Chapter 1

SEA LEVEL RISE AND WETLAND LOSS: AN OVERVIEW

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INTRODUCTION

Along the Atlantic and Gulf coasts of the United States, beyond the reach of the ocean waves, lies a nearly unbroken chain of marshes and swamps. Part land and part water, our coastal "wetlands" support both terrestrial and aquatic animals, and boast biological productivities far greater than found on dry land.

Many birds, alligators, and turtles spend their entire lifetimes communing between wetlands and adjacent bodies of water, while land animals that normally occupy dry land visit the wetlands to feed. Herons, eagles, sandpipers, ducks, and geese winter in marshes or rest there while migrating. The larvae of shrimp, crab, and other marine animals find shelter in the marsh from larger animals. Bluefish, flounder, oysters, and clams spend all or part of their lives feeding on other species supported by the marsh. Some species of birds and fish may have evolved with a need to find a coastal marsh or swamp anywhere along the coast (Teal and Teal 1969). Wetlands also act as cleansing mechanisms for ground and surface waters.

The importance of coastal wetlands was not always appreciated. For over three centuries, people have drained and filled marshes and swamps to create dry land for agriculture and urban development. Flood control levees and navigation channels have prevented fresh water, nutrients, and sediment from reaching wetlands, resulting in their conversion to open water. Marshes have often been used as disposal sites for channel dredging, city dumps, and hazardous waste sites.

In the 1960s, however, the public began to recognize the importance of environmental quality in general and these ecosystems. In 1972, the U.S. Congress added Section 404 to the federal Clean Water Act, which strengthened the requirement that anyone wishing to fill a coastal wetland obtain a permit from the Army Corps of Engineers, and added the requirement of approval by the Environmental Protection Agency. Several coastal states enacted legislation to sharply curtail destruction of coastal wetlands.

These restrictions have substantially reduced conversion of wetlands to dry land in coastal areas. The rate of coastal wetland loss declined from 1000 to 20 acres per year in Maryland (Redelfs 1983), from 3100 to 50 acres per year in New Jersey (Tiner 1984), and from 444 to 20 acres per year in Delaware (Hardisky and Klemas 1983). The rate of conversion to dry land in South Carolina has been reduced to about 15 acres per year (South Carolina Coastal Council 1985).[1]

Nevertheless, these restrictions have not curtailed the conversion of wetlands to water. The majority of coastal wetland loss in the United States is now taking place in Louisiana, which loses fifty square miles of wetlands per year, mostly to open water. Navigation channels, canals, and flood control levees have impeded the natural mechanisms that once enabled the wetlands of the Mississippi Delta to keep pace with subsidence and rising sea level. The majority of coastal wetland loss in South Carolina results from impoundments that have converted wetlands to open water during part of the year.[2]

In the next century, moreover, conversion of wetlands to open water may overshadow conversion to dry land throughout the coastal zone of the United States. Increasing concentrations of carbon dioxide and other gases are expected to warm our planet a few degrees Celsius (C) by a mechanism commonly known as the "greenhouse effect." Such a warming could raise sea level one meter or so by expanding ocean water, meeting mountain glaciers, and causing polar ice sheets to melt or slide into the oceans. Because most of America's coastal wetlands are less than one meter above sea level, a large fraction of our coastal wetlands could be threatened by such a rise.

Offsetting this potential threat are two compensating factors. A rise in sea level would flood areas that are now dry land, creating new wetlands. Moreover, wetlands can grow upward by accumulating sediment and organic material. The potential of these two factors to prevent a major loss of wetlands in the next century, however, may be limited. People who have developed the land just inland of today's wetlands may be reluctant to abandon their houses, which new wetland creation would require. Although wetlands have been able to keep pace with the rise in sea level of the last few thousand years, no one has demonstrated that they could generally keep pace with an accelerated rise.

This report examines the vulnerability of U.S. coastal wetlands (excluding Alaska and Hawaii) to a possible rise in sea level of one or two meters through the year 2100. By coastal wetlands, we refer to marshes, swamps, and other plant communities that are flooded part, but not all, of the time, and that are hydraulically connected to the sea. This chapter, written for the general reader, summarizes the other chapters and their implications, as %ell as the basis for expecting a global warming and rise in sea level; nature's response to a rising sea; the impacts of human interference with the mechanisms by which wetlands adjust to sea level rise; and policies that might limit future loss of coastal wetlands.

Chapters 2 (Kana, Baca, & Williams) and 3 (Kana, Eiser, Baca & Williams) describe field surveys that were used to estimate the potential impacts of sea level rise on wetlands in the area of Charleston, South Carolina, and Long Beach Island, New Jersey, respectively. In Chapter 4, Armentano, Park, & Cloonan use topographic maps to estimate the potential loss for 52 regions throughout the United States. Finally, in Chapter 5, EPA's Office of Wetland Protection responds to the challenges presented in the preceding chapters.

This report leaves unanswered many questions that will need to be investigated for society to rationally respond to the implications of a substantial rise in sea level: What portion of our wetlands will he able to keep pace with rising sea level? In how many areas would it be economical for communities to hold back the sea by erecting levees and bulkheads, at the expense of their wetlands? Should wetland protection policies seek to slow an inevitable loss of coastal marshes and swamps, or to ensure that a particular fraction of wetlands are maintained *in perpetuity?*

We hope that this report will stimulate the additional research and policy analysis necessary for society to rationally respond to the risk of wetland loss caused by a rise in sea level.

THE BASIS FOR EXPECTING A RISE IN SEA LEVEL

Post Changes In Climate and Sea Level

Throughout geologic history, sea level has risen and fallen by over three hundred meters (one thousand feet). Although changes in the size and shape of the oceans' basins have played a role over very long periods of time (Hays and Pitman 1973), the most important changes in sea level have been caused by changes in climate. During the last ice age (18,000 years ago), for example, the earth was about five degrees Celsius colder than today, glaciers covered most of the northern hemisphere, and sea level was one hundred meters (three hundred feet) lower than it is today (Donn, Farrand, and Ewing 1962).

Although most of the glaciers have melted since the last ice age, polar glaciers in Greenland and Antarctica still contain enough water to raise sea level more than seventy meters (over two hundred feet) (Untersteiner 1975). A complete meeting of these glaciers has not occurred in the last two million years, and would take tens of thousands of years even if the earth warmed substantially. However, unlike the other glaciers, which rest on land, the West Antarctic Ice Sheet rests in the ocean and is thus more vulnerable. Warmer ocean water would be more effective than warmer air at melting glaciers and could melt the ice shelves that prevent the entire glacier from sliding into the oceans. Mercer (1970) suggests that the West Antarctic Ice Sheet completely disappeared during the last interglacial period (which was one or two degrees warmer than today and occurred 100,000 years ago), at which time sea level was five to seven meters (about twenty feet) above its present level.

Over periods of decades, climate can influence sea level by heating and thereby expanding (or cooling and contracting) sea water. In the last century, tidal gauges have been available to measure relative sea level in particular locations. Along the Atlantic Coast, sea level has risen about 30 centimeters (one foot) in the last century (Hicks, Debaugh, and Hickman 1983). Studies combining tide gauge measurements around the world have concluded that average global sea level has risen ten to fifteen centimeters (four to six inches) in the last one hundred years (Barnett 1983; Gornitz, Lebedeff, and Hansen 1982). About five centimeters of this rise can be explained by the thermal expansion of the upper layers of the oceans resulting from the observed global warming of 0.4C in the last century (Gornitz, Lebedeff, and Hansen 1982). Meltwater from mountain glaciers has contributed two to seven centimeters since 1900 (Meier 1984). Figure 1-1 shows that global temperature and sea level appear to have risen in the last century. Nevertheless, questions remain over the magnitude and causes of sea level rise in the last century.

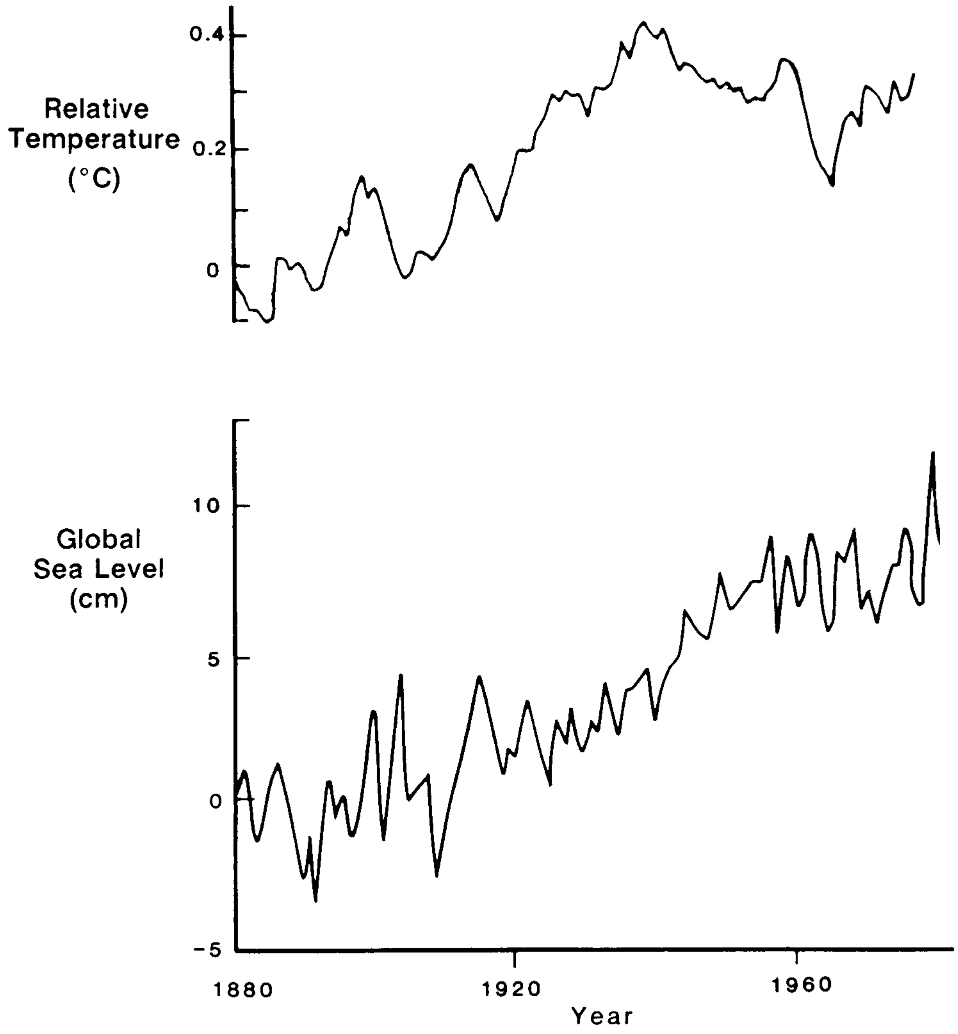
The Greenhouse Effect and Future Sea Level Rise

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

A planet's temperature is determined primarily by the amount of sunlight it receives, the amount of sunlight it reflects, and the extent to which its atmosphere retains heat. When sunlight strikes the earth, it warms the surface, which then reradiates the heat as infrared radiation. However, water vapor, CO_2, and other gases in the atmosphere absorb sow of the radiation

FIGURE 1-1

GLOBAL TEMPERATURES AND SEA LEVEL TRENDS IN THE LAST CENTURY



Sources: *Temperature curve from: HANSEN, J.E., D. JOHNSON, A. LACIS, S. LEBEDEFF, D. RIND, AND G. RUSSELL, 1981. Climate Impact of Increasing Atmospheric Carbon Dioxide,* Science *213:957-966. Sea level curve adapted from: GORNITZ, V., S. LEBEDEFF, and J. HANSEN, 1982. Global Sea Level Trend in the Past Century.* Science *215:1611-1614.*

rather than sowing it to pass undeterred through the atmosphere to space. Because the atmosphere traps heat and warms the earth in a manner somewhat analogous to the glass panels of a greenhouse, this phenomenon is generally known as the "greenhouse effect." Without the greenhouse effect of the gases that occur in the atmosphere naturally, the earth would be approximately 33 °C (60 °F) colder than it is currently (Hansen et al. 1984).

In recent decades, the concentrations of "greenhouse gases" have been increasing. Since the industrial revolution, the combustion of fossil fuels, deforestation, and cement manufacture have released enough CO_2 into the atmosphere to raise the atmospheric concentration of carbon dioxide by 20 percent. As Figure 1-2 shows, the concentration has increased 8 percent since 1958 (Keeling, Bacastow, and Whorf 1982).[3] Recently, the concentrations of methane, nitrous oxide, chlorofluorocarbons, and a few dozen other trace gases that also absorb infrared radiation have also been increasing (Lacis et al. 1981). Ramanathan et al. (1985) estimate that in the next fifty years, these gases will warm the earth as much as the increase in CO_2 alone.

Although there is no doubt that the concentration of greenhouse gases is increasing, the future rate of that increase is uncertain. A recent report by the National Academy of Sciences (NAS) examined numerous uncertainties regarding future energy use patterns, economic growth, and the extent to which CO_2 emissions remain in the atmosphere (Nordhaus and Yohe 1983). The Academy estimated a 98 percent probability that CO_2 concentrations will he at least 450 parts per million (1.5 times the year-1900 level) and a 55 percent chance that the concentration will be 550 parts per million by 2050. The Academy estimated that the probability of a doubling of CO_2 concentrations by 2100 is 75 percent. Other investigators had estimated that a doubling is likely by 2050 (Wuebbles, MacCracken, and Luther 1984).

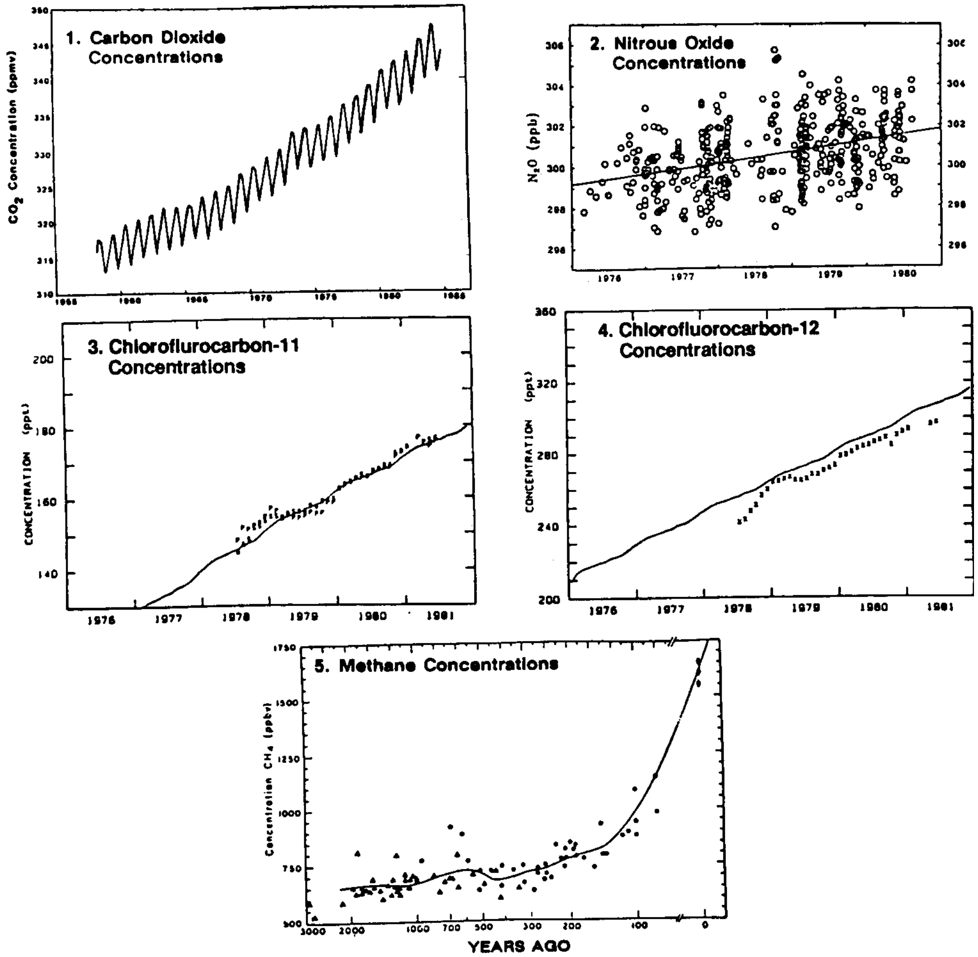
If the impact of the trace gases continues to be equal to the impact Of CO_2, the NAS analysis implies that the "effective doubling" of all greenhouse gases has a 98 percent chance of occurring by 2050.[4] An international conference of scientists recently estimated that an effective doubling by 2030 is likely (UNEP, WMO, ICSU 1985). However, uncertainties regarding the emissions of many trace gases are greater than those for CO_2. Although the sources of chlorofluorocarbons (CFCs) are well known, future emissions involve regulatory uncertainties. Because these gases can cause deterioration of stratospheric ozone, forty nations have tentatively agreed to cut emissions of the most important CFCs by 50 percent. However, additional cutbacks may be implemented, and other nations may sign the treaty; on the other hand, emissions of gases not covered by the treaty may increase.

Considerable uncertainty also exists regarding the impact of a doubling of greenhouse gases. Physicists and climatologists generally agree that a doubling would directly raise the earth's average temperature by about IºC if nothing else changed. However, if the earth warmed, many other aspects of climate would be likely to change, probably amplifying the direct effect of the greenhouse gases. These indirect impacts are known as "climatic feedbacks."

Figure 1-3 shows estimates by Hansen et al. (1984) of the most important known feedbacks. A warmer atmosphere would retain more water vapor, which is also a greenhouse gas, and would warm the earth more. Snow and floating ice would melt, decreasing the amount of sunlight reflected to space, causing additional warming. Although the estimates of other researchers differ slightly from those of Hansen et al., climatologists agree that these two feedbacks would amplify the global warming from the other greenhouse gases. However, the impact of clouds is far less certain. Although recent investigations have estimated that changes in cloud height and cloud cover would add to the warming, the possibility that changes in cloud cover would offset part of the warming cannot be ruled out. After evaluating the evidence, two panels of the National Academy of Sciences concluded that the eventual warming from a doubling of greenhouse gases would be between 1.5º and 4.5ºC (3º-8ºF) (Charney et al. 1979; Smagorinsky 1982).

FIGURE 1-2

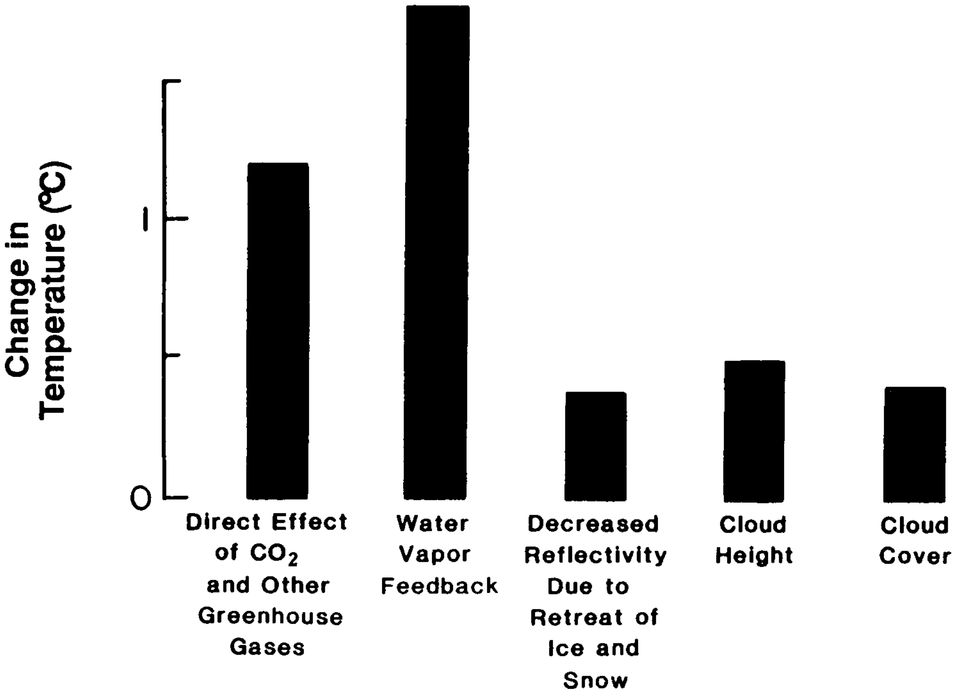
CONCENTRATIONS OF SELECTED GREENHOUSE GASES OVER TIME



1. *Keeling, C.D., R.B. Bacastow, and T.P. Whorf, 1982. Measurements of the Concentration of Carbon Dioxide at Mauna Loa, Hawaii.* Carbon Dioxide Review 1982, *edited by W. Clark. New York: Oxford University Press, 377-382. Unpublished data from NOAA after 1981.*
2. *Weiss, R.F., 1981. "The Temporal and Spatial Distribution of Tropospheric Nitrous Oxide."* Journal of Geophysical Research. *86(C8):7185-95.*
3. *Cunnold, D.M., et al., 1983a. The Atmospheric Lifetime Experiment. 3. Lifetime Methodology and Application to Three Years of CFCL3 Data.* Journal of Geophysical Research. *88(C13):8401-8414.*
4. *Cunnold, D.M., et al., 1983b. The Atmospheric Lifetime Experiment. 4. Results for CF2CL2 Based on Three Years Data,* Journal of Geophysical Research. *88(C13):8401-8414.*
5. *Rasmussen, R.A., and M.A.K. Khalil, 1984. Atmospheric Methane in the Recent and Ancient Atmospheres: Concentrations, Trends, and Interhemispheric Gradient,* Journal of Geophysical Research. *89(D7): 11599-605.*

FIGURE 1-3

ESTIMATED GLOBAL WARMING DUE TO A DOUBLING OF GREENHOUSE GASES: DIRECT EFFECTS AND CLIMATIC FEEDBACKS



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

Sources: *Adapted from: HANSEN, J.E., A. LACIS, D. RIND, and G. RUSSELL, 1984. Climate Sensitivity to Increasing Greenhouse Gases. In* Greenhouse Effect and Sea Level Rise: A Challenge for This Generation, *edited by M.C. Barth and J.G. Titus. New York: Van Nostrand Reinhold, p. 62.*

A global warming could raise sea level by expanding ocean water, melting mountain glaciers, and causing ice sheets in Greenland and Antarctica to melt or slide into the oceans. Four major reports have assessed the possible significance of these factors, as shown in Table 14 and Figure 14. All predict that the global warming will cause the rate of sea level rise to accelerate.

Revelle (1983) estimated that Greenland and mountain glaciers could each contribute 12 cm to sea level in the next century, and that thermal expansion could contribute 30 cm. Based on current trends, Revelle concluded that other factors could contribute an additional 16 cm, for a total rise of 70 cm, plus or minus 25 percent. Hoffman et al. (1983) developed a variety of sea level rise scenarios based on high and low assumptions for all the major uncertainties. They estimated that sea level was most likely to rise between 26 and 39 cm by 2025 and 91 to 137 cm by 2075.

The National Academy of Sciences Polar Research Board Report *Glaciers, Ice Sheets, and Sea Level* (Meier et al. 1985) examined the possible glacial contribution to sea level rise by the year 2100. The panel endorsed estimates that alpine (Meier 1984) and Greenland (Bindschadler 1985) glaciers mould each contribute 10 to 30 centimeters. Thomas (1985) estimated that the antarctic contribution resulting from a four-degree warming would most likely be 28 cm, but could be as high as 2.2 meters. However, the panel concluded that the antarctic contribution could be anywhere from a 10-centinxter drop (due to increased snowfall) to a one-meter rise.

Hoffman et al. (1986) revised their earlier projections in light of the glacial process models developed in the Polar Board report and new information on future concentrations provided by Nordhaus and Yohe (1983) and Ramanathan et al. (1985). Although the revised assumptions had a minor impact on their estimates of thermal expansion, it substantially lowered their estimates of snow and ice contributions until after 2050. They estimated the rise by 2025 to be between 10 and 21 cm, and by 2075 to be between 36 and 191 cm.[5] Thomas (1986) estimated the likely rise through 2100 to be 64 to 230 cm.

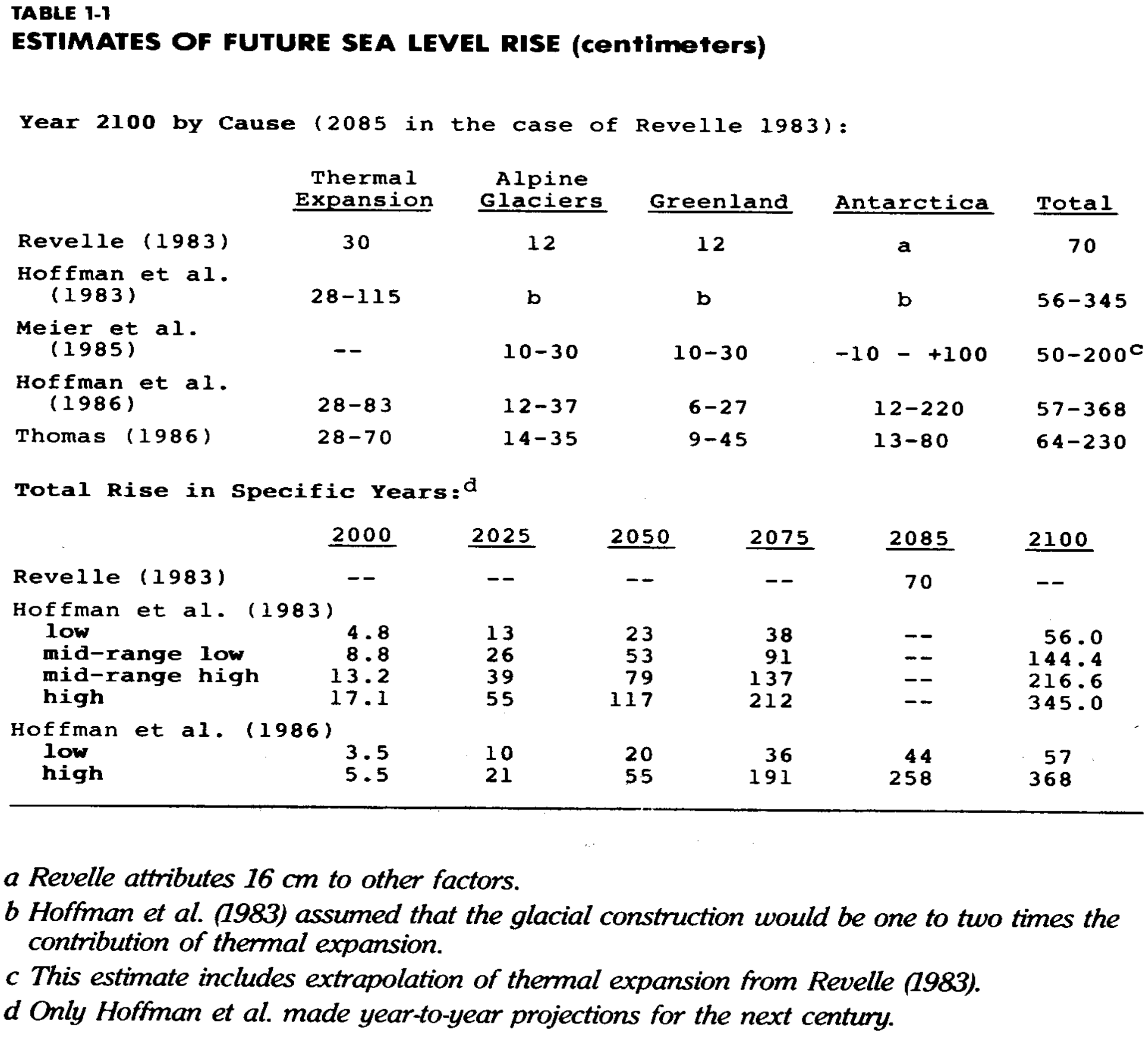


TABLE 1-1

ESTIMATES OF FUTURE SEA LEVEL RISE (centimeters)

Year 2100 by Cause (2085 in the case of Revelle 1983):

	Thermal Expansion	Alpine Glaciers	Greenland	Antarctica	Total
Revelle (1983)	30	12	12	a	70
Hoffman et al. (1983)	28-115	b	b	b	56-345
Meier et al. (1985)	--	10-30	10-30	-10 - +100	50-200[c]
Hoffman et al. (1986)	28-83	12-37	6-27	12-220	57-368
Thomas (1986)	28-70	14-35	9-45	13-80	64-230

Total Rise in Specific Years:[d]

	2000	2025	2050	2075	2085	2100
Revelle (1983)	--	--	--	--	70	--
Hoffman et al. (1983)						
low	4.8	13	23	38	--	56.0
mid-range low	8.8	26	53	91	--	144.4
mid-range high	13.2	39	79	137	--	216.6
high	17.1	55	117	212	--	345.0
Hoffman et al. (1986)						
low	3.5	10	20	36	44	57
high	5.5	21	55	191	258	368

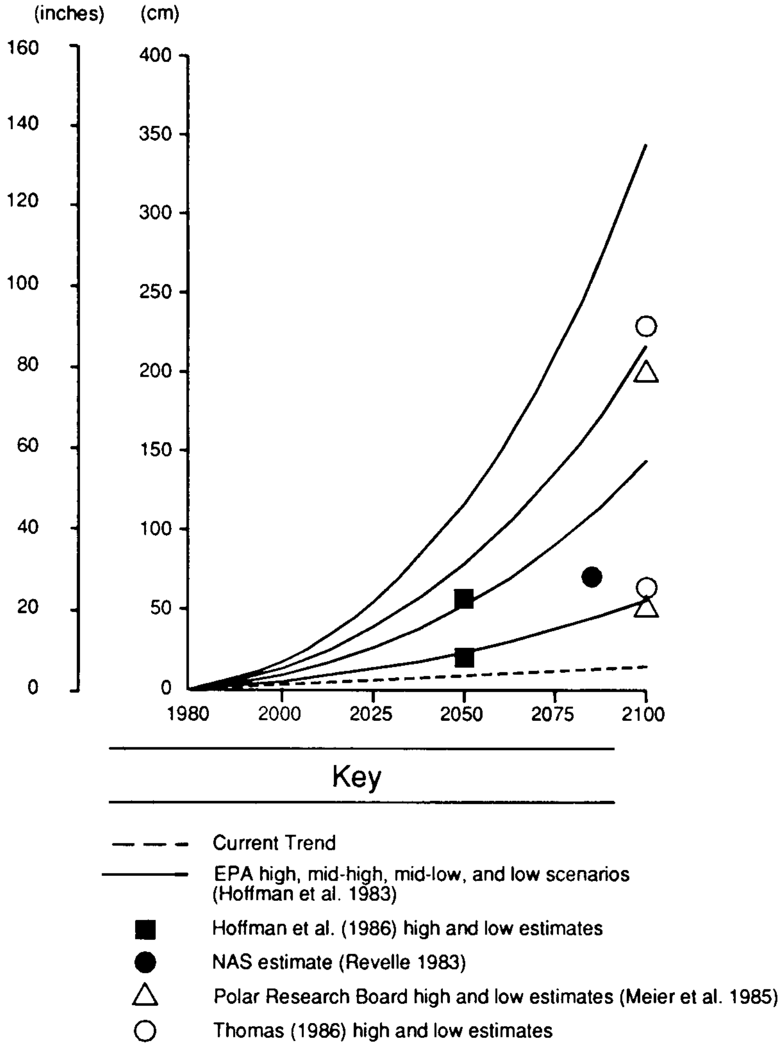
a Revelle attributes 16 cm to other factors.

b Hoffman et al. (1983) assumed that the glacial construction would be one to two times the contribution of thermal expansion.

c This estimate includes extrapolation of thermal expansion from Revelle (1983).

d Only Hoffman et al. made year-to-year projections for the next century.

FIGURE 1-4
GLOBAL SEA LEVEL RISE SCENARIOS



Note: *The EPA 1983 Mid-Low and Mid-High scenarios am called "low" and "high" for the remainder of this chapter and throughout Chapters 2, 3, and 4.*

In this study, we examine the implications of the mid4ow and mid-high scenarios from Hoffiman et al. (1983), shown in Table 1-1 and Figure 1-4. (For simplicity, we call these scenarios "low" and "high.") Although it might be desirable to undertake a worst-case analysis of a larger rise, the scenarios me used are broadly representative of the studies that have been undertaken so far. Because much of the U.S. coast is sinking, the relative rise at a particular location will generally be greater. Table 1-2 lists the expected rise in sea level under the low and high scenarios for different areas of the United States.

TABLE 1-2
RELATIVE SEA LEVEL RISE IN THE UNITED STATES

	Historic Subsidence Rate (mm/yr)	Historic Relative Sea Level Trend (mm/yr)	Low Scenario 1980-2100 (cm)	High Scenario 1980-2100 (cm)
Portland, Maine	1.1	2.3	157.6	229.8
Boston, Massachusetts	1.1	2.3	157.6	229.8
Newport, Rhode Island	1.4	2.6	161.2	233.4
New London, Connecticut	1.0	2.2	156.4	228.6
New York, New York	1.6	2.8	163.6	235.8
Sandy Hook, New Jersey	3.0	4.2	186.4	252.6
Atlantic City, New Jersey	2.8	4.0	178.0	250.2
Philadelphia, Pennsylvania	1.4	2.6	161.2	233.4
Baltimore, Maryland	2.0	3.2	168.4	240.6
Annapolis, Maryland	2.5	3.7	174.4	246.6
Hampton Roads, Virginia	3.1	4.3	181.6	253.8
Charleston, South Carolina	2.2	3.4	170.8	243.0
Fernandina, Florida	0.5	1.7	150.4	222.6
Miami Beach, Florida	1.1	2.3	157.6	229.8
Cedar Key, Florida	0.8	2.0	154.0	226.2
Pensacola, Florida	1.2	2.4	158.8	231.0
Eugene Island, Louisiana	8.8	10.0	250.0	322.2
Galveston, Texas	5.1	6.3	205.6	277.8
San Diego, California	0.7	1.9	152.8	225.0
Los Angeles, California	-0.6	0.6	137.2	209.4
San Francisco, California	0.0	1.2	144.4	216.2
Astoria, Oregon	-1.7	-0.5	124.0	196.2
Seattle, Washington	0.7	1.9	152.8	225.0
Sitke, Alaska	-3.6	-2.4	101.2	173.4
Worldwide	0	1.2	144.4	216.6

Source: *Derivations of historic rates of relative sea level rise due to subsidence are based on an assumption of a 1.2 mm/yr global rise in sea level. Projections are based on mid-low and mid-high estimates from Hoffman et al. 1983, with historic subsidence (from Hicks, Debaugh, and Hickman 1983) added.*

NATURAL IMPACTS OF SEA LEVEL RISE

There are three major ways by which sea level rise can disrupt wetlands: inundation, erosion, and saltwater intrusion. In some cases, wetlands will be converted to bodies of open water; in other cases, the type of vegetation will change but a particular area will still be wetlands However, if sea level rises slowly enough, the ability of wetlands to grow upward-by trapping sediment or building upon the peat the sediment creates-can prevent sea level rise from disrupting the wetlands.

In explaining potential impacts of sea level rise, we focus on what the impact would be if wetlands did not grow upward, and leave it to the reader to remember that this potential "vertical accretion" can offset these impacts. The actual impact will depend on the "net substrate change," i.e., the difference between sea level rise and wetland accretion. In this report, all estimates of future wetland loss are based on the assumption that current rates of vertical accretion continue. An important area for future research will be to determine whether future climate change and sea level rise will accelerate or slow the rate of wetland accretion. Even if wetlands are able to accrete more rapidly in the future, however, existing literature provides little reason to believe that wetlands will generally be able to keep up with a one- or two-meter rise in sea level.

Tidal Flooding

Because periodic flooding is the essential characteristic of salt marshes, increases in the frequency and duration of floods can substantially alter these ecosystems. Salt marshes extend seaward to roughly the elevation that is flooded at mean tide, and landward to roughly the area that is flooded by spring tide (the highest astronomical tide every 15 days). Salt marsh plants are different from most plants found inland in that they tolerate salt water to varying degrees (Teal and Teal 1969). Coastal wetlands flooded once or twice daily support "low marsh" vegetation, while areas flooded less frequently support high marsh species. Transition wetlands can be found above the high marsh, in areas flooded less frequently than twice a month.

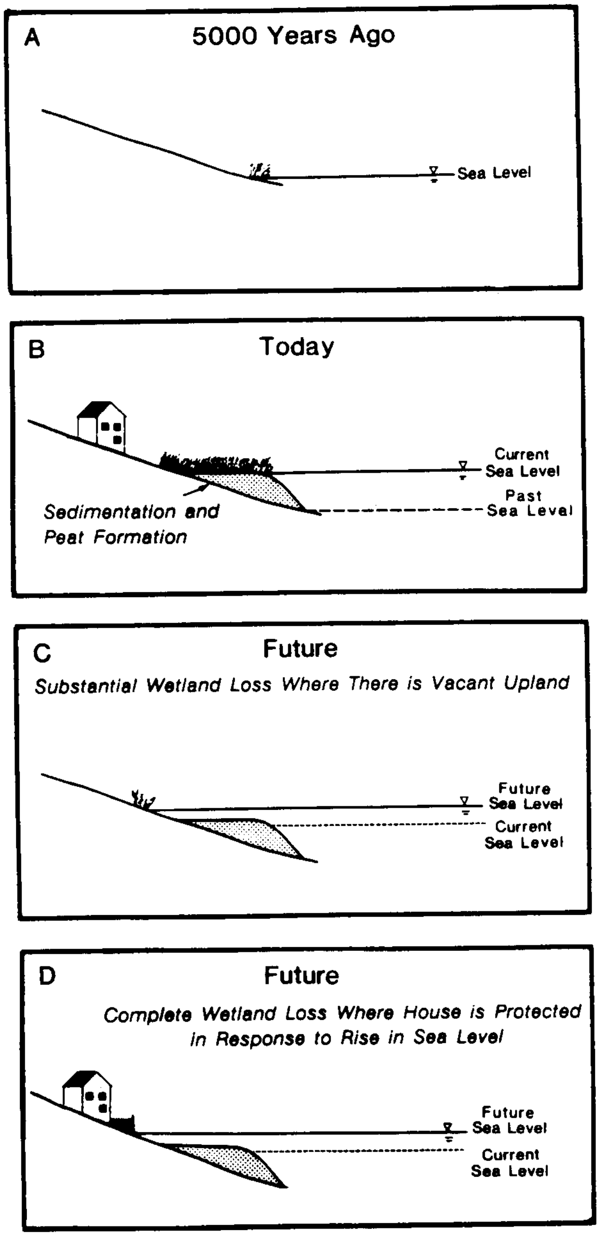
The natural impact of a rising sea is to cause marsh systems to migrate upward and inland. Sea level rise increases the frequency and/or duration of tidal flooding throughout a salt marsh. If no inorganic sediment or peat is added to the marsh, the seaward portions become flooded so much that marsh grass drowns and marsh soil erodes; portions of the high marsh become low marsh; and upland areas immediately above the former spring tide level are flooded at spring tide, becoming high marsh. If nearby rivers or floods supply additional sediment, sea level rise slows the rate at which the marsh advances seaward.

The net change in total marsh acreage depends on the slopes of the marsh and upland areas. If the land has a constant slope throughout the marsh and upland, then the area lost to marsh drowning will be equal to the area gained by the landward encroachment of spring high tides. *In most areas, however, the slope above the marsh is steeper than the marsh; so a rise in sea level causes a net loss of marsh acreage.* Two extreme examples are noteworthy: marshes immediately below cliffs in New England and along the Pacific Coast could drown without being replaced inland. In Louisiana, thousands of square miles of wetlands are within one meter of sea level, with very narrow ridges in between and very little adjacent upland between one and two meters above sea level. A one-meter rise in sea level could drown most of the wetlands there without necessarily creating any significant new marsh (Louisiana Wetland Protection Panel, 1987; Gagliano et al. 1981).

Figure 1-5 illustrates why there is so much more land at marsh elevation than just above the marsh. Wetlands can grow upward fast enough to keep pace with the slow rise in sea level that most areas have experienced in the recent past (Kaye and Barghoorn 1964; Coleman and Smith 1964; Redfield 1967). Thus, areas that might have been covered with two or three meters of water (or more) have wetlands instead (Figures 1-5A, 1-5B). If sea level rise accelerates only slightly, marshes that are advancing today may have sufficient sediment to keep pace with sea level. But if sea level rise accelerates to one centimeter per year (projected for 2025-2050), the sea will be rising much more rapidly than the demonstrated ability of wetlands to grow upward in most areas (Armentano et al., Chapter 4) and the increase in wetland acreage of the last few thousand years will be negated (Figure 1-5C). If adjacent upland areas are developed, all the wetlands could be lost (Figure 1-5D).

An important factor in determining the vulnerability of marshes to sea level rise is the tidal range, the difference in elevation between the mean high tide and mean low tide. Coastal wetlands are generally less than one tidal range above mean sea level.[6] Thus, if the sea rose by one tidal range overnight, all the existing wetlands in an area would drown. Tidal ranges vary greatly throughout the United States. Along the open coast, it is over four meters in Maine, somewhat less than two meters (about five feet) along the mid-Atlantic, and less than one meter (about two feet) in the Gulf of Mexico (NOAA 1985). The shape of an embayment can amplify or dampen the tidal range, however. Most notably, the estuaries behind barrier islands with widely separated inlets can have tidal ranges of thirty centimeters (one foot) or less. The tidal range of Chesapeake Bay is about fifty centimeters (NOAA 1985).

FIGURE 1-5
EVOLUTION OF A MARSH AS SEA LEVEL RISES



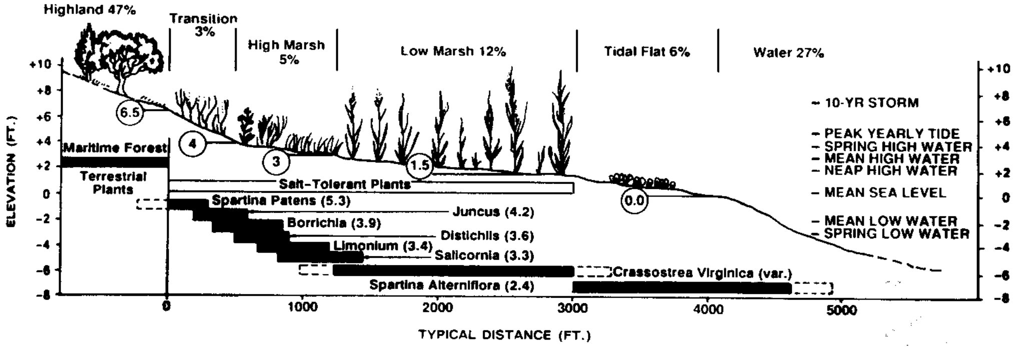
Coastal marshes have kept pace with the slow rate of sea level rise that has characterized the last several thousand years. Thus, the area of marsh has expanded over time as now lands were inundated, resulting in much more wetland acreage than dry land just above the wetlands (A and B). If in the future, sea level rises faster than the ability of the marsh to keep pace, the marsh area will contract (C). Construction of bulkheads to protect economic development may prevent now marsh from forming and result in a total loss of marsh in some areas (D).

To investigate **some** of these issues, Kana et al. (Chapters 2 and 3) estimate the impact of accelerated sea level rise on wetlands in the areas of Charleston, South Carolina, and Long Beach Island, New Jersey. Charleston has a tidal range of almost two meters, while the New Jersey area has tidal ranges between sixty and **one** hundred centimeters. In each area, they surveyed a dozen marsh profiles to develop a "composite transect," an average cross section of the marsh. Based on previous studies, they assume that the marshes in both areas could grow upward at a rate of five millimeters per year.

Figure 1-6 illustrates the composite transect of the Charleston marshes. The low marsh, whose elevation is between 45 and 90 centimeters 0.5 to 3.0 feet) is 550 meters (1800 feet) wide. The high marsh, with elevation between 90 and 120 centimeters (3.0 to 4.0 feet), is about 210 meters (700 feet) wide; the transition wetlands, with elevation between 120 and 195 centimeters (4.0 to 6.5 feet), are generally about 150 mters (500 feet) wide. Thus, the average slopes found in the low, high, and transition marsh areas are 0.08, 0.14, and 0.50 percent, respectively, confirming that the slope of the profile increases as one moves inland from the marsh. (The slope immediately above the marsh is approximately 0.55 percent.)

FIGURE 1-6

COMPOSITE TRANSECT-CHARLESTON, S.C.



Composite wetlands transect for Charleston illustrating the approximate percent occurrence and modal elevation for key indicator species or habitats based on results of 12 surveyed transects. Minor species have been omitted. Elevations are with respect to 1929 NGVD, which is about 15 cm lower than current sea level. Current tidal ranges are shown at right.

Source: *Kana et al. (Chapter 2)*

A word on what we mean by elevation is in order. Old maps often have contours representing, for example, five feet above sea level. However, because sea level has been rising, a contour that was five feet above sea level fifty years ago may only be four and one-half feet above sea level today. To avoid potential confusion, most maps today express elevations with respect to the "National Geodetic Vertical Datum" (NGVD) reference plane, which is a fixed reference that is unaffected by changes in sea level.

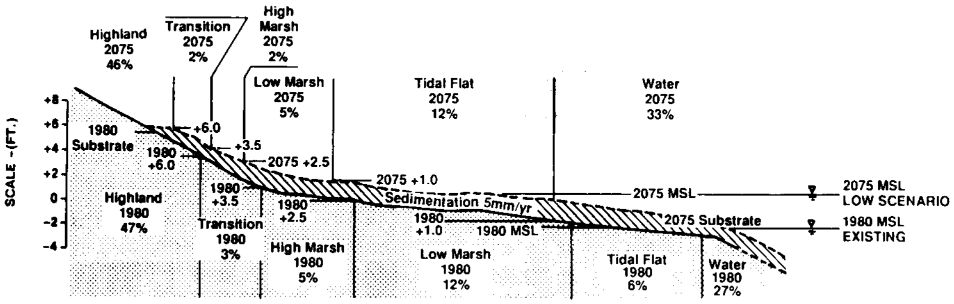
NGVD was developed in 1929 by estimating mean sea level at twenty-six sites along the North American coast for the preceeding couple of decades. For these sites, zero elevation (NGVD) is the same as mean sea level over that period. For other sites, however, the zero elevation is not necessarily mean sea level for that period. NGVD was developed by a surveying technique, known as "leveling," between the twenty-six sites; mean sea level, on the other hand, may be higher or lower at a particular location depending on such factors as rainfall, winds, currents, and atmospheric pressure. This distinction is usually unimportant; even USGS topographic maps printed before 1973 refer to elevations above "mean sea level" when they really mean NGVD. For most practical purposes, the reader of this report can assume that zero elevation at a particular site refers to the level of the sea between 1910 and 1929. All elevations in this report are with respect to NGVD unless otherwise stated.

The other type of elevational reference is the "tidal datum." Depending upon context, terms such as "mean sea level" can refer to a theoretical concept or a legal definition. The legal definition of mean sea level (MSL) is the average water level observed at a location over the period 1960-78; mean high water (MHW) and mean low water (MLW) are the averages of all high and low tides, respectively, over that period; mean tidal range is the difference between mean high water and mean low water. However, wetlands respond to actual conditions, the average water level of today. Thus, unless otherwise stated, the term mean sea level in this report refers to the average water levels of today, not the legal tidal datum.

Figure 1-7 illustrates the impact on the composite marsh profile of the low scenario for the period 1980-2075, which implies an 87-centinieter (2.9-foot) rise in relative sea level for the Charleston area. Because Kana et al. assume that sedimentation would enable the surface to rise 48 centimeters, the net rise in sea level is equivalent to an instantaneous rise of 39 centimeters (15 inches). As the figure shows, the area of low and high marsh would each decline by about 50 percent as they shifted upward and inland. For the high scenario rise of 159 centimeters (5.2 feet), the loss would be approximately 80 percent.

FIGURE 1-7

SHIFT IN WETLANDS ZONATION ALONG A SHORELINE PROFILE



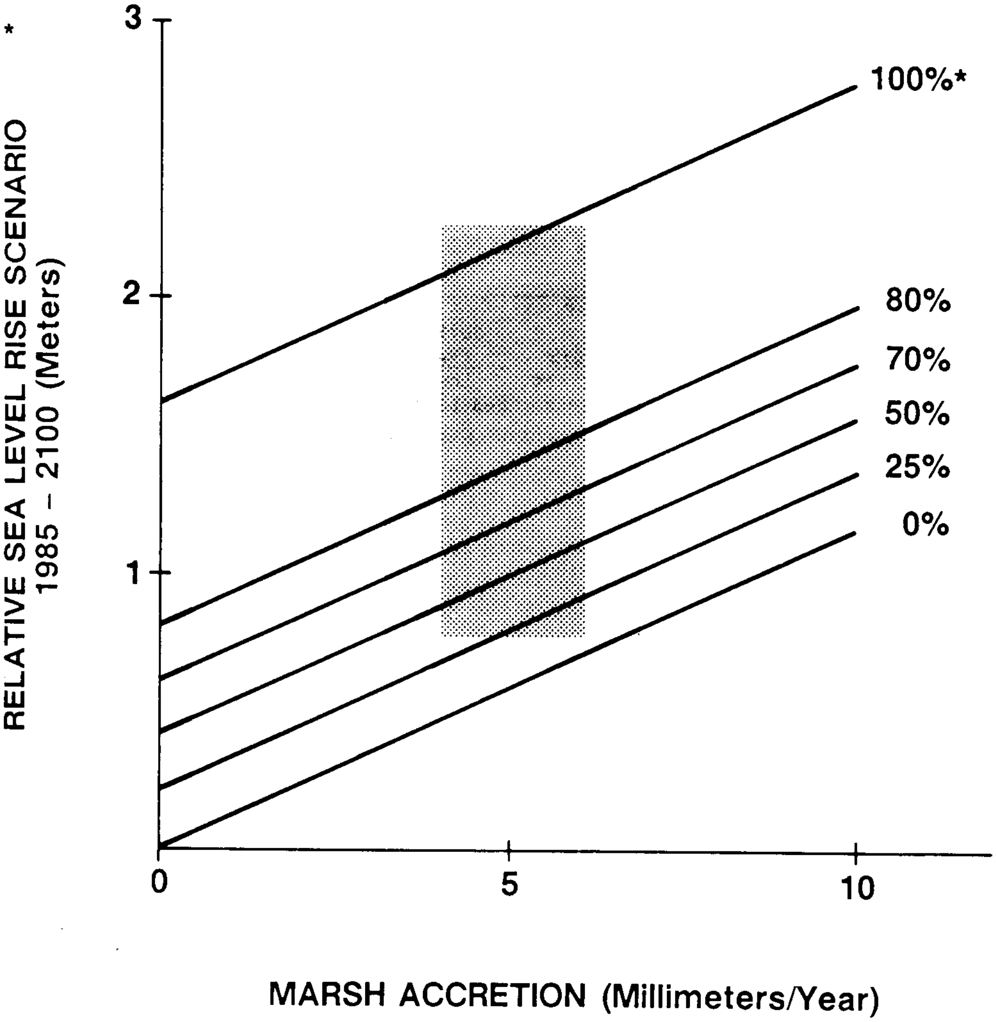
Conceptual model of the shift in wetlands zonation along a shoreline profile if sea level rise exceeds sedimentation by 40an. In general, the response will be a landward shift and altered areal distribution of each habitat because of variable slopes at each elevation interval

Source: *Kana et al. (Chapter 2)*

Although Kana et al. considered alternative scenarios of sea level rise, they did not investigate alternative rates of wetland accretion. However, using the data presented in Figure 1-6, one can derive Figure 1-8, which shows marsh loss for various combinations of vertical accretion and sea level rise. For example, an 80 percent loss could occur (1) if the marsh grows upward at I centimeter per year and sea level rises 1.9 meters by 2100 or (2) if sea level rises 80 centimeters and the marsh stops accreting. The shaded region illustrates the most likely range based on current literature: global sea level rise of 50-200 centimeters and accretion of 4-6 millimeters per year. Within this likely range, a negligible loss of wetlands is possible; however, over half the shaded region shows an 80 percent loss of marsh by 2100.

FIGURE 1-8

PERCENT MARSH LOSS IN THE CHARLESTON AREA BY 2100 FOR COMBINATIONS OF SEA LEVEL RISE AND MARSH ACCRETION



The shaded area represents the most likely range of sea level rise (50-200 cm, global; 75-225 cm, relative to Charleston) and marsh accretion (4-6 mm/yr).

*Wetland loss in excess of 80 percent occurs only if today's uplands are protected.

To put the significance of these estimates in perspective, one would expect the Charleston area to lose less than 0.5 percent of its wetlands in the next century if current rates of conversion for development continue. Although a substantial amount of marsh was filled as the city was built, conversion of wetlands to dry land came to a virtual halt with the creation of the South Carolina Coastal Council. Since 1977, the state has lost only 35 of its 500,000 acres to dry land (South Carolina Coastal Council 1985). Impoundments have transformed another 100 acres.[7] Extrapolating these trends would imply a loss of about 1,500 acres in the next century, about 0.3 percent of the state's coastal wetlands. Thus, sea level rise would be the dominant cause of wetland loss.[8]

In the New Jersey study area, the high marsh dominates. Thus, there would not be a major loss of total marsh acreage for the low scenario through 2075; the high marsh would simply be converted to low marsh. For the high scenario, however, there would be an 86 percent loss of marsh, somewhat greater than the loss in the Charleston area. Table 1-3 illustrates the projected shifts in wetlands for the South Carolina and New Jersey Case studies through the year 2075; Table 14 shows projected changes in marsh area for net rises in sea level (over accretion) ranging from 10 to 100 cm.

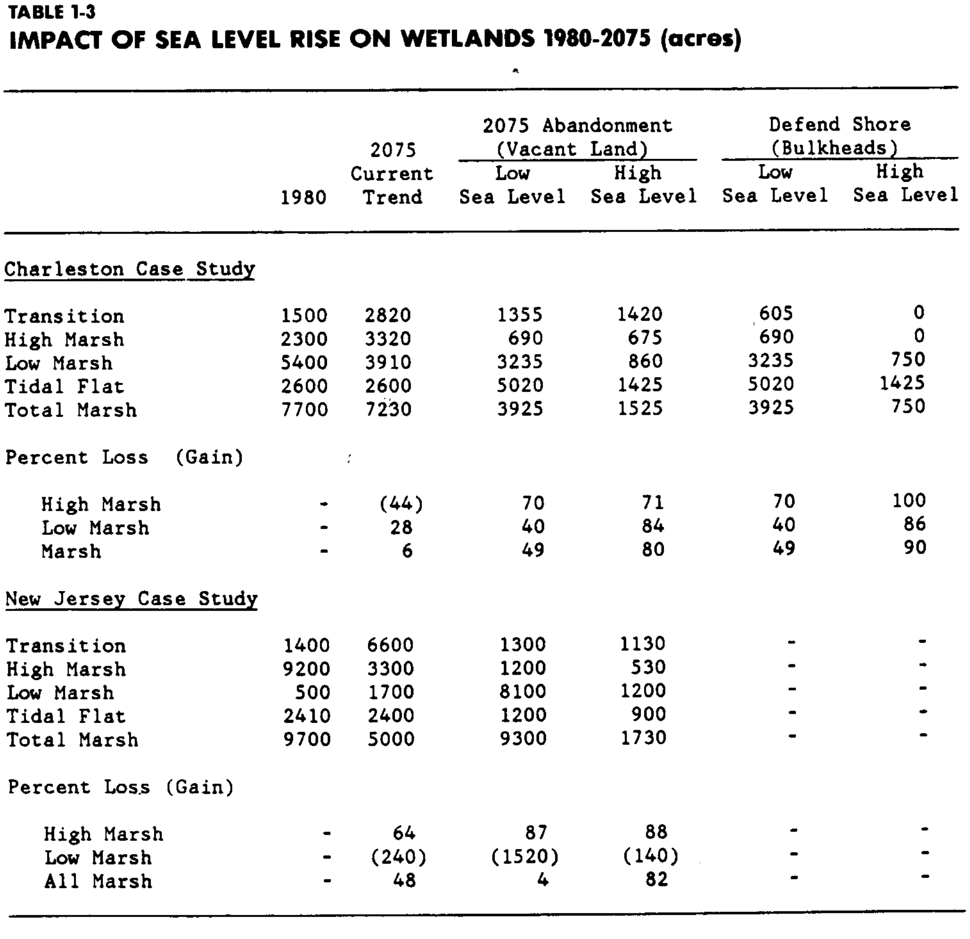


TABLE 1-3

IMPACT OF SEA LEVEL RISE ON WETLANDS 1980-2075 (acres)

			2075 Abandonment (Vacant Land)		Defend Shore (Bulkheads)	
	1980	2075 Current Trend	Low Sea Level	High Sea Level	Low Sea Level	High Sea Level
Charleston Case Study						
Transition	1500	2820	1355	1420	605	0
High Marsh	2300	3320	690	675	690	0
Low Marsh	5400	3910	3235	860	3235	750
Tidal Flat	2600	2600	5020	1425	5020	1425
Total Marsh	7700	7230	3925	1525	3925	750
Percent Loss (Gain)						
High Marsh	-	(44)	70	71	70	100
Low Marsh	-	28	40	84	40	86
Marsh	-	6	49	80	49	90
New Jersey Case Study						
Transition	1400	6600	1300	1130	-	-
High Marsh	9200	3300	1200	530	-	-
Low Marsh	500	1700	8100	1200	-	-
Tidal Flat	2410	2400	1200	900	-	-
Total Marsh	9700	5000	9300	1730	-	-
Percent Loss (Gain)						
High Marsh	-	64	87	88	-	-
Low Marsh	-	(240)	(1520)	(140)	-	-
All Marsh	-	48	4	82	-	-

Source: *Kana et al. (Chapters 2 and 3).*

TABLE 1-4

WETLAND AREA AS A PERCENT OF TODAY'S ACREAGE FOR A 10- to 100-cm RISE IN SEA LEVEL IN EXCESS OF VERTICAL ACCRETION*

Sea Level Rise	Charleston, SC			Tuckerton, NJ			Great Bay, NJ		
	High Marsh	Low Marsh	Total Marsh	High Marsh	Low Marsh	Total Marsh	High Marsh	Low Marsh	Total Marsh
0 cm	29.9	70.1	100.0	93.9	6.1	100.0	95.8	4.2	100.0
10	22.6	64.6	87.2	60.1	43.2	103.4	76.0	23.9	99.9
20	15.4	59.0	74.4	26.3	80.5	106.8	56.2	43.5	99.7
30	8.1	52.9	61.0	11.5	98.6	110.2	36.4	63.3	99.7
40	7.8	41.1	48.9	11.5	102.0	113.6	16.5	70.3	86.8
50	7.8	30.7	38.5	11.5	89.5	101.0	5.2	61.9	67.1
60	7.8	23.4	31.2	11.5	55.8	67.3	5.2	42.0	47.2
70	7.8	16.2	24.0	11.5	22.0	33.5	5.2	22.2	22.4
80	7.8	11.7	19.5	11.5	21.6	33.2	5.2	3.9	9.1
90	7.8	11.7	19.5	11.5	21.6	33.2	5.2	3.8	9.0
100 cm	7.8	11.7	19.5	11.5	21.6	33.2	5.2	3.8	9.0

**Calculations are based on the assumption that development does not prevent new wetlands from forming inland. If adjacent lowlands are protected, rises of between 1 and 1.6 m would destroy the remaining marsh.*

Barrier Islands, Deltas, and Saltwater Intrusion

Although most marshes could probably not keep pace with a substantial acceleration in sea level rise, three possible exceptions are the marshes found in river deltas, tidal inlets, and on the bay sides of barrier islands. River and tidal deltas receive much more sediment than wetlands elsewhere; hence they might be able to keep pace with a more rapid rise in sea level. For example, the sediment washing down the Mississippi river for a long time was more than enough to sustain the delta and enable it to advance into the Gulf of Mexico, even though relative sea level rise there is approximately one centimeter per year, due to subsidence (Gagliano, Meyer Arendt, and Wicker 1981). A global sea level rise of one centimeter per year would double the rate of relative sea level rise there to two centimeters per year; thus, a given sediment supply could not sustain as great an area of wetlands as before. It could, however, enable a substantial fraction to keep pace with sea level rise.

In response to sea level rise, barrier islands tend to migrate landward as storms wash sand from the ocean side beach to the bay side marsh (Leatherman 1982). This "overwash" process may enable barrier islands to keep pace with an accelerated rise in sea level. However, it is also possible that accelerated sea level rise could cause these islands, to disintegrate. In coastal Louisiana, where rapid subsidence has resulted in a relative sea level rise of one centimeter per year, barrier islands have broken up. The Ship Island of the early twentieth century is now known as "Ship Shoal" (Pendland, Suter, and Maslow 1986).

Marshes often form in the flood (inland) tidal deltas (shoals) that form in the inlets between barrier islands. Because these deltas are in equilibrium with sea level, a rise in sea level would tend to raise them as well, with sediment being supplied primarily from the adjacent islands.

Moreover, if sea level rise causes barrier islands to breach, additional tidal deltas will form in the new inlets, creating more marsh, at least temporarily. In the long run, however, the breakup of barrier islands mould result in a loss of marsh. Larger waves would strike the wetlands that form in tidal deltas and in estuaries behind barrier islands. Wave erosion of marshes could also be exacerbated if sea level rise deepens the estuaries. This deepening would allow ocean waves to retain more energy and larger waves to form in bays. Major landowners and the government of Terrebonne Parish, Louisiana, consider this possibility a serious threat and are taking action to prevent the breakup of Isle Demiere and others around Terrebonne Bay (Terrebonne Parish 1984).

Sea level rise could also disrupt coastal wetlands by a mechanism known as saltwater intrusion, particularly in Louisiana and Florida. In many areas the zonation of wetlands depends not so much on elevation as on proximity to the sea, which determines salinity. The most seaward wetlands are salt marshes or their tropical equivalent, mangrove swamps. As one moves inland, the fresh water flowing to the sea reduces salinity, and brackish wetlands are found. Still farther inland, the freshwater flow completely repels all salt water, and fresh marshes and cypress swamps are found.

Although these marshes may be tens (and in Louisiana, hundreds) of kilometers inland, their elevation is often the same as that of the saline wetlands. A rise in sea level enables salt water to penetrate upstream and inland, particularly during droughts. In many areas, the major impact would be to replace freshwater species with salt-tolerant marsh. However, many of the extensive cypress swamps in Louisiana, Florida, and South Carolina, as well as sow "floating marshes," lack a suitable base for salt marshes to form. These swamps could convert to open water if invaded by salt, which is already occurring in Louisiana (Wicker et al. 1980).

HUMAN INTERFERENCE WITH NATURE'S RESPONSE TO SEA LEVEL RISE

Although the natural impact of the projected rise in sea level is likely to reduce wetland acreages, the ecosystems would not necessarily be completely destroyed. However, human activities such as development and river flow management could disable many of the natural mechanisms that allow wetlands to adapt to a rising sea, and thereby substantially increase the loss of wetlands over what would occur naturally. In some areas the impacts could be so severe that entire ecosystems could be lost.

Development and Bulkheads

Although environmental regulations have often prevented or discouraged people from building on wetlands, they have not prevented people from building just inland of the marsh. As the final box in Figure 1-5 shows, wetlands could be completely squeezed between an advancing sea and bulkheads erected to protect developed areas from the sea. A few jurisdictions, such as Massachusetts, currently prohibit additional construction of bulkheads that prevent inland advance of marshes[9] However, these provisions were enacted before there was a concern about accelerated sea level rise; it is unclear whether they would be enforced if sea level rise accelerates. Moreover, bulkheads are already found along much of the shore and are generally exempt from such provisions.

The amount of sea level rise necessary for development to prevent new marsh from forming would depend on the extent to which development is set back from the wetlands. In Maryland, for example, the Chesapeake Bay Critical Areas Act forbids most new development within 1,000 feet of the marsh; thus, if the sea rises 50 centimeters (the highest part of the marsh) in excess of the vertical accretion, there may still be 1,000 feet of marsh. Additional rises in sea level, however, would eventually squeeze out the marsh.

In the Charleston area, development is prohibited in the transition wetlands, which extend 75 centimeters (2.5 feet) above the high marsh. Thus, Kana, Baca, and Williams (Chapter 2) estimate that in the low scenario, protecting development will not increase the loss of marsh through 2075, although it would increase the loss of transition wetlands. For the high scenario, however, protecting development would result in a 100 percent loss of high marsh (compared with a 71 percent loss), and would increase the loss of low marsh slightly (from 84 to 86 percent) by 2075. As Figure 1-8 shows, a two-meter rise by 2100 could result in a 100 percent loss of all marsh if development is protected.

Kana et al. do not explore the implications of protecting development in the New Jersey study. About one half of the marsh in that study falls within Brigantine National Wildlife Refuge, and hence is off-limits to development. New development in the other part of the study area must be set back 50 to 300 feet from the marsh.[10] Although the buffer zone would offer some protection, eventually the marshes here would also be squeezed out.

The development of coastal areas may have one positive impact on the ability of marshes to adapt to a rising sea. The development of barrier islands virtually guarantees that substantial efforts will be undertaken to ensure that developed islands do not break up or become submerged as the sea rises. Thus, these coastal barriers will continue to protect wetlands from the larger ocean and gulf waves for at least the next several decades and, in some cases, much longer.[11]

This positive contribution may be offset to some extent by human interference with the natural overwash process of barrier islands. Under natural conditions, storms would supply marshes on the bay sides of barrier islands with additional sediment, to enable them to keep pace with sea level rise. On developed barrier islands, however, public officials generally push the overwashed sand back to the Oceanside beach, which could inhibit the ability of these barrier marshes to keep pace with sea level rise. In many instances, however, these marshes have already been filled for building lots.

Louisiana and Other River Deltas

Although natural processes would permit a large fraction of most river deltas to keep pace with sea level, human activities may thwart these processes. Throughout the world, people have dammed, leveed, and channelized major rivers, curtailing the amount of sediment that reaches the deltas. Even at today's rate of sea level rise, substantial amounts of land are converting to open water in Egypt and Mexico (Milliman and Meade 1983).

In the United States, Louisiana is losing over 100 square kilometers (about 50 square miles) per year of wetlands (Boesch 1982). Until about one hundred years ago, the Mississippi Delta gradually expanded into the Gulf of Mexico. Although the deltaic sediments tend to settle and subside about one centimeter per year, the annual flooding permitted the river to overflow its banks, providing enough sediment to the wetlands to enable them to keep pace with relative sea level rise, as well as expand farther into the Gulf of Mexico.

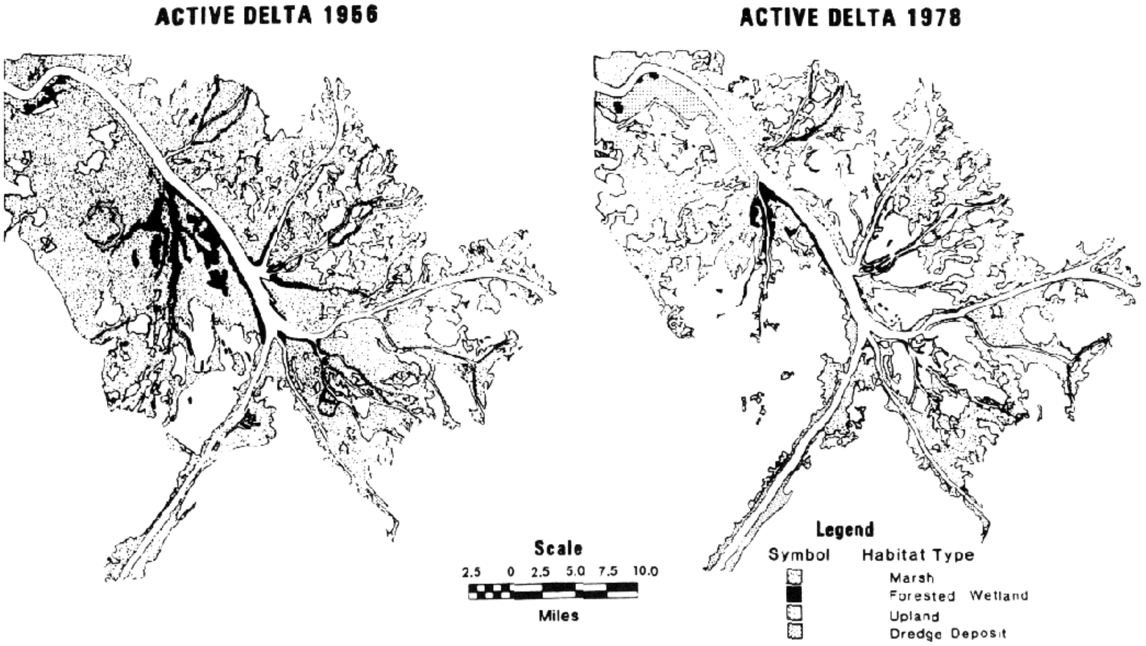
In the middle of the 19th century, however, the Corps of Engineers learned of a new way to reduce dredging costs at the mouth of the Mississippi River. Two large jetties were built to confine the river flow, preventing the sediment from settling out and creating shoals and marsh in and around the shipping lanes. Instead, the sediment is carried out into the deep waters of the Gulf of Mexico. The "self-scouring" capability of the channels has been gradually increased over the years. The banks of the lower part of the river are maintained to prevent the formation of minor channels that might carry sediment and water to the marsh, and thereby slow the current. The system works so well that dredging operations in the lower part of the river often involve deliberately resuspending the dredged materials in the middle of the river and sowing it to wash into the Gulf of Mexico, rather than disposing of the dredged spoils nearby. Although the channelization of the river has enabled cost-effective improvements in navigation, it prevents sediment, fresh water, and nutrients from reaching the wetlands near the mouth of the river.

Since the 1930s, levees have been built along both sides of the river to prevent the river from overflowing its banks during spring flooding, and several minor "distributaries" (alternative channels that lead through the wetlands to the Gulf of Mexico) have been sealed off. Although these actions have reduced the risk of river flooding in Louisiana, they also prevent sediment and fresh water from reaching the wetlands. As a result, wetlands are gradually submerged, and salt water is intruding farther inland, killing some cypress swamps and converting freshwater marsh to brackish and saline marsh. Finally, dams and locks on the upper Mississippi, Arkansas, Missouri, and Ohio Rivers (and improved soil conservation practices) have cut in half the amount of sediment flowing down the river, limiting the growth of wetlands in the Atchafalaya delta, the one area that has not (yet) been completely leveed and channelized.

Canals and poor land use practices have also resulted in wetland loss (Turner, Costanza, and Scaife 1982). However, levees and channels are particularly important because they disable the mechanisms that could enable the wetlands to repair themselves and keep pace with sea level. With almost no sediment reaching the wetlands, an accelerated rise in sea level could destroy most of Louisiana's wetlands in the next century.

Figure 1-9 illustrates the disintegration of wetlands at the mouth of the main channel of the Mississippi River between 1956 and 1978. Because there are no levees this far downstream, this marsh loss is attributable to navigation projects. Figure 10 illustrates changes in Terrebonne Parish's wetlands from 1955 to 1978. Note the extensive conversion of fresh marsh to saline and brackish marsh, as well as the conversion of cypress swamps to open water. Figure 141 shows the generally expected shoreline for Louisiana in the year 2030 if current management practices and sea level trends continue. Although projects to slow the rate of wetland loss may improve this picture, accelerated sea level rise could worsen it. Figure 142 shows the loss expected if sea level rises 55 cm by 2050.

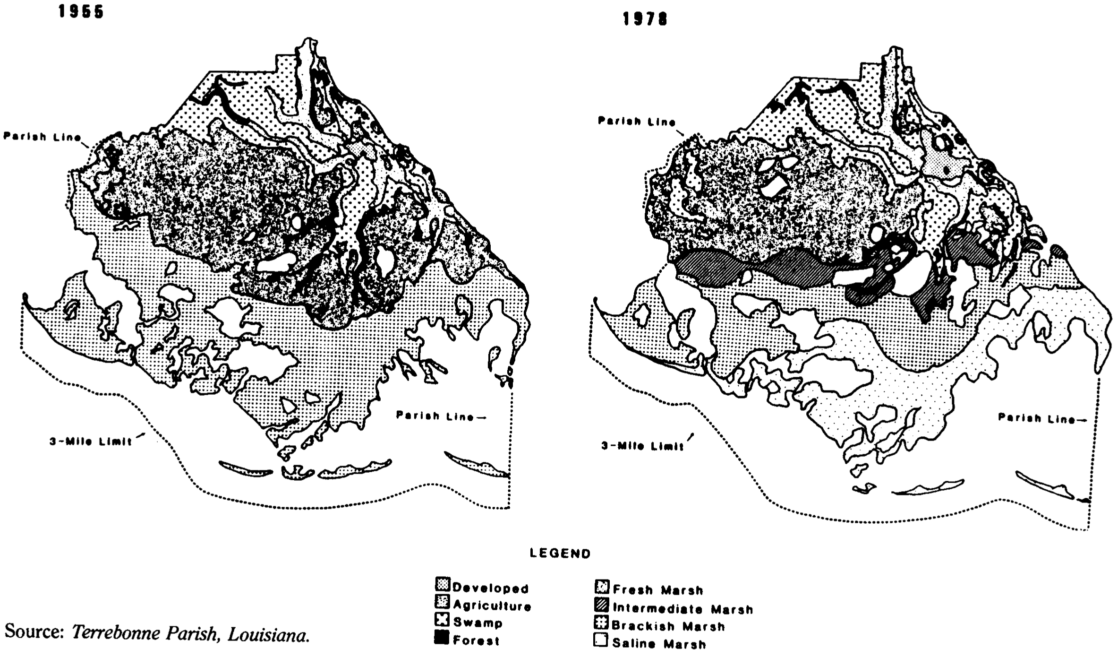
FIGURE 1-9
WETLAND LOSS AT THE MOUTH OF THE MISSISSIPPI RIVER



Source: *National Coastal Ecosystems Team, U.S. Fish and Wildlife Service.*

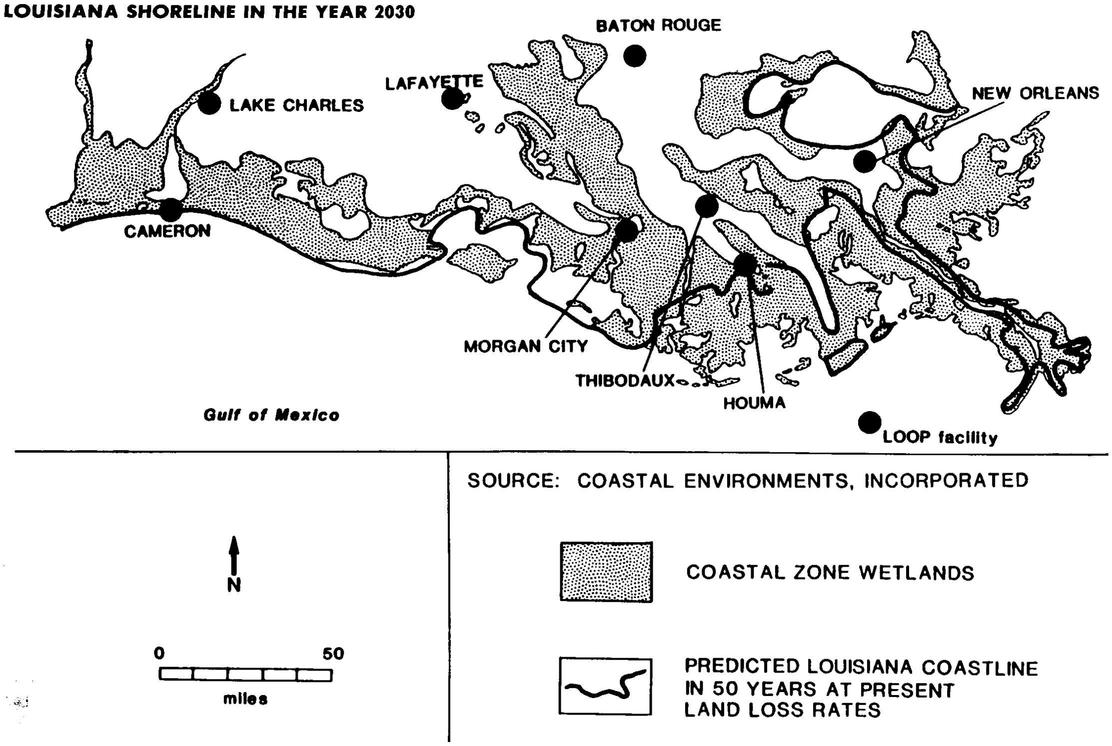
FIGURE 1-10

CHANGES IN TERREBONNE PARISH HABITATS: 1955-1978



Source: *Terrebonne Parish, Louisiana.*

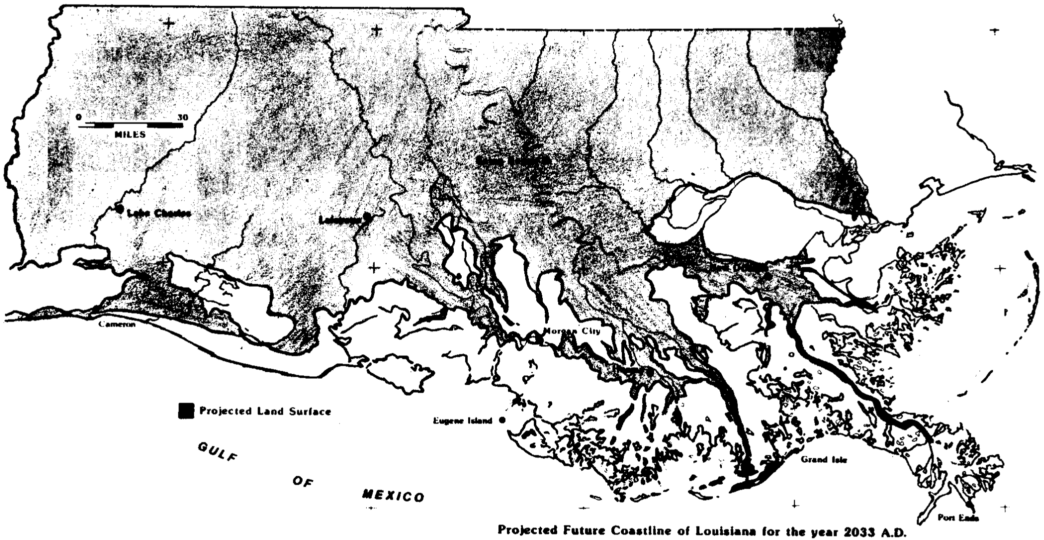
FIGURE 1-11
LOUISIANA SHORELINE IN THE YEAR 2030



SOURCE: COASTAL ENVIRONMENTS, INCORPORATED

FIGURE 1-12

PROJECTED FUTURE COASTLINE OF LOUISIANA FOR THE YEAR 2033 GIVEN A RISE IN SEA LEVEL OF 54.9 CM



Projected Future Coastline of Louisiana for the year 2033 A.D.
(EPA Sea Level Rise Scenario)

Louisiana Geological Survey

Source: *U.S. Environmental Protection Agency and Louisiana Geological Survey 1987.*

NATIONWIDE LOSS OF WETLANDS: A FIRST APPROXIMATION

Methods

The case studies of South Carolina and New Jersey illustrate the hypothesis that a rapid rise in sea level would drown more wetlands than it would create. Nevertheless, to demonstrate the general applicability of this hypothesis requires more than two case studies. Although this project did not have the resources necessary to conduct additional field surveys, we wanted to develop at least a rough estimate of the likely nationwide loss of coastal wetlands.

Armentano et al. (Chapter 4) use topographical maps, information on tidal ranges, and a computer model to estimate the impacts of sea level rise on 57 sites comprising 4800 square kilometers (1,200,000 acres) of wetlands, over 17 percent of all U.S. coastal wetlands. For each square kilometer they assigned a single elevation. If the map has ten-foot contours, and most of a square is between five and fifteen feet above sea level, they assigned the entire square an elevation of ten feet. If the map shows that a particular area is marsh, they *gave* it the marsh designation and an elevation based on a linear interpolation between the shoreline and the first contour, generally at elevation 10 feet. Their data base also considered whether a particular area is developed or undeveloped, and whether there is an existing flood-protection wall or bulkhead.

Although their data base was much more coarse, Armentano et al. use a more sophisticated model for projecting the impact of sea level rise than Kana et al. The latter simply subtracted estimated vertical accretion from relative sea level rise for the year 2075, to yield an estimate of net substrate change for the entire period. Armentano et al. also subtract vertical accretion from relative sea level rise, but in five-year increments. Once an area is below spring high tide, it is assumed to be marsh; once it is below mean low water, it converts from marsh to open water. This procedure makes it possible to display results of wetland loss for particular years, and to consider changes in marsh accretion rates during the forecast period. Arrnentano et al. also account for changes in exposure to waves due to destruction of barrier islands and spits.

Because elevations are estimated crudely, one should be suspicious of individual results. Although marsh is generally found at elevations ranging from mean sea level to spring tide, Amientano et al. assign it all to a single elevation for a particular cell based on contours that generally describe elevation of adjacent dry land, not the elevation of the marsh, rounded to the *nearest* half meter. If the change in water depth (relative sea level rise minus accretion) is small, the model assumes no loss of marsh; whereas some marsh would actually be lost. Conversely, for a water depth greater than the estimated elevation above man low water, all the marsh is assumed lost; whereas the marsh between that elevation and spring high tide would actually remain marsh. Similarly, the model may tend to underestimate marsh creation for small rises in sea level while overestimating creation for larger rises.

The estimates by Armentano et al. were based on a number of conservative assumptions that may tend to understate wetland loss. They assumed that the New England, Florida, and Texas marshes are not subsiding, whereas tide gauges indicate that these areas are subsiding between one and two millimeters per year (Hicks et al. 1983). Moreover, they assumed that sea level rise would not convert marsh until mean low water had risen above the marsh; by contrast marsh is often not found below mean sea level, and in the case of Charleston, Kana et al. found that it is generally at least 30 centimeters above today's mean sea level (NGVD elevation 45 centimeters). Finally, the linearity assumption tends to understate marsh loss in areas where the profile is concave, as in Figures 1-5 and 1-6 and most coastal areas.

Regional Results

Armentano et al. emphasize that their estimates should not be considered as statistically valid estimates of wetland loss in particular U.S. coastal regions. Nevertheless, we believe that the results provide a useful and indicative first approximation.

Table 1-5 summarizes their estimates for the low and high sea level rise scenarios. The first two columns of the bottom half show their estimates of the wetland loss that would take place if development prevented new marsh from forming inland. The other two columns show their estimates of the net change in wetland acreage assuming that development does not prevent new marsh from forming except where the shoreline already has bulkheads, levees, or other shore protection structures. These assumptions are both extreme. Complete protection of all existing dry land would be very unlikely, as would a total abandonment of all (currently) unprotected areas just inland of the wetlands. The extent to which development retreats would depend both on economics and on public policies regarding the appropriate level of wetland protection in the face of rising sea level. An investigation of these issues, however, was outside the scope of that study.

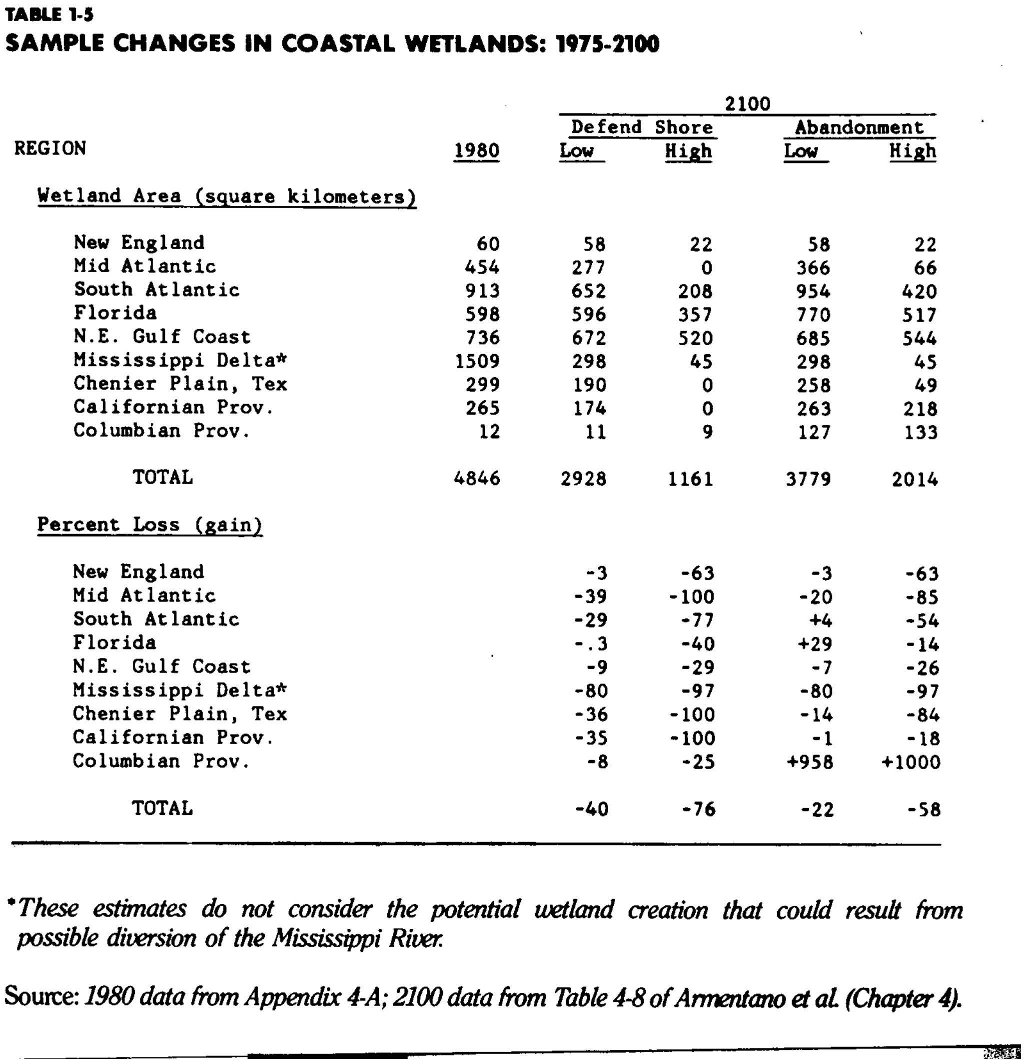


TABLE 1-5

SAMPLE CHANGES IN COASTAL WETLANDS: 1975-2100

		2100			
		Defend Shore		Abandonment	
REGION	1980	Low	High	Low	High
Wetland Area (square kilometers)					
New England	60	58	22	58	22
Mid Atlantic	454	277	0	366	66
South Atlantic	913	652	208	954	420
Florida	598	596	357	770	517
N.E. Gulf Coast	736	672	520	685	544
Mississippi Delta*	1509	298	45	298	45
Chenier Plain, Tex	299	190	0	258	49
Californian Prov.	265	174	0	263	218
Columbian Prov.	12	11	9	127	133
TOTAL	4846	2928	1161	3779	2014
Percent Loss (gain)					
New England		-3	-63	-3	-63
Mid Atlantic		-39	-100	-20	-85
South Atlantic		-29	-77	+4	-54
Florida		-.3	-40	+29	-14
N.E. Gulf Coast		-9	-29	-7	-26
Mississippi Delta*		-80	-97	-80	-97
Chenier Plain, Tex		-36	-100	-14	-84
Californian Prov.		-35	-100	-1	-18
Columbian Prov.		-8	-25	+958	+1000
TOTAL		-40	-76	-22	-58

**These estimates do not consider the potential wetland creation that could result from possible diversion of the Mississippi River.*

Source: *1980 data from Appendix 4-A; 2100 data from Table 4-8 of Armentano et al. (Chapter 4).*

Armentano et al. estimate that the low scenario would have relatively little impact on New England's marshes, largely due to their ability to keep pace through peat formation. Nevertheless, peat formation would not be likely to keep pace with the more rapid rate of sea level rise implied by the high scenario, which could result in two-thirds of these marshes being lost. Similar situations could be expected in Florida and the Northeast Gulf Coast although a flatter coastal plain in these regions would offer a greater potential for wetland creation if development did not stand in the way. The assumption by Armentano et al. that Florida wetlands could accrete one centimeter per year may be unduly optimistic.

The middle and southern Atlantic coastal marshes would be more vulnerable than New England to the low sea level rise scenario, largely because smaller tidal ranges there imply that existing wetlands are found at lower elevations than the New England wetlands, while vertical accretion was generally assumed to he less than in the case of Florida and the Northeast Gulf Coast. These estimates appear to imply less wetland loss than the case studies by Kana et al. In the high scenario, however, estimates by Armentano et al. are considerably higher and more closely consistent with Kana et al., as w discuss below.

To understand the implications of Armentano et al., it is useful to compare their procedures and results -with those of Kana et al., where there is site-specific information. In the case of Charleston, Armentano et al. estimate that the low scenario (net substrate change, III centimeters) implies a 37 percent loss and a 21 percent gain through 2100, for a net loss of 16 percent. The transacts of Kana et al. imply that the low scenario would result in a 100 percent loss of existing marsh with an 18 percent gain, for a net loss of 82 percent Had the Armentano et al. approach been applied to the Charleston case study, it would have attributed an initial elevation of 1.0 meters to the marsh,[12] which is not unreasonable given that it ranges from 0.5 to 1.3 meters-although 80 percent of the marsh is below 1.0 meters. However, their procedure would require the net substrate change to be one meter plus one-half the tidal range, for a total rise of 1.8 meters, before the marsh would convert to water. Thus, the model of Armentano et al. estimates Charleston's wetlands to be much less vulnerable than the field surveys by Kana et al. suggest.[13]

In the case of the New Jersey wetlands, the groups arrived at similar results. Armentano et al. estimate a 75 percent wetland loss through 2075 in the high scenario and no loss in the low scenario, while Kana et al. estimate an 86 percent loss in the high scenario and a 6 percent gain in the low The tendency of Armentano et al. to assign a fairly high elevation to the marsh is more appropriate in areas where high marsh dominates. Moreover, five-foot contours were available in this case. Table 1-6 summarizes the Armentano et al. and Kana et al. finding.

TABLE 1-6

COMPARISON OF ARMENTANO ET AL. AND KANA ET AL. STUDY RESULTS SHOWS THAT USE OF TOPOGRAPHIC MAPS CAN UNDERESTIMATE VULNERABILITY OF WETLANDS TO SEA LEVEL RISE (percent loss of wetlands)

	Low Scenario		High Scenario	
	Abandonment	Defend Shore	Abandonment	Defend Shore
Charleston, South Carolina (2100)				
Armentano et al.	16	37	28	55
Kana et al.[1]	82	100	84	100
Tuckerton, New Jersey (2075)				
Armentano et al.	0	-	75	
Kana et al.	4	-	82	

[1] *There results are derived from the profiles estimated by Kana et al.*

The Mississippi Delta and Texas Chenier Plain wetlands appear to be the most vulnerable. As Table 1-5 shows, 36 percent of the latter would be lost in the low scenario, and all could be lost in the high scenario. Abandonment would increase the portion of wetlands surviving the next century by about 15 percent of today's acreage. Armentano et al. estimate that 80 and 97 percent of Louisiana's wetlands would be lost for the low and high scenarios, respectively. However, me caution the reader that their model did not consider the potential positive impacts of a diversion of the Mississippi River, which could enable a fraction of the wetlands to survive a more rapidly rising sea level.

Although the Pacific Coast wetlands examined appear to be as vulnerable to sea level rise as Atlantic and Gulf coast wetlands, Armentano et al. found that the former have greater potential for wetland creation with sea level rise. In the Californian study areas, 35 to 100 percent of the existing wetlands could be lost; however, the net loss would be I to 18 percent if developed areas were abandoned.

The Pacific Northwest study site could experience a tenfold increase in metland area for either scenario, if uplands are abandoned. However, me suggest that the reader not attribute undue significance to the Columbia River results. This study site accounted for less than 5 per- cent of the Pacific Coast marshes considered. The result is a useful reminder of the fact that some areas could gain substantial amounts of wetland acreage. We do not recommend, however, that any of the regional results be taken too seriously until they can be verified by additional study sites and a more detailed examination of wetland and upland transacts, such as those in Chapters 2 and 3.

Nationwide Estimate

The results of Armentano et al. can be used to derive a rough estimate of the potential nationwide loss of coastal wetlands. However, the reader should note that Armentano et al. did not use a completely random method for picking study areas, and that their elevation estimates mere rounded to the nearest quarter meter. Thus, they warn the reader that estimates based on their projections are not statistically valid.

Armentano et al. sought to include study sites for all major sections of coast. However, they did not attempt to ensure that the wetland acreage of the sites in a particular region are directly proportional to the total acreage of wetlands in that region. Therefore, to derive a nationwide estimate of the loss of wetlands one should meight estimates of "percentage loss by region" by actual wetland acreages in the various regions.

A recent study by the National Ocean Service estimates coastal wetland acreage by state (Alexander, Broutman, and Field 1986). We modified those estimates to exclude swamp acreage in regions where Armentano et al. did not investigate swamps. The term "coastal wetland" in this report refers to tidal wetlands and non-tidal wetlands that are hydraulically connected to the sea, such as cypress swamps in Louisiana. The NOS study includes all swamps in coastal counties, some of which are well inland and not hydraulically connected to the sea, particularly in North Carolina and New Jersey.

The first column of Table 1-7 shows the adjusted estimates of wetlands acre4e by region. Because the Pacific Coast wetlands represent such a small fraction of the total, me have combined the California and Pacific Northwest regions. The rest of the table shows the implied wetland losses and gains estimated using the percentages reported by Armentano et al. The greatest losses would appear to be in Louisiana and the southern and middle Atlantic coast. However, we caution the reader that the region-specific estimates have less credibility than the nationwide estimate.

Of the estimated 6.9 million acres of coastal wetlands, 3.3 million could be lost under the low scenario. If human activities do not interfere, however, 1.1 million acres might be created. Under the high scenario, 5.7 million acres (81 percent) would be lost, while 1.9 million acres could potentially be created.

These estimates of the nationwide loss of wetlands are based on dozens of assumptions. Nevertheless, they seem to support the simple hypothesis that the area of wetlands today is greater than what would be at the proper elevation for supporting wetlands if sea level rose a meter or two. Thus, if rates of vertical accretion remain constant, a rise of this magnitude in the next century would destroy most U.S. coastal wetlands.

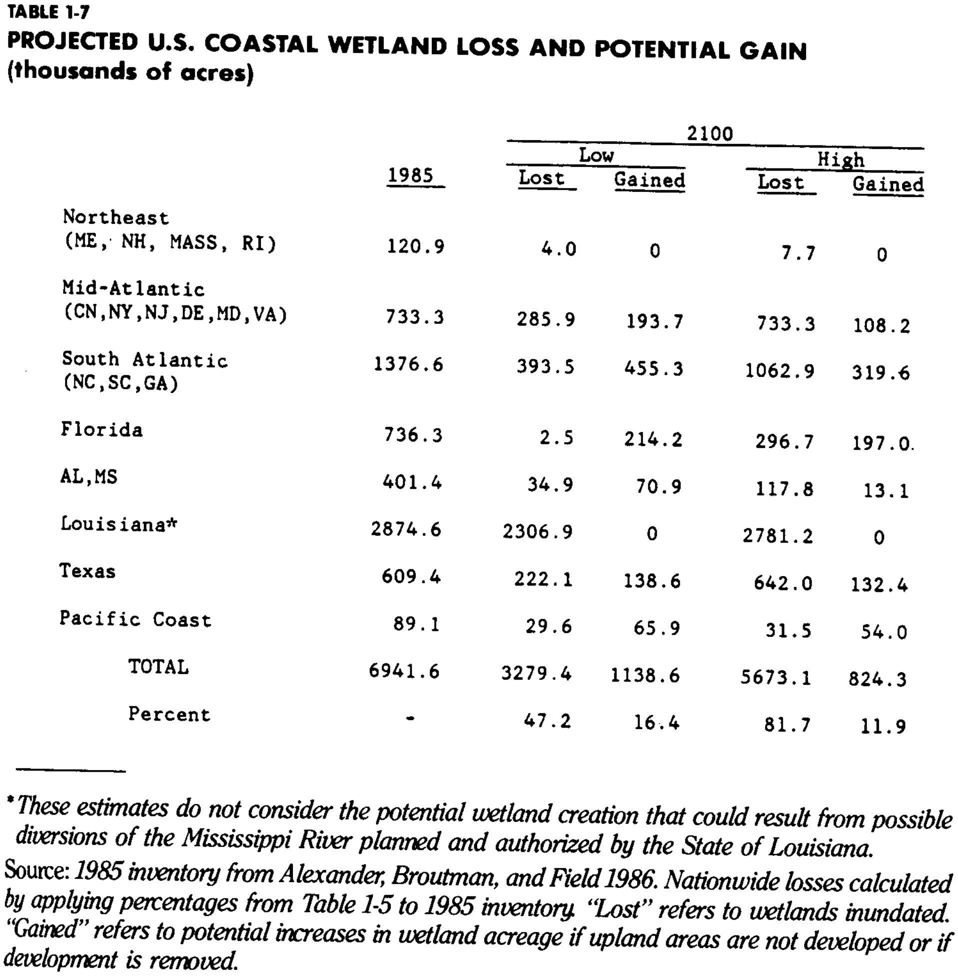


TABLE 1-7

PROJECTED U.S. COASTAL WETLAND LOSS AND POTENTIAL GAIN (thousands of acres)

		2100			
		Low		High	
	1985	Lost	Gained	Lost	Gained
Northeast (ME, NH, MASS, RI)	120.9	4.0	0	7.7	0
Mid-Atlantic (CN,NY,NJ,DE,MD,VA)	733.3	285.9	193.7	733.3	108.2
South Atlantic (NC,SC,GA)	1376.6	393.5	455.3	1062.9	319.6
Florida	736.3	2.5	214.2	296.7	197.0
AL,MS	401.4	34.9	70.9	117.8	13.1
Louisiana*	2874.6	2306.9	0	2781.2	0
Texas	609.4	222.1	138.6	642.0	132.4
Pacific Coast	89.1	29.6	65.9	31.5	54.0
TOTAL	6941.6	3279.4	1138.6	5673.1	824.3
Percent	-	47.2	16.4	81.7	11.9

These estimates do not consider the potential wetland creation that could result from possible diversions of the Mississippi River planned and authorized by the State of Louisiana.

Source: *1985 inventory from Alexander, Broutman, and Field 1986. Nationwide losses calculated by applying percentages from Table 1-5 to 1985 inventory. "Lost" refers to wetlands inundated. "Gained" refers to potential increases in wetland acreage if upland areas are not developed or if development is removed.*

PREVENTING FUTURE WETLAND LOSSES

Future losses of wetlands from sea level rise could be reduced by (1) slowing the rate of sea level rise, (2) enhancing wetlands' ability to keep pace with sea level rise, (3) decreasing human interference with the natural processes by which wetlands adapt to sea level rise, or (4) holding back the sea while maintaining the marshes artificiafly.[14]

Society could curtail the projected future acceleration of sea level rise by limiting the projected increases in concentrations of greenhouse gases. Seidel and Keyes (1983) projected that reducing $C0_2$ emissions with bans on coal, shale oil, and synfuels (but not oil and gas) would delay a projected two degree (C) warming from 2040 to 2065; because of the thermal delay of the oceans, the resulting thermal expansion of ocean water would be delayed ten to fifteen years.[15] Other trace gases might also be controlled. Hoffman et al. (1986) showed that the acceleration of sea level rise could be significantly delayed through controls of greenhouse gas emissions.

Although limiting the rise in sea level from the greenhouse effect might be the preferred solution for most parties involved in the wetland protection process, it would also be largely outside of their control. The nations of the world would have to agree to replace many industrial activities with processes that do not release greenhouse gases, perhaps at great cost. A decision to limit the warming would have to weigh these costs against many other possible impacts of the greenhouse warming which are understood far less than wetland loss from a rise in sea level, including the economic impacts of sea level rise; environmental consequences for interior areas, such as an increase in desertification; and possible disruptions of the world's food supply. Perhaps the most important challenge related to this option is that it would have to be implemented at least fifty years before the consequences it attempts to avert would have taken place.

Because me may have passed the time when it would be feasible to completely prevent an accelerated rise in sea level, wetland protection officials may also want to consider measures that would enable wetlands to adapt to rising sea level. Enhancing the ability of wetlands to keep pace with sea level rise has the advantage that such measures, which include marsh building, enhanced sedimentation, and enhanced peat formation, would not have to be implemented until sea level rise has accelerated.

Current environmental policies often require marsh building to mitigate destruction of wetlands. Although this measure will continue to be appropriate in many instances, it can cost tens of thousands of dollars per acre, which would imply tens of billions of dollars through 2100 if applied universally. Enhanced sedimentation may be more cost-effective; it is generally cheaper to save an acre of marsh than to create an acre of new marsh. Technologies that promote vertical growth of marshes generally spray sediment in a manner that imitates natural flooding (Deal 1984). Although these technologies look promising, they are barely past the development stage and may also prove too costly to apply everywhere. Although processes for enhancing peat formation might prove feasible, reduced peat formation might also result from climate change.

Allowing wetlands to adapt naturally to sea level rise would not prevent a large reduction in acreage, but might allow the ecosystems themselves to survive. This option would consist primarily of removing human impediments to sedimentation and the landward migration of met- lands. The sediment washing down the Mississippi River, for example, would be sufficient to sustain a large part of Louisiana's wetlands, if human activities do not continue to force sediment into the deep waters of the Gulf of Mexico. However, the costs of restoring the delta would be immediate, while the benefits would accrue over many decades. Similarly, measures could be taken to ensure that the wetlands in tidal deltas adjacent to barrier island inlets are not deprived of sediment by groins and jetties built to keep sand on the islands and out of the inlet.

For the extensive mainland marshes not part of a tidal delta, a natural adaptation would require the wetlands to migrate landward and up the coastal plain. Such a policy would also be costly. It would be necessary to either prevent development of areas just upland of existing wetlands, or to remove structures at a later date if and when the sea rises. Preventing the development of the upland areas would require either purchasing all the undeveloped land adjacent to coastal marshes or instituting regulations that curtailed the right to build on this property. The former option would be costly to taxpayers, while the latter option would be costly to property owners and would face legal challenges that might result in requirements for compensation.

Developing upland areas and later removing structures as the sea rises would allow costs to be deferred until better information about sea level rise could be obtained. This option could be implemented either through an unplanned retreat or a planned retreat. Howard, Pilkey, and Kaufman (1985) discuss several measures for implementing a planned retreat along the open coast. Although North Carolina and other coastal areas have required houses to be moved inland in response to erosion along the open coast-where shore protection is expensive-it may be more difficult to convince people that the need for wetland protection also justifies removal of structures.

There is also a class of institutional measures that increases the flexibility of future generations to implement a retreat if it becomes necessary, without imposing high costs today. For example, permits for new construction can specify that the property reverts to nature one hundred years hence if sea level rises so many feet. Such a requirement can ensure the continued survival of coastal wetlands, yet is less likely to be opposed by developers than policies that prohibit construction. Moreover, with the government's response to sea level rise decided, real estate markets can incorporate new information on sea level rise into property values. The State of Maine (1987) has adopted this approach, specifying that houses are presumed to be moveable. In the case of hotels and condominiums, the owner must demonstrate that the building would not interfere with natural shorelines in the event of a rise in sea level of up to three feet, or that he or she has a plan for removing the structure if and when such a rise occurs.

Finally, it might be possible to hold back the sea and maintain wetlands artificially. For small amounts of sea level rise, tidal gates might be installed that open during low tide but close during high tide, thereby preventing saltwater intrusion and lowering average water levels. For a larger rise, levees and pumping systems could be installed to keep wetland water levels below sea level. Although these measures would be expensive, they would also help to protect developed areas from the sea. Terrebonne Parish, Louisiana, is actively considering a tidal protection system and a levee and pumping system to prevent the entire jurisdiction from converting to open water in the next century (Edmonson and Jones 1985). They note, however, that effective measures to enable shrimp and other seafood species to migrate between the protected marshes and the sea have not yet been demonstrated.

Measures to ensure the continued survival of wetland ecosystems as sea level rises need to be thoroughly assessed. We may be overlooking opportunities where the cost of implementing solutions in the near term would be a small fraction of the costs that would be required later. Only if these measures are identified and investigated will it be possible to formulate strategies in a timely manner.

CONCLUSIONS

An increasing body of evidence indicates that increasing concentrations of greenhouse gases could cause sea level to rise one or two meters by the year 2100. If current development and river management practices continue, such a rise would destroy the majority of U.S. coastal wetlands. Yet these losses could be substantially reduced by timely anticipatory measures, including land use planning, river diversion, and research on artificially enhancing coastal wetlands, as well as by a reduction in emissions of greenhouse gases.

Case studies of South Carolina and New Jersey marshes indicate that a two-meter rise would destroy 80 to 90 percent of the coastal marshes, depending on development practices, while a one-meter rise would destroy 50 percent or less. The large body of research previously conducted in Louisiana suggests that its marshes and swamps would be far more vulnerable. Yet anticipatory measures, if implemented soon, could save a large fraction of these wetlands.

For the rest of the nation, no site-specific research has been undertaken. Most of these wetlands are also within one or two meters of sea level. Preliminary analysis by Armentano et al.

suggests that coastal wetlands throughout the nation would be vulnerable to such a rise, with the possible exception of areas with large tidal ranges or substantial terraces two or three meters above sea level.

Basic and applied research on the ability of wetlands to adjust to rising sea level would be valuable. Because sea level rose one meter per century on average from 15,000 B.C. until 5,000 B.C., it may be possible to better assess the response of wetlands to such a rise in the future. Research on how to artificially promote vertical accretion or control water levels is also important. Such research could benefit coastal states throughout the nation in the long run, although the short-run benefits of protecting Louisiana's wetlands—40 percent of the total—suggests that such research should be initiated soon.

When is the appropriate time to respond to the potential loss of wetlands to a rising sea? If technical solutions are possible, it might be sufficient to wait until sea level rise accelerates. Where planning measures are appropriate, a thirty- to fifty-year lead time might be sufficient. Where policies are implemented that will determine the subsequent vulnerability of wetlands to sea level rise, it would be appropriate to consider sea level rise when those decisions are made. If society intends to avert a large rise in sea level, a lead time of fifty to one hundred years may be necessary.

Wetland protection policies and related institutions such as land ownership are currently based on the assumption that sea level is stable. Should they be modified to consider sea level rise today, after the rise is statistically confirmed, or not at all? This question will not only require technical assessments, but policy decisions regarding the value of protecting wetlands, our willingness to modify activities that destroy them, and the importance of preparing for a future that few of us will live to see.

NOTES

[1] Several reviewers suggested that these figures may overstate the decline in me6and loss because they exclude conversion for agriculture and other nonregulated wetland destruction.

[2] U.S. Fish and Wildlife Service, Charleston, South Carolina Office, personal communication, March 1986.

[3] This curve shows the concentration for Mauna Loa, Hawaii, which is sufficiently remote to represent the average northern hemispheric concentration. Measurements at the South Pole suggest that the concentration for the southern hemisphere lags at most a couple of years, since most of the sources are in the northern hemisphere.

[4] Studies on the greenhouse effect generally discuss the impacts of a carbon dioxide doubling: By "effective doubling of all greenhouse gases" we refer to any combination of increases in the concentration of the various gases that causes a warming equal to the warming caused by a doubling of carbon dioxide alone over 1900 levels. If the other gases contribute as much warming as carbon dioxide, the effective doubling would occur when carbon dioxide concentrations have reached 450 ppm, 1.5 times the year-1900 level.

[5] These estimates did not consider meltwater from Antarctica or ice discharge from Greenland.

[6] Low marsh is found below mean high tide, which is defined as one-half the tidal range above sea level; high marsh extends up to the spring high tide, generally less than three quarters of a tidal range above sea level; and transition wetlands are somewhat higher.

[7] Personal communication. U.S. Fish and Wildlife Service, Charleston Office. The estimates exclude -forested wetlands and freshwater marshes, which are *cleared*_for agriculture and silviculture.

[8] A few reviewers noted that this hypothesis remains to be demonstrated. If insufficient flooding limits vertical accretion, a more rapid sea level rise would accelerate wetland accretion. However, there is little doubt that wetlands in Louisiana cannot keep pace with a rise of I cm/year in the absence of substantial sediment nourishment.

[9] For Massachusetts, see M.G.L. Ch. 13, S. 40 Reg. 310 C.M.R. 9.10 (2) of Massachusetts General Laws.

[10] As specified by the New Jersey Administrative Code, Wetland Buffer Policy, 7:7E-3.26.

[11] A few reviewers pointed out that coastal protection structures such as snowfences and seawalls can increase the probability of an eventual breakup. However, the longer-ten-n strategy of raising the beach profile and island with fill does not share that liability.

[12] The marsh would range from 0 to 2,500 feet from shore, while the ten-foot contour would be 3,500 feet from shore; the midpoint of the marsh would be about 1,200 feet from shore. A linear interpolation implies that this point has a one-meter elevation.

[13] The Armentano et al. model has additional complexities, but the factors described here are most important in explaining the discrepancy with the Kana et al. results.

[14] This report does not address the issue of whether wetlands should be maintained. It is possible that in some cases open water areas replacing wetlands would support sea grasses that provide ecological benefits as great as the benefits of the wetlands they replace.

[15] Computer printout of results from Seidel and Keyes 1983

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