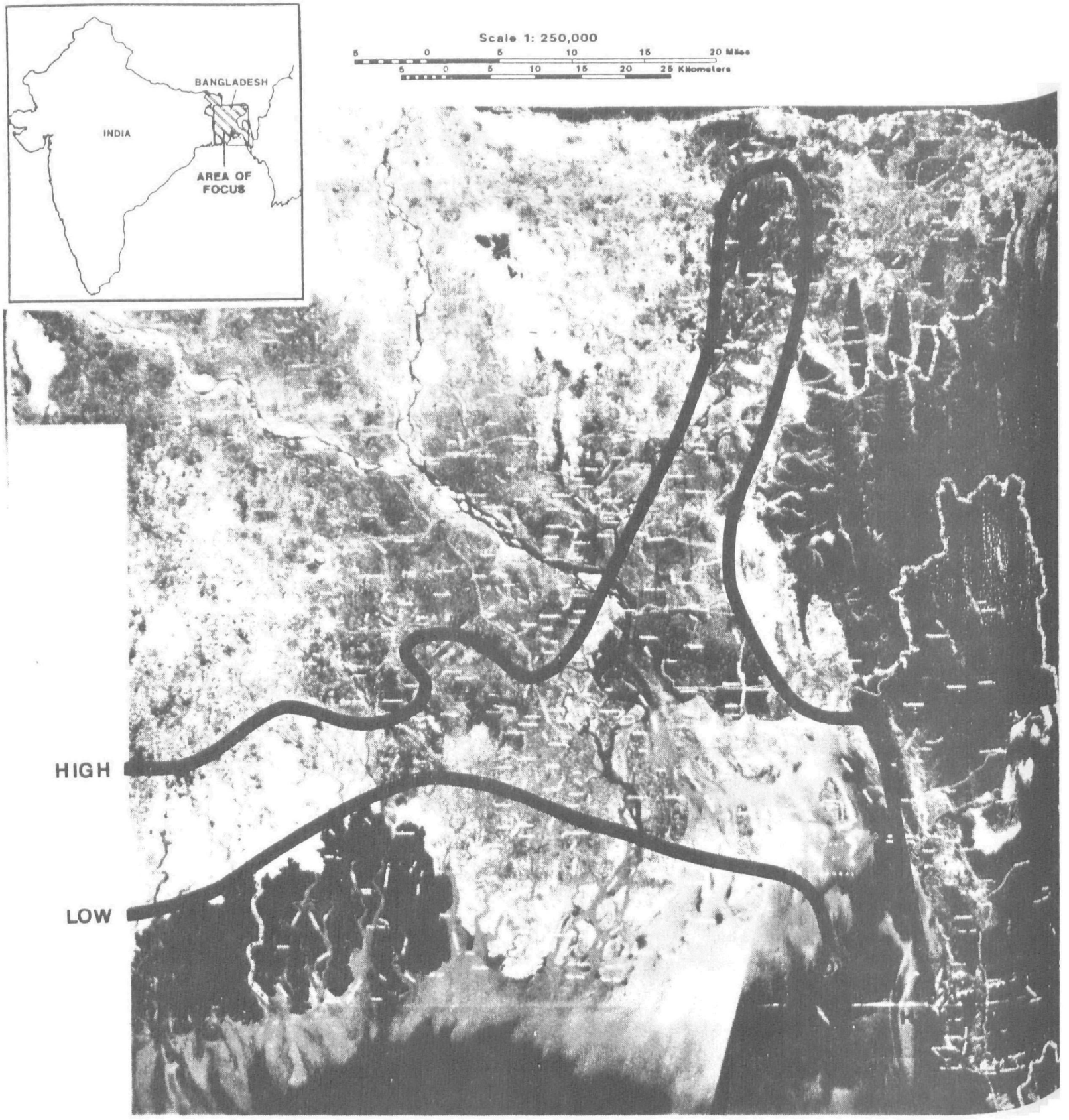

Figure 5. Infrared Aerial Photograph of Bangladesh
Source: World Bank and Plate 4 of Volume 1 of this report

When superimposed on shoreline retreat from the low and high sea level rise scenarios (Figure 6), the spatial distribution of population shows that approximately 9% of the nation's present population would be directly affected by a 1-m rise, and 27% of the total population would be affected by a 3-m rise. The densely populated area around the southwestern city of Khulna, where population density exceeds 2,900 per square kilometer, stands between the 1-m and 3-m transgression lines (Figure 7). Similarly, the heavily populated environs of the Meghna River eastward of Dhaka would clearly be greatly affected in the case of a 3-m relative sea level rise.

Exposure of the population to storm surge is an extremely grave consideration in Bangladesh. On average, 1.5 severe cyclonic storms attack the country each year with storm surge reaching as far as 160 km inland in recent times (Bird and Schwartz 1985). The May 1985 storm is estimated to have killed over 5,000 people, and the tragic November 1970 storm surge is believed to have taken the lives of over a quarter of a million people. Assuming a similar 160-km reach in the case of a 3-m relative sea level rise, the area likely to be exposed to storm surges 100 years hence can be seen in Figure 7 as the area extending 160 km beyond the 3-m line. The plight of Dhaka is obvious. With increasing population densities in the future, through the combined effects of natural population increase and loss of territory to coastal transgression, the exposure to severe storm surges will only increase.

In the context of storm surge, a noteworthy feature of today's delta is the 6,000-km^2 mangrove and nepa palm Sundarban Forest Preserve in Khulna District on the southwestern coast. A maze of heavily forested waterways, this preserve, with no permanent settlement, stands out clearly in Figure 7. Immediately behind, however, are heavily settled areas, including the densely populated environs of Khulna. It may be presumed that the Sundarban forest provides vital protection for these settled areas by acting as a buffer against the force of storm surges. Loss of this buffer could greatly increase the threat of storm surges, and the forest appears to be vulnerable to even a 1-m rise in relative sea level. Indeed, near-term monitoring for the killing effects of heightened salinity may be warranted at the Preserve's coastal margins.

Agricultural production represents approximately 55% of the nation's gross domestic product, and it is estimated that over 85% of the nation's population depends on agriculture for its livelihood. Major crops alone account for about 40% of gross domestic product. Net cropped/agricultural areas (represented by horizontal hatching in Figure 8) are obviously the major use of land in Bangladesh. We estimate that about 8.5% of the nation's agricultural output originates in the area seaward of the 1-m relative sea level rise scenario, this represents about 11% of the nation's crops. Estimated agricultural output originating seaward of the 3-m scenario line totals 21% of the nation's agricultural output, or about 27% of the nation's crops.

A major consideration for agricultural productivity is the intrusion of salt water into the nation's fresh ground water resources. Current estimates suggest that saltwater intrusion now extends as far as 150 miles or about 240 km inland (Zaman 1983). Assuming, however, that the high scenario unfolds, the wedge of saltwater could be driven another 240 km northward. If the Bengal rivers are effectively dammed, it is conceivable that nearly the entire nation could be affected by the intrusion of salt water.

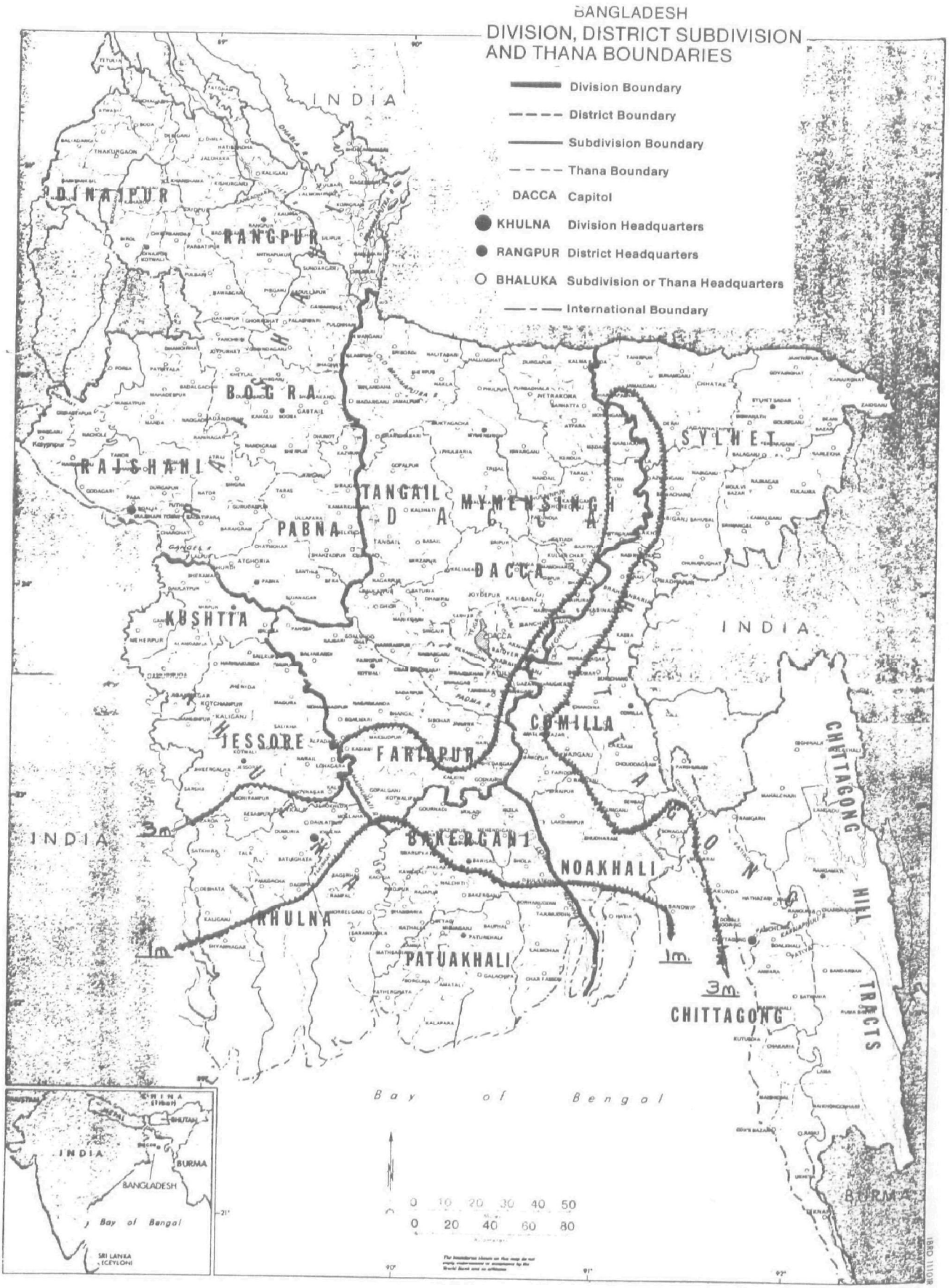

Figure 6. One-meter and Three-meter Transgression Scenarios for Relative Sea Level Rise in the Ganges-Brahmaputra-Meghna River Delta

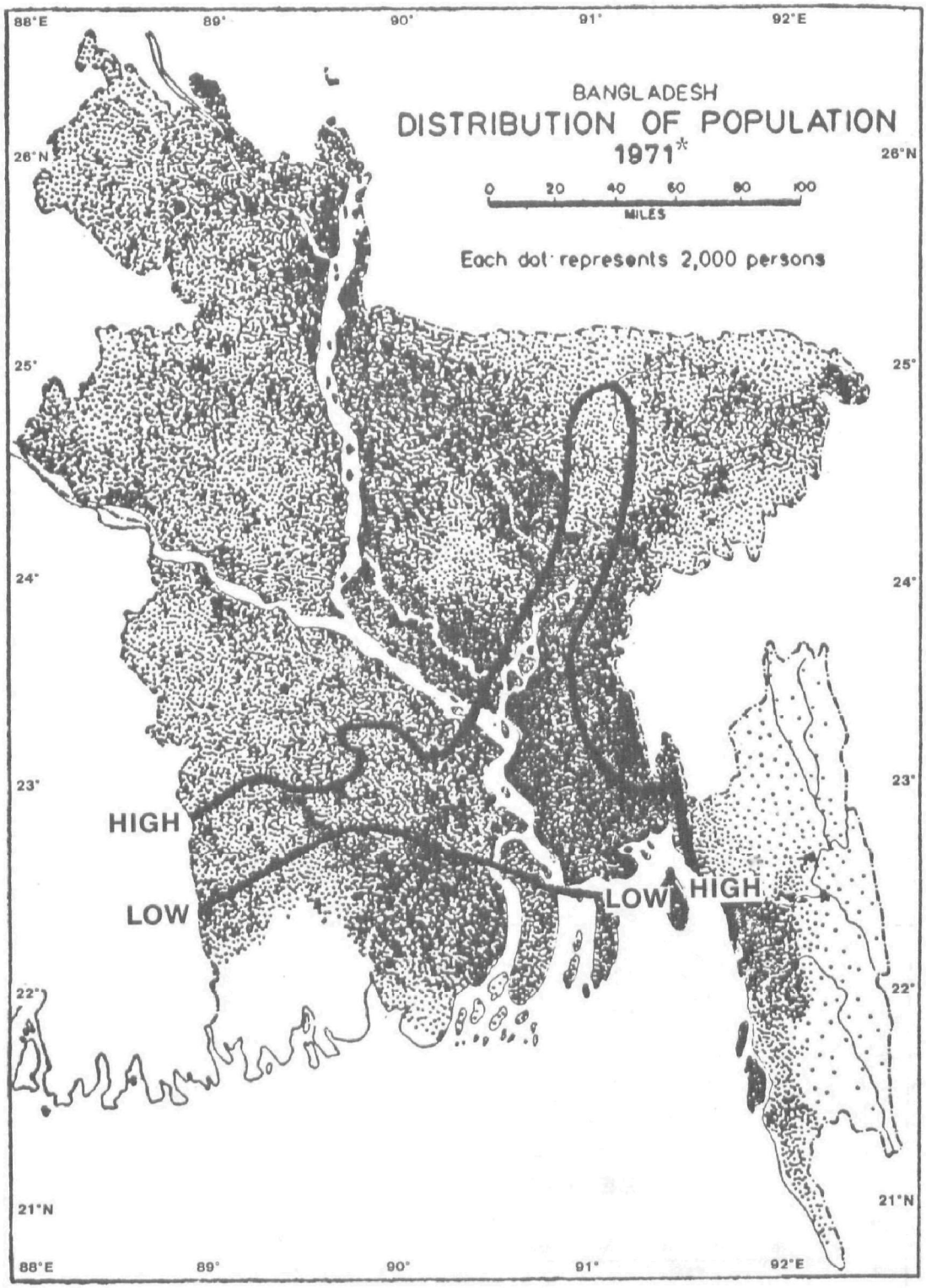

Figure 7. Distribution of Population in Bangladesh
Source: Ahmad 1976

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* 1971 Distribution used for graphical presentation only. Projected 1985 population by district used in scenario estimates reported in text.

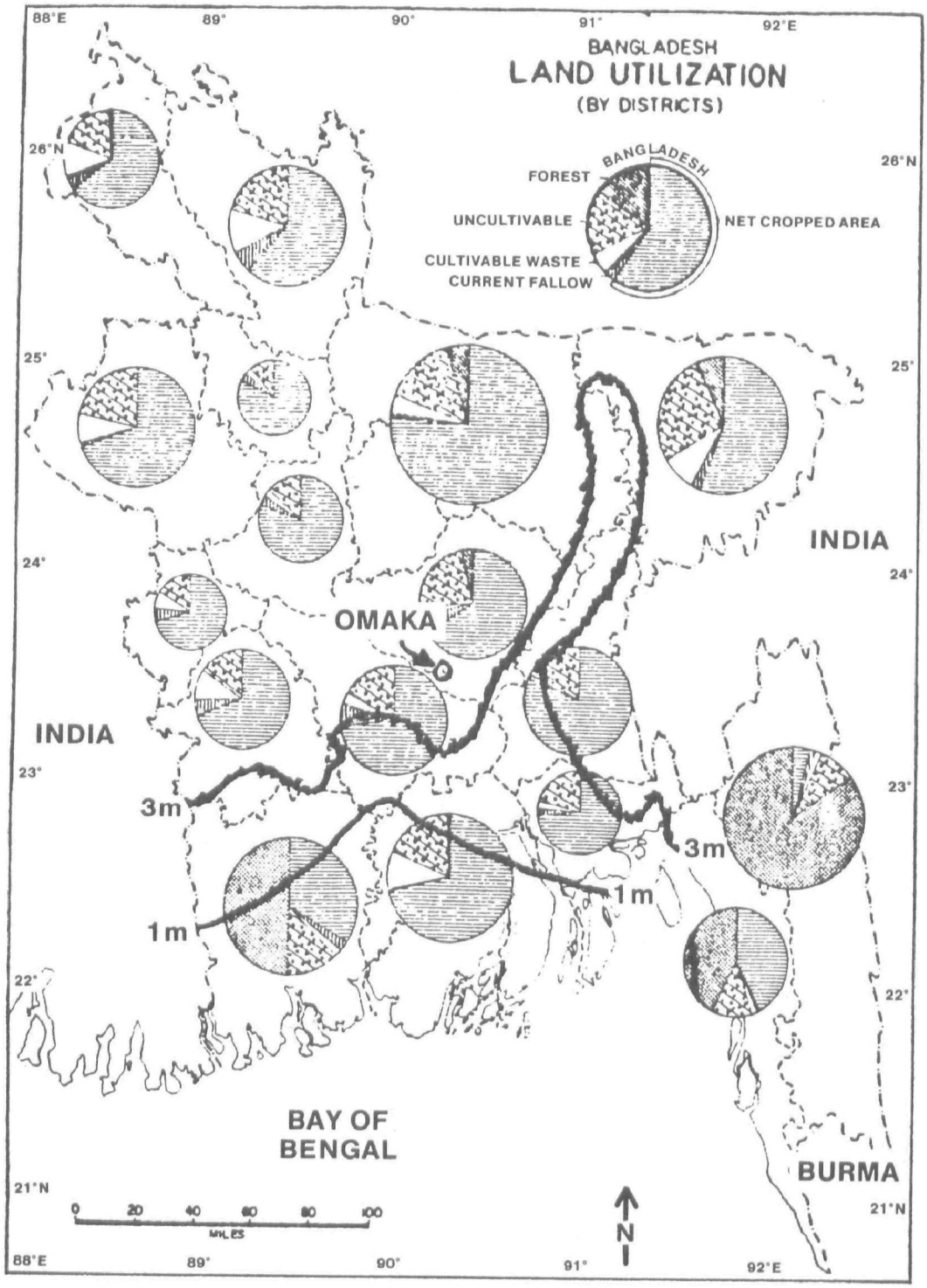

Figure 8. Land Utilization in Bangladesh
Source: Ahmad 1976

It will be difficult to replace the croplands lost to sea level rise because the countryside is already so extensively cultivated. Of the 24.5 million acres in the nation estimated to be cultivable, approximately 22.5 million acres, or more than 90%, are already in cultivation (Zaman 1983). Currently fallow areas (Figure 8) constitute a negligible percentage of land utilization. Further prospects for increasing agricultural usage in northern districts (the only area possibly unaffected by salt water intrusion) are also a relatively small proportion of the total (Figure 8). Increasing the intensity of agricultural land utilization through multiple cropping strategies may show some promise as a response to loss of agricultural lands. Of the nation's net cropped area, over half is currently used for only one crop per year, while 39% is used for two crops annually and about 7% is fully utilized in the production of three crops (Quarterly Economic Review of Bangladesh 1985). However, much of the land in the delta least likely to be affected by coastal transgression is in relative topographic highs produced by old delta sediments of distinctly poor fertility and is less productive for agriculture than the extensive new delta most likely to be flooded.

These differences in agricultural productivity can be discerned in Figure 9, which shows that areas with relatively poor rice production, northwest of Dhaka and along the northwestern boundaries with India, are the old deltaic soils of low agricultural value. Rice accounts for 90% of the nation's total grain output, 73% of the nation's cropped area, and 28% of the nation's gross domestic product. It is the vital food staple for the nation's population. As seen in Figure 9, a significant portion of the nation's rice producing areas would be lost from a low rise, an even more would be lost with a 3-m rise.

The other vital crop in the nation's agricultural output is jute (Figure 10). Jute and jute products represent some 55% of the nation's export revenues and approximately 50% of agricultural earnings. Approximately 2-2.5 million acres are devoted to jute production, representing 11% of the nation's total agricultural area. Although only about 0.8% of the nation's jute production originates in the area seaward of the shoreline for a 1-m rise, a 3-m rise would affect nearly 16% of the production, which would be close to 9% of the nation's current export revenues.

The loss of land would also affect fishing. Although fish production only accounts for about 5% of GDP, it represents an estimated 80% of the nation's total production of animal protein. About 1.5 million people depend on fishing activities for their livelihood. The nation annually produces about 700,000 tons of fish, 80% of which are freshwater species. Fish products are the nation's fourth leading export commodity after jute products, jute, and leather, exceeding even exports of tea. We estimate that 7.5% of the nation's major fishing centers are in the area affected by the 1-m relative sea level rise. Forty-one percent of the nation's fishing centers are within the area affected by the 3-m scenario. It seems likely, however, that fishing centers are subject to considerable relocation and the fishing industry, in part due to its largely artisan nature, may be in a position to respond with great flexibility over the coming century to changing configurations and conditions in the distribution of the nation's aquatic resources. More drastic would be the combined effect of decreased river flow <u>and</u> sea level rise. In the Nile Delta, the offshore sardine industry ceased

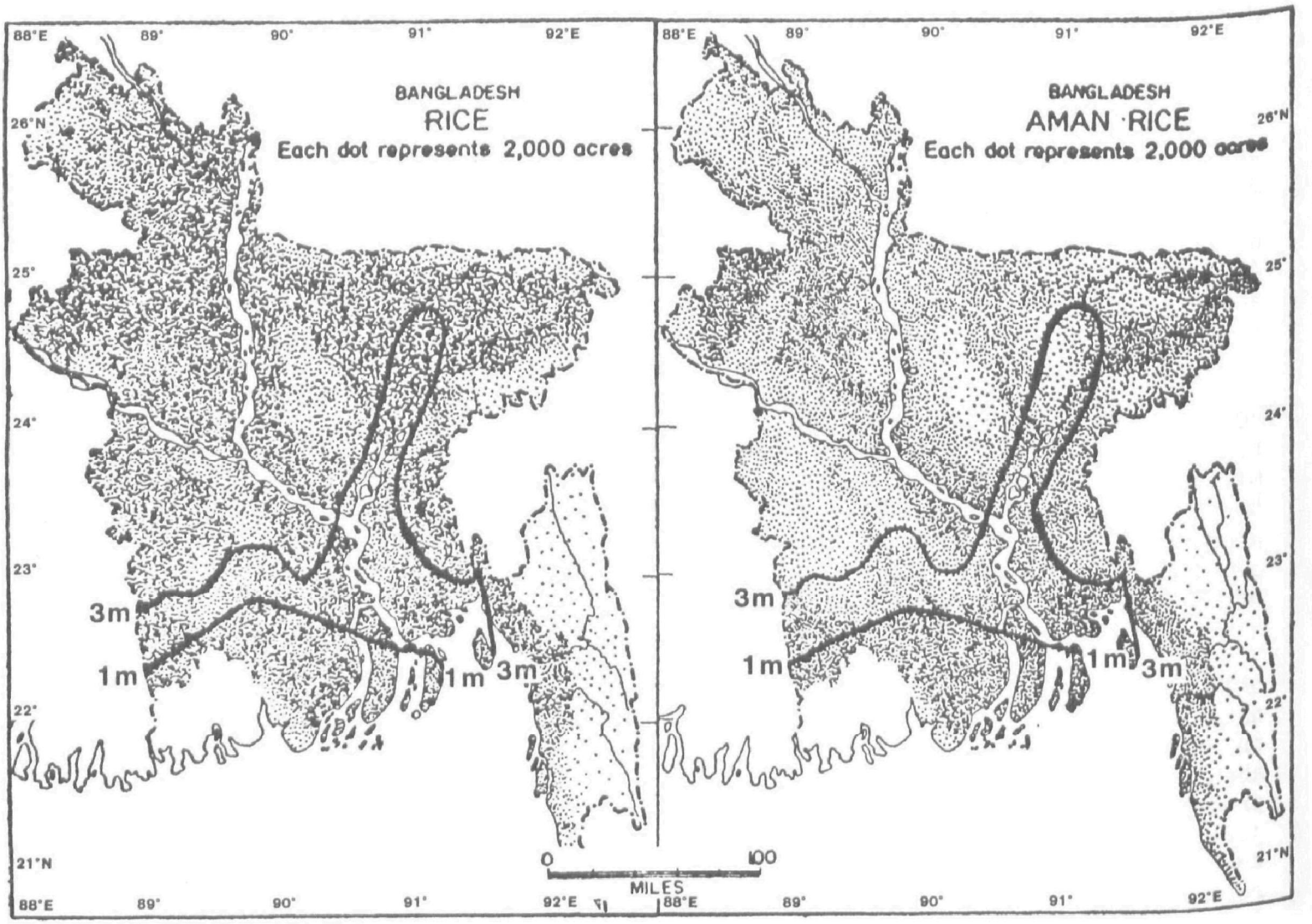

Figure 9. Rice and Aman Rice Production in Bangladesh
Source: Ahmad 1976

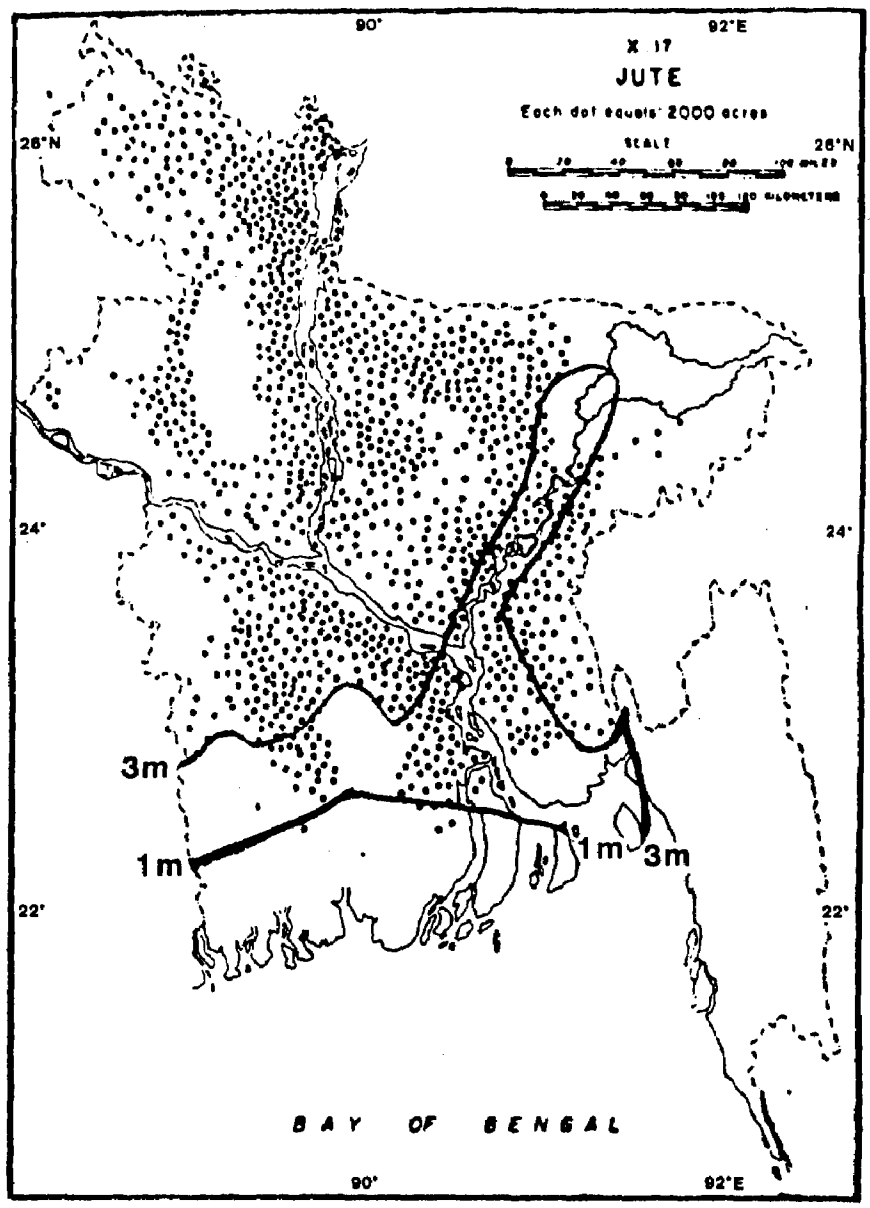

Figure 10. Jute Production in Bangladesh
Source: Er-Rashid 1977

within a few years after the fertile Nile waters stopped entering the Mediterranean. Similarly, since the construction of the Kotri barrage on the Indus River, fish catch per fishing boat in coastal waters has fallen by nearly 75% (Quraishee 1985).

Large industries in Bangladesh are portrayed in Figure 11. Many are associated with jute products, and as with the case of jute production, we see that only a relatively minor proportion is found within the area likely to be affected by a 1-m relative sea level increase. However, a significant portion of the nation's industrial activity appears to be situated within the area affected by the 3-m rise.

The current economic activities originating in potentially affected areas within Bangladesh are summarized in disaggregated form in Table 2. For purposes of this disaggregation, we assume conservatively and for the sake of simplicity that, except for the Sundarban and Chittagong forests, agriculture is uniformly distributed over the nation's entire land area. About 11% of agricultural GDP is thus contained within the area affected by the low scenario and about 27.5% within the area affected in the 3-m scenario. Economic data indicate that approximately 1.5% of the nation's industrial activity originates within the area likely to be affected by a 1-m rise, with 5.5% of industrial production originating within the area affected by a 3-m case. We assume that transport, storage, and communications; trade and services; banking and insurance; and professional and miscellaneous services are distributed in the same way as industry. In a similar manner, we assume that construction activities; power, water, and sanitation; housing; and public administration and defense are distributed as population, whose distribution we know from other sources (Central Agency for Public Mobilization and Statistics 1982). Thus, between 9% and 10% of those activities currently originate within the area that would be affected if the sea rises 1 m, while nearly 28% originate within the area that would be threatened by a 3-m rise in relative sea level. Altogether, some 8% of the nation's current GDP is estimated to originate within the area that could be lost in the 1-m scenario, while about 20% originates in the area to be threatened by 3-m rise.

As shown in Figure 12, there may be some reason to fear that a 3-m rise in relative sea level would threaten more areas than portrayed in our scenario. Notice that a large area surrounding the upper reaches of the 3-m contour along the Meghna River already is subject to severe flooding. If the high scenario unfolds, flooding might intensify in these regions. Similar additional effects might be expected in the moderately flooded regions surrounding the Padma River and the confluence of the Ganges and Brahmaputra Rivers north of the central portion of our 3-m contour and extending northwesterly and southwesterly into currently highly flooded areas.

We emphasize again the massive delivery of sediments to the Ganges-Brahmaputra-Meghna Delta by these rivers. The sediment currently delivered to the mouth of the delta appears to be maintaining a near equilibrium, a balanced state with the forces of tectonic and deltaic subsidence, to maintain a nearly static situation with little noticeable deltaic progradation and little noticeable net erosion. Any significant reduction in the delivery of these sediments to the delta, however, could disrupt this balance and expose the delta to the same kinds of erosion that have been witnessed in the Nile.

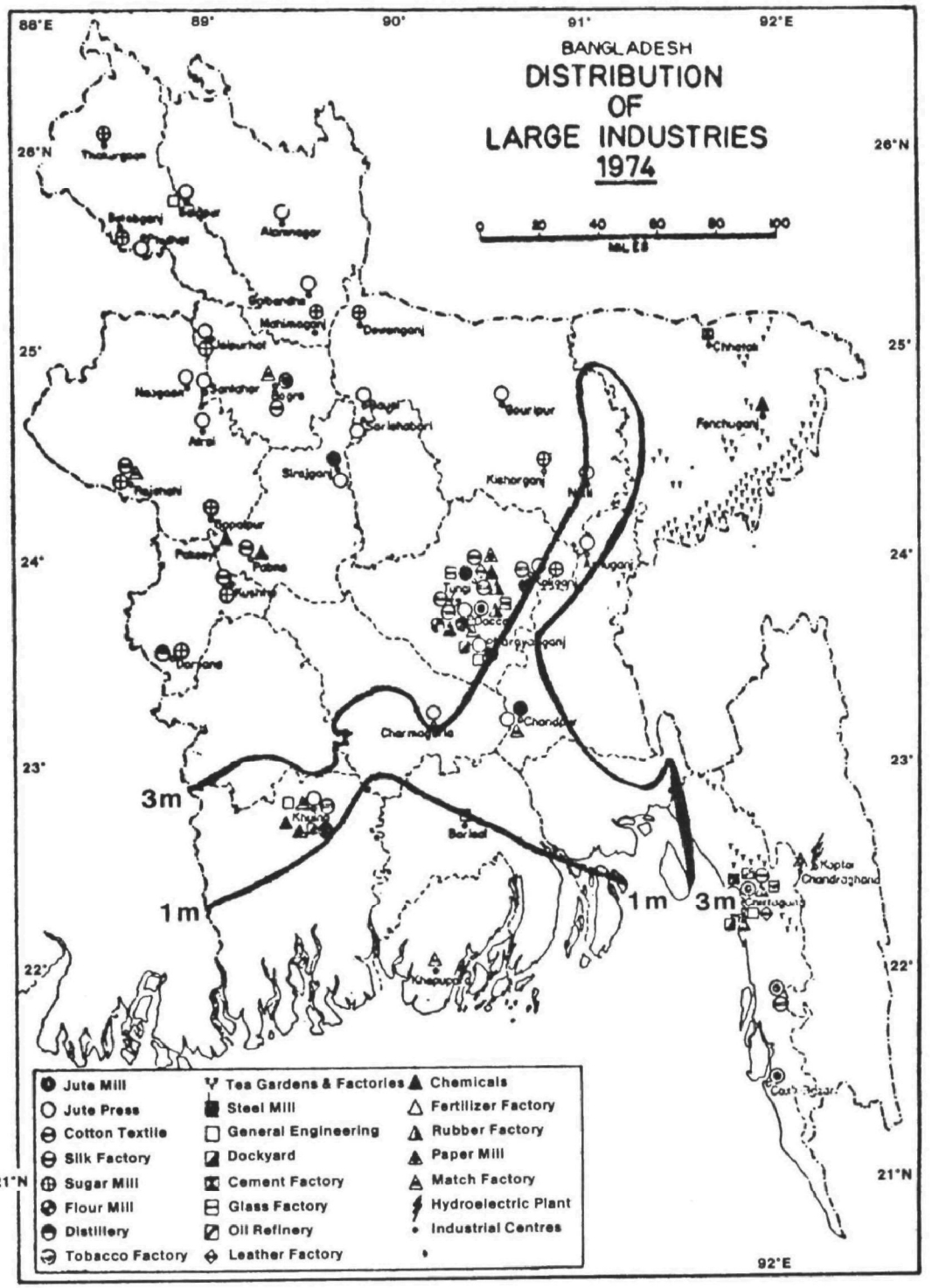

Figure 11. Distribution of Large Industries in Bangladesh
Source: Ahmad 1976

Table 2. Economic Activity and Population Originating in Affected Region: Bangladesh (1984-85)

Activity*	One-Meter Scenario	Three-Meter Scenario
Agriculture	20,685	51,450
Industry	590	21,615
Construction	1,750	5,065
Power, Water, and Sanitation	235	670
Transportation, Storage, and Communications	400	1,470
Trade Services	510	1,870
Housing 2,735	7,895	
Public Administration and Defense	1,680	4,860
Banking and Insurance	95	355
Professional and Miscellaneous Services	445	1,635
GDP in Affected Region	29,125	775,435
Total GDP	390,015	390,015
Percent of GDP	8	20

*Values in millions of Takas (TK) in 1984/85. ($1 U.S. = TK 25.35 in 1984)

Total Estimated Population (1985)	92.8 million	92.8 million
Estimated Population in Affected Region	8.5 million	24.8 million
Percent Population in Affected Region	9	27

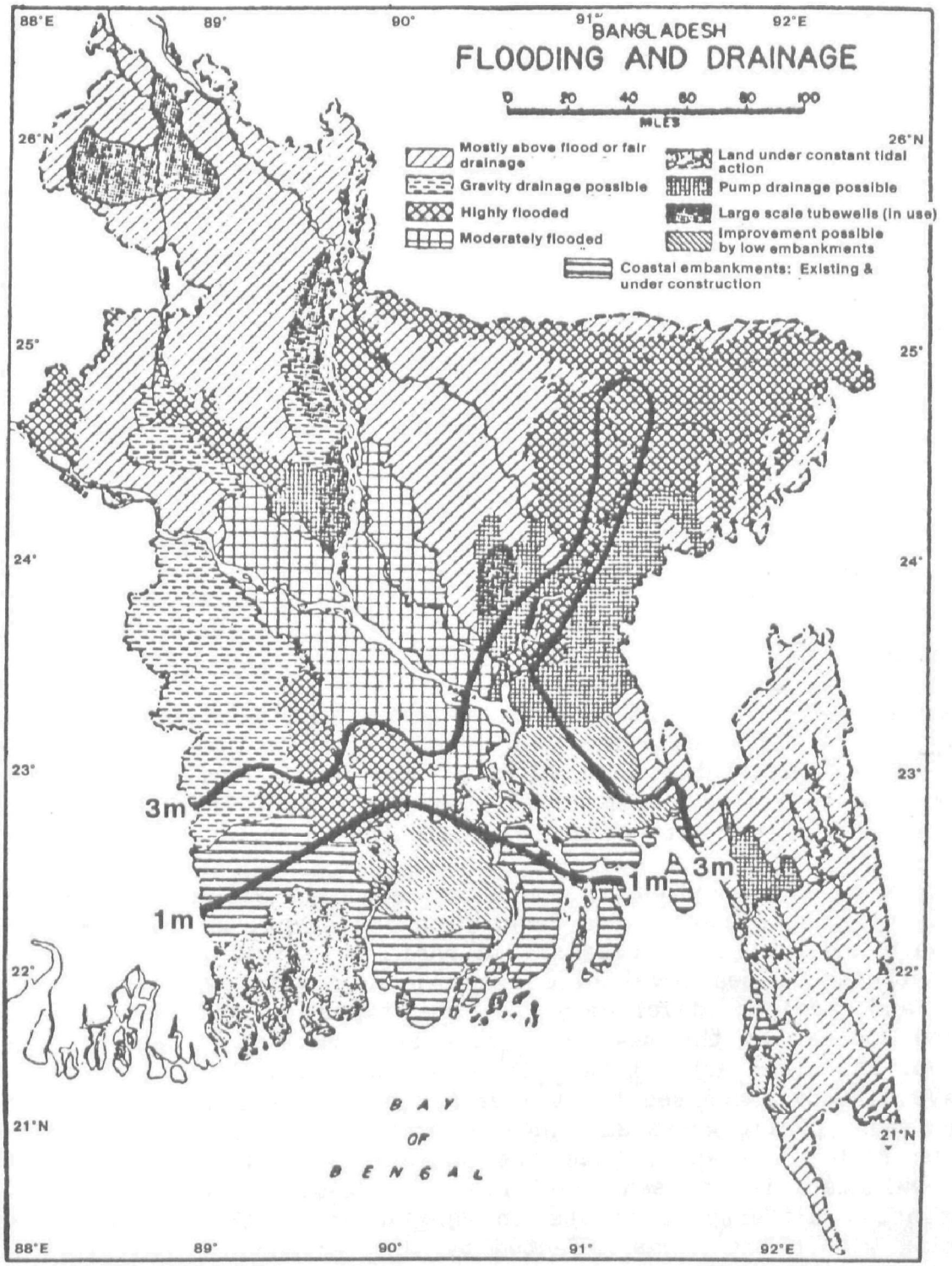

Figure 12. Flooding and Drainage in Bangladesh
Source: Ahmad 1976

Careful attention to this possibility seems warranted in the planning and design of upstream water management projects such as dams and barrages.

Assuring such careful attention, however, is greatly complicated by the sensitive international nature of the problem. Bangladesh shares the Ganges Basin with two of its neighboring states, India and Nepal, and the Brahmaputra Basin with India, China, and Bhutan. Of the total drainage area of the Ganges-Brahmaputra-Meghna River system, only 7.5% lies within Bangladesh (Zaman 1983). Already, a serious dispute between Bangladesh and India has arisen over India's construction and use of the barrage on the Ganges at Farakka. This dispute led in 1972 to the creation of the Indo-Bangladesh Joint Rivers Commission and in 1977 to the Ganges Waters Agreement. Nonetheless, tensions continue over this issue, and it seems very likely that future difficulties can be expected in allocation and management of the aquatic and sediment resources of these complex international river systems.

SUMMARY

In Egypt, about 12%-15% of the nation's arable area falls within the region threatened by a one meter rise and some 20% falls within the area that could erode with a three meter rise. (These represent approximately 0.5% and 0.8%, respectively, of Egypt's total land area.) We estimate that 15% of current GDP originates within the area affected in the 1-m scenario, with 20% of current GDP originating in the area affected in the 3-m scenario.

Approximately 11.5% and 27% of the land in Bangladesh would be threatened by rises in sea level of one and three meters, respectively. We estimate that 8.5 and 25 million people (9% and 27% of the total population) reside within these areas. Given our assumptions, 8% to 20% of the nation's gross domestic product currently originates in these areas.

Approximately 12% to 15% of Egypt's arable land (0.5% of the total area) could be lost if the sea rises one meter, while a three meter rise would threaten 20% of the arable land (0.8% of the total area). These areas are currently home to 7.7 and over 10 million people (16% and 21%). We estimate that 15% and 20% of the nations's GDP originates in these areas.

In view of the substantial human and economic stakes involved in these two sea level rise scenarios for Bangladesh and Egypt, we believe it is clear that private and public agencies should begin to include consideration of the possible effects of sea level rise over the next century in their long-range planning and project development. The types of activities that seem threatened soonest by the sea level rise are subsistence agriculture, storm protection, and urban activities. There seems little doubt that major public works have already increased the vulnerability of areas in Egypt to sea level rise, and major public works such as upstream dams and barrages in Bangladesh, or in its co-basin states, have the potential for greatly increasing that nation's vulnerability to sea level rise. Indeed, as can be seen from Table 3, substantial differences exists in Bangladesh in the economic activities originating within the areas affected by the 1-m and 3-m relative sea level rise scenarios.

Table 3. Summary of Activities Originating in Affected Areas

Account (1985 Value)	One-Meter Scenario	Three-Meter Scenario
Percent of Land Area		
Bangladesh	11.5	27.5
Egypt (3.5% settled)	12-15	29
Percent of Population		
Bangladesh	9	27
Egypt	16	21
Polpulation (Millions)		
Bangladesh (92.8)	8.5	24.8
Egypt (48.6)	7.7	10.1
Percent of Gross Domestic Product		
Bangladesh	8	20
Egypt	15	20
Gross Domestic Product (Millions)		
Bangladesh (390,015 Taka)	21,125	77,435
Egypt (29,872 Pounds)	4,441	6,053

There is an obvious need for refined estimates based on better, more disaggregated data about land-use patterns, population distribution, and distribution of economic production. Official projections of these variables would also allowt projection of economic exposure to account for economic and population growth, assuming no sea level rise, for comparison with transgression scenarios. Equally important, particularly in view of the fact that in both deltaic areas the rate of subsidence will probably affect local sea level rise more than global rise over the next 60 years, is documenting the fluvial and coastal environment. In Egypt it is too late, the Nile being completely dammed. But in the case of Bangladesh, we need to document how the river flows, how the sediment is carried in the lower reaches of the delta, and where the sediment ultimately accumulates. If rivers can be dammed or diverted in ways that minimize adverse impacts on sedimentation, then coastal inundation and erosion might be minimized.

Similar scenarios can be constructed for other developing nations. Of the three factors controlling these scenarios, nothing can be done to control local subsidence. Nations, however, can have some effect in helping regulate

both locally and internationally the emissions to the atmosphere that lead to the greenhouse effect. More importantly, each nation has substantial control over the managing and damming of its rivers, although extended and difficult international negotiations may be necessary. With proper measures, coastal erosion may be minimized to reduce the human acceleration of shoreline retreat. Further, recognizing the threats of socioeconomic dislocations posed by sea level rise, nations likely to be affected can begin to plan for such a rise by taking appropriate actions.

In spite of the simplifications necessitated by a first-order assessment, it seems indisputable that when added to the expected subsidence of fifty centimeters through 2100, even a 50-cm rise in global sea level implied by our low scenario would have serious implications for Bangladesh and Egypt. However, it seems reasonable to conclude that if the sediment washing continues to reach the delta, the impacts on Bangladesh can be reduced substantially, although it would be far more difficult to do so in the case of Egypt. Neither maintaining natural deltaic processes nor slowing the rise in sea level due to the greenhouse effect would be easy, but for Bangladesh and Egypt, even the most modest success in that direction would be well worth the effort in terms of both economics and human lives.

ACKNOWLEDGMENTS

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Sea Level Rise: The Reaction of a Coastal Realtor

Kenneth J. Smith
New Jersey Shore and Beach
Manahawken, New Jersey USA

I appreciate the opportunity to present my reaction to the issue of sea level rise. I am a coastal realtor from New Jersey, and I grew up on a barrier island just north of Atlantic City called Long Beach Island. I purchased my current home a couple of years ago, and after reviewing the preceding papers I am proud of the foresight I must have had to have chosen a site about 10 kilometers (6 miles) inland and 20 meters (80 feet) above sea level.

Although this report has an international focus I mention the New Jersey coast very briefly, because it is a microcosm of developed coasts worldwide. Many of the challenges and problems of developed shorelines are evident here. We have everything from bustling deepwater ports to low-lying, fully habited barrier islands, and an extensive tidal marsh system.

About 25 percent of the U.S. population lives within a 480-kilometer (300-mile) radius of Atlantic City, and one gets the feeling in the summer that they are all at the Jersey shore. In the summer we are crowded beyond belief, and our access roads are backed up for miles. Our 200 kilometers (125 miles) of beach are almost 100 percent developed, with real estate worth many billions of dollars. To give you an idea of our values, an oceanfront lot, if you can find one, averages about half a million dollars, and oceanfront houses rent for about two thousand dollars per week.

What this tells me is that people love the shore and have no qualms about paying to be near it. The location of New Jersey's beaches, just a short drive from the New York and Philadelphia urban areas, has predetermined our role as a provider to tourism. If millions of people converge on our beaches, they need the development that facilitates their enjoyment of those beaches. A place to sleep, take a shower, restaurants, amusement parks, marinas--all of these combine to enhance a summer vacation. In my view the development is as valuable to recreation as the beaches and bays.

It is a paradox that, given the economic and recreational benefits of a developed coast, we always seem to have insufficient funds for shore protection--not just in New Jersey, but nationwide, and I suspect in other countries as well. This lack of funds is based partially on budget constraints at every level of government; yet, even when we can show tremendous benefit-cost ratios, the funds to protect our coasts are difficult to find.

What does this have to do with sea level rise? Quite a bit. There are two main philosophies of coastal management which I will call the "stabilizationists" and the "naturalists."

The "stabilizationists" include the "can do" people: the Corps of Engineers, coastal engineering firms, property owners, local officials, and most tourists. I include myself in this group. We believe that the technology exists to maintain most beaches in their present positions, not forever, but for many years to come, and that the value of the existing development, both economic and recreational, justifies spending the money to do it.

The "naturalists" or "back to nature" proponents insist, with varying degrees of intensity, that because there is nothing we can ultimately do to stop the ocean, we should begin the depopulation of our barrier islands and the abandonment of our coast. They exhibit, at best, a cavalier attitude and, at worst, an arrogant disdain toward coastal property owners, and have managed to obstruct meaningful shore protection projects in every locality.

Unfortunately, many of the "naturalists" are government officials who are responsible for shore protection. So when the issue of sea level rise began to emerge, it was "right up their alley." Although the predicted sea level rise has a large range of uncertainty, you can bet that in the future this issue will become a cornerstone of their argument against funding shore-protection projects.

The reaction of our local residents, officials, and realtors to projected sea level rise ranges from a healthy skepticism to a rather macho detachment from the subject. I have heard comments such as, "What do you care? You won't be around to see it!" The scientific community is often dismissed as "a bunch of eggheads who don't want us here anyway." I wince when I hear comments like that, but I suspect sea level rise will be taken more seriously as more evidence comes in.

The disdain of the ordinary coastal citizen is understandable, however, since most of the discussion of sea level rise seems to come from the "naturalist" camp. Many theories have been used to justify the condemnation or confiscation of coastal property, so sea level rise is seen by many people as just another empty theory.

I do not feel that way; I believe the problem is serious. What concerns me is the rapidity of the increase of carbon dioxide and the other gases. It appears that we are racing into a climate that is unknown to man. The solutions, if there are any, should begin to be contemplated now, as part of a concerted, global effort.

Even a mid-range sea level rise scenario will have a profound effect on our coastline throughout the world. The resulting retreat of our beaches would severely threaten and possibly wipe out our barrier island development. The flooding of our ports, the salt contamination of our aquifers, the drowning of our marshes--all of these possibilities need to be taken very seriously.

People of the "can do" persuasion have relied on the technologies of beach nourishment and hard structures to protect our coastal development. But the coastal zone is dynamic, and it is difficult to include long-term certainty in our planning. Plans to abandon our property or retreat from our coast at this point would surely produce such enormous litigation as to be counterproductive. For the near future, I can only hope that the rise will be perceptible enough to be seriously considered, and slow enough that we can prepare for it.

Is there a point where a global constituency will say "enough" and begin to reduce the emissions that produce this climatic change? I don't know. This earth sometimes seems like a cancer patient who can't stop smoking. But it is a beautiful world, and we are its stewards. Certainly, the future is what we make it, and I hope that we will see increased funding for climatic research. I congratulate UNEP, EPA, and all of the other authors for their focus on this important issue.