Chapter 4

IMPACTS ON COASTAL WETLANDS THROUGHOUT THE UNITED STATES

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INTRODUCTION

Although wetland responses to sea level rise can be estimated only in association with uncertainties inherent in making future projections, the major factors controlling wetland sea level responses can be modeled. This chapter considers possible coastal wetland responses to future sea level rise in the conterminous United States, in order to provide information needed to understand future threats to coastal resources during an anticipated period of unprecedented climatic change.

Our primary objectives have been to interpret our present understanding of wetland adjustments to sea level rise in terms of a future acceleration of present sea level rise rates, and to outline a method for projecting future regional-level responses that could result from global warming. The research focuses on relatively large-scale spatial patterns as opposed to specific site responses. Therefore, local features often are subsumed within more widespread characteristics in order to detect regional trends.

SCOPE AND BACKGROUND

The present study considers all coastal wetlands below 3.5 m elevation along the Atlantic, Gulf, and Pacific coasts of the conterminous United States. Among the wetland types considered, salt marshes predominate, although important brackish and freshwater marshes occur in each coastal region. In subtropical Florida, mangrove swamps usually replace salt marshes. Although all wetland types meeting the elevation criterion are considered, shifts between wetland types are not explicitly treated, for reasons given later.

The chief information base for this study consists of current knowledge of wetland adjustments to sea level rise inferred for the past several thousand years, particularly during the present century. The sedimentary sequence laid down under salt marsh conditions forms a record of coastal history, thus providing a basis for dating the location of the intertidal zone at various times in the past. In many areas, reconstruction of past shorelines and of sediment profiles reveals that the wetlands and sea level have been in approximate equilibrium for the past several millennia. This condition appears typical of many Atlantic coast wetlands. However, the pattern is not universal, and departures from this trend would be expected to influence wetland responses to accelerated sea level rise. Thus, in recent decades, Texas and Louisiana wetlands have been inundated by rising sea levels in response to land subsidence and reduced sediment supply (Davis 1985). Net loss of wetland area in Louisiana has resulted despite rapid vertical accretion rates (Hatton, Delaware, and Patrick 1983). Elsewhere, at various times in the recent past, expansion of wetlands has occurred (e.g., Redfield 1972).

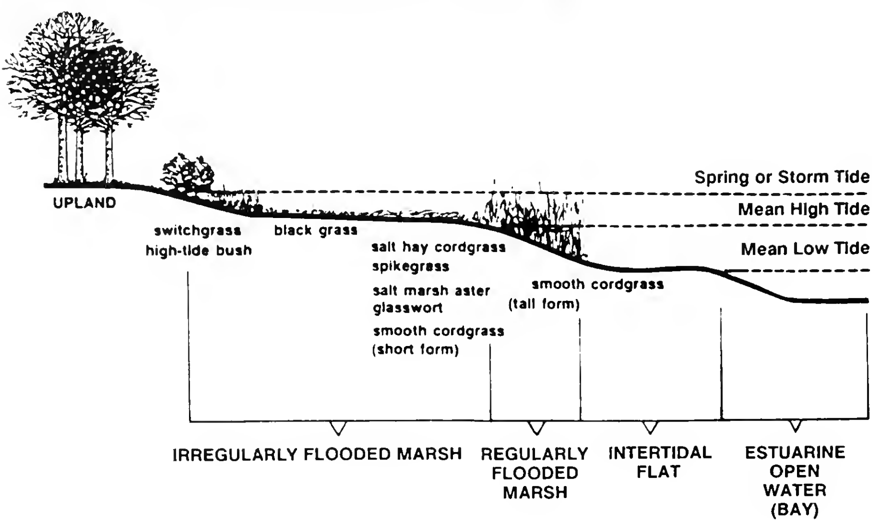
Similarly, Johannesson (cited in Seliskar and Gallagher 1983) reports that the marsh advanced seaward into an Oregon estuary at over 21 m per year during 1887-1939, but has since slowed to about 0.15 m per year. However, in the current era such expansion appears restricted to local sites. Important factors determining wetland response to sea level rise include the topography of the wetland bottom, changes in upstream sediment supply and in growth rates of marsh vegetation, and more recently, the presence of artificial structures such as sea walls.

Salt marshes (saline wetlands) typically occupy zones bordering landward freshwater environments and marine or brackish bays and estuaries, except in high-energy tidal areas directly facing the open sea. However, under low energy conditions (e.g., the Florida panhandle), marshes may front the open sea. All salt marshes are technically defined as vegetated saline intertidal flats. Atlantic Gulf marshes originally covered about 2.02 x 10^6 ha (Davis 1985), and in the United States as a whole, about 3 x 10^6 ha in 1922 (Teal and Teal 1969). Since then, U.S. coastal wetlands were lost at a rate of 0.2 percent per year through 1954, and 0.5 percent per year through 1974 (Gosselink and Bauman 1980). More recently, loss rates have diminished as a consequence of protective legislation (Tiner 1984).

Three major salt marsh groups are recognized in North America: (1) Bay of Fundy, New England, (2) Atlantic-Gulf Coastal Plain, and (3) Pacific. Along the Pacific coast only 10-20 percent of the coastal area is suitable for marsh buildup because marsh development has been limited by coastal uplift. In contrast, about 71 percent of the shoreline of the Atlantic and Gulf coasts is associated with mud deposits in estuaries, lagoons, or salt marshes (Emery and Uchupi 1972).

Salt marshes can be grouped into distinct vegetation zones determined by the extent of tidal inundation (Figure 4-1). In the Atlantic and Gulf areas, low marsh zones subject to protracted daily tidal flooding are dominated by *Spartina alterniflora*, except in subtropical latitudes. Along

FIGURE 4-1
CROSS-SECTION OF A TYPICAL NORTHEASTERN ATLANTIC COAST SALT MARSH (from Tiner 1984)



the Pacific, several species are found, including *Salicornia virginica, Spartina californicus,* and *Distichlis spicata.* High marsh zones situated above daily high tides, but subject to spring and storm tides, are dominated by *Spartina patens* and *Distichlis spicata* in the east, *Juncus roemerianus* along the Gulf of Mexico, and by several species in the west, including *Distichlis spicata, Juncus balticus,* and *Deschampsia caespitosa.* Landward of the saline marshes, brackish and tidal freshwater marshes are found; these are particularly diverse and a number of subtypes have been defined for both the Atlantic and Pacific coasts. They are typified by salinities below 0.5 ppt and often can be distinguished from freshwater marshes found beyond tidal influence along the Atlantic Coast (Odum and Fanning 1973). Tidal freshwater marshes are especially extensive in Louisiana, which contains 210,000 ha, or 30 percent of the total marsh area of the Mississippi Delta (Gosselink 1984).

REGIONAL WETLAND DIFFERENCES RELEVANT TO SEA LEVEL ADJUSTMENTS

Tidal range, tidal regularity, and substrate type influence marsh boundaries in relation to a specific tidal datum and therefore help determine adjustments to rising sea levels. Atlantic tides are regular and nearly equal in semidiurnal range, whereas in the Pacific, tides exhibit a diurnal inequality. Gulf Coast tides are irregular but of small amplitude; thus the distinction between high and low marshes is less significant and the general marsh surface approximates mean high water. In Massachusetts, however, the low marsh corresponds to the upper-middle intertidal zone beginning between half-tide level and mean highwater neap. Along the Pacific coast, the low marsh ends at the landward edge at about mean highwater neap.

Regions also differ in their proportion of salt marsh types. Thus, New England marshes consist mostly of high marsh meadow, with low marsh plants found mostly along tidal creek borders (Miller and Egler 1950). South of Chesapeake Bay, low marshes increase in frequency. In Georgia about 60 percent of the marsh area is stream side-levee marsh and low-marsh meadow (Odum and Fanning 1973).

Along the Gulf, however, irregularly flooded *Juncus roemerianus* marsh may predominate. In southern California, marshes exhibit a conspicuous middle-marsh zone between low and high zones. Despite the smaller marsh areas of the Pacific coast, its marsh floras are more diverse, tidal ranges are greater, and the resulting zonation more complex.

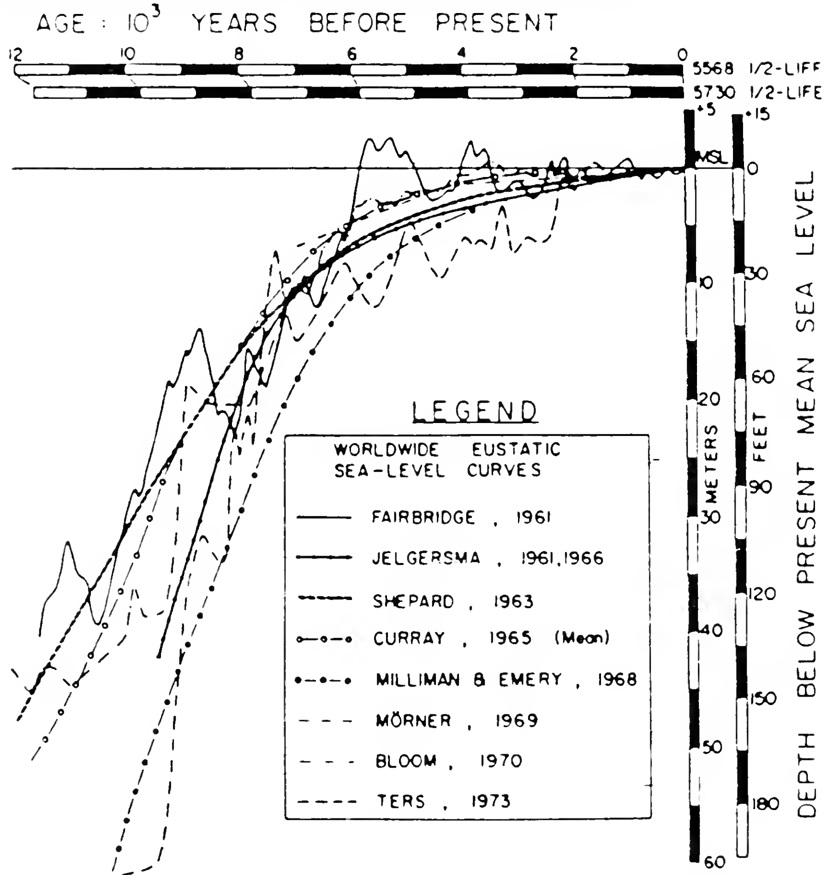
Northeastern Atlantic marshes commonly are dominated by brown or gray silt and clay overlain by thin peat. In New England, because most glacially derived silts and clays have been deposited in lakes and swamps or have been swept out to sea, less inorganic material remains available for marsh deposition (Meade 1969). Instead, thick peat beds have accumulated (Redfield 1965, 1972) to depths as great as 59 m in offshore Pleistocene deposits. Inorganic sediments often dominate sediments where glacial deposits have been reworked or coarse materials have been ice-rafted to the marsh. Elsewhere in this region, however, organic material predominates in marsh peat (Armentano and Woodwell 1975).

South of Chesapeake Bay, peat substrates are relatively rare, except in Louisiana and Florida. In California, thick peat layers are rare and sediments contain little carbon. In the southeast, tidal flushing prevents peat accumulations as do rapid decay rates and slow rates of coastal submergence.

PAST SEA LEVEL RISE AND MARSH ACCRETION

Although scientists differ as to rates of sea level rise, all agree that the Holocene Epoch has been marked by a long-term trend of rising sea level (Figure 4-2). This transgression followed a great lowering of sea level during the Pleistocene when cooling climate triggered the advance of

FIGURE 4-2
ESTIMATES OF SEA LEVEL RISE WORLDWIDE (1961-1973)



Estimates by various geologists as to the world's sea level over the past Holocene Epoch. The dominant cause of change is climatic, although tectonics and compaction effects are also involved (from Davis 1985).

polar ice sheets. Within the long-term pattern, short-term fluctuation in sea level, including temporary regression, occurred in response to shifts in climate and glacial movements. Overall, however, a period of rapid eustatic sea level rise, lasting about 4,000-5,000 years, accompanied the melting of Pleistocene glaciers. During this period, river valleys and adjacent coastal areas were drowned and marsh vegetation developed inland, but not extensively as long as sea level continued to rise rapidly. Thereafter, sea level rise slowed to near zero, but has continued gradually throughout, creating conditions favorable for marsh development and long-term accretion at rates equaling or exceeding sea level rise (Emery and Uchupi 1972, Redfield 1972, Davis 1985).

During the period of rising sea level, opposing isostatic uplift of the land surface in response to reduced glacial overload has occurred in some places, at rates sufficient to cause emergence of subtidal areas despite the rising sea level (Holmes 1965). Elsewhere (e.g., The Netherlands), land subsidence reinforces sea level rise effects. Typically, sea level records report only net heights that incorporate land surface movements. The relative significance of isostatic and eustatic effects is spatially variable; but in New England, based on carbon-14 dating of marsh peat, eustatic sea level rise has accounted for about 80 percent of the rising shoreline over the past 2-3,000 years (Nixon 1982).

The rate of sea level rise during the rapid phase beginning 11-12,000 years ago reached as high as 16 mm per year over the Texas coastal shelf and 8 mm per year over the Atlantic coastal shelf (Emery and Uchupi 1972). These values are mean rates determined from regression lines of radiocarbon dating for the period from 1,000 to 15,000 years ago. The Atlantic rate appears typical of most shelf areas of the world. The Texas rate suggests that the shelf itself has subsided relative to most other shelf areas (Emery and Uchupi 1972).

Results from a variety of radiocarbon studies of peat deposits from present subtidal areas show that during the past 4,000 years, sea level has risen 3-6 m (Emery and Uchupi 1972). In general, during the past several thousand years, eustatic sea level rise has averaged around 1 mm per year. Intervals of no net rise have been deduced from past records, as have periods of more rapid rise. Typical rates as measured at several northeastern tidal stations in the United States are given in Table 4-1. A larger number of tidal station records, broken down regionally and corrected for latitudinal effects, is available in Hicks (1978) for the entire country. These records show that sea level rise over the period 1940-1975 has averaged 1.5 mm per year for the conterminous United States. However, within regions and shorter time periods, deviations from the mean are common. Thus, submergence of the Connecticut coast has averaged 2.6 mm per year from 1940 to 1972, with an anomalous rate of 10 mm per year from 1964 to 1972, a rate approaching late glacial eustatic transgression (Harrison and Bloom 1977).

TABLE 4-1

RATES OF NET SEA LEVEL RISE ALONG THE NORTHEAST ATLANTIC COAST (from Nixon 1982)

LONG-TERM RATES (over the past 2-3,000 years). Data of Bloom and Stuiver (1963), Redfield (1967), Keene (1971), Oldale and O'Hara (1980), and Rampino and Sanders (1980).

Location	mm/yr	ft/ century
New Hampshire	1.1	0.36
Northeastern MA (probably also NH and ME)	0.8	0.26
Southeastern MA*	1.0	0.33
Cape Code to Virginia	1.1	0.36
Connecticut	0.9	0.30
Long Island, NY	1.0	0.33

SHORT-TERM RATES (1940-1975) from tidal gauge records. From Hicks (1978).

Location	mm/yr	ft/ century
Eastport, ME	3.5	1.15
Portland, ME	2.0	0.66
Portsmouth, NH	1.8	0.60
Boston, MA	1.5	0.49
Woods Hole, MA	2.9	0.95
Newport, RI	2.5	0.82
New London, CT	2.6	0.85
New York, NY	3.1	1.02

**The published value of 0.01 m/100 yr is a typographical error in Oldale and O'Hara (1980) [Nixon 1982].*

Under conditions of slow sea level rise or short-term equilibrium, salt marsh establishment and growth can occur. In fact, some observers conclude that marsh formation can occur only under these conditions. However, others have noted that salt marshes generally, with the exception of Gulf Coastal areas, have kept pace with sea level rise even in the past 35 years when the rate of sea level rise has increased noticeably (Nixon 1982). Under favorable conditions, young salt marshes can accrete at very high rates. Redfield (1972) found that *Spartina alterniflora* sediments accreted at over 50 mm per year in Barnstable marsh (Massachusetts). Generally, however, rates are far slower and may exceed measured sea level rise rates by only a small amount (Table 4-2). According to McCaffrey (cited in Nixon 1982), salt marshes may continue to accrete even during a short period of sea level decline.

The factors principally responsible for determining accretion rates are sediment loads, current velocity, and flooding frequency and duration. Local site differences in these factors account for differences among and within marshes. Thus, in low, silty Oregon marshes, accretion rates varied between 5 and 17 mm per year (Seliskar and Gallagher 1983). Five high marshes in Connecticut varied in sediment accretion from 2.0-6.6 mm per year in correlation with tidal range and therefore increased flooding (Harrison and Bloom 1977). Year-to-year differences were attributed to storm frequency, with greater accretion during storm years. Conditions are similar along the Pacific coast where studies in British Columbia and Oregon showed that most deposition occurred during a few annual storms (Seliskar and Gallagher 1983).

Based on Table 4-2, accretion rates do not appear to increase with decreasing latitude, although marsh productivity does. However, Mississippi Delta marshes appear to accrete at exceptionally high rates, suggesting that local sedimentation and sea level rise rates may be more important than climate in determining accretion rates. Most studies indicate that low marsh zones, in contrast to high marsh zones, have been accreting over the measurement period at a rate clearly exceeding sea level rise rate. Conspicuous exceptions are found throughout the Mississippi Deltaic Plain, at least in interdistributary back marshes (Table 4-2), although on levees rapid accretion exceeds the sea level rise rate. Particularly in Louisiana, and to a lesser extent elsewhere, measured sea level rise clearly is a net rate that includes a significant downwarping effect from coastal overburden. Furthermore, the potential capacity of Louisiana salt marshes to accrete cannot be determined from measured rates because of significant interruption of normal fluvial sedimentation processes by human alteration of Mississippi River flowages (Hatton, DeLaune, and Patrick 1983; Gosselink 1984).

Accretion in high marshes has seldom been studied, but as found by Harrison and Bloom (1977), rates are below those of low marshes probably because delivery of suspended sediment in tidal waters is greatly reduced. Although increasing sea level rise might be expected to increase sediment supplies and in situ productivity in high marsh, gradual conversion to low marsh might occur when the threshold tolerance for exposure and flooding of *Spartina alterniflora* and *S. patens*, respectively, is exceeded.

Few data are available on sedimentation rates in coastal brackish and freshwater marshes. In Louisiana, accretion in freshwater marshes appears to be only marginally less than in salt marshes, indicating the continuing (although reduced) importance of fluvial sediment sources as well as high productivity rates (Table 2, Hatton, DeLaune, and Patrick 1983). In other areas, sedimentation in coastal freshwater marshes can be inferred for sites of considerable age, given the influence of rising sea levels. However, further data must be sought on fresh and brackish sites before conclusions can be drawn as to their capacity for responding to accelerated sea level rise.

TABLE 4-2

SURFACE ACCRETION RATES MEASURED IN SELECTED ATLANTIC AND GULF MARSHES COMPARED WITH THE MEAN RATE OF SEA LEVEL RISE (modified from Hatton et al. 1983).

Other values are given in the text.

State	Vegetation Zone	Marsh Accretion Rate (mm/yr)	Method	Mean Sea Level Rise (mm/yr)	Source
Massachusetts	Low salt marsh	18.3 (1.5-51.8)	Stratigraphic	3-4	Redfield (1972)
Connecticut	Low salt marsh	8-10	Particle layer	2.6	Bloom (in Richard 1978)
Connecticut	High salt marsh	2- 6.6	Particle layer	2.6	Harrison & Bloom (1977)
New York	Low salt marsh	4.0	210Pb	2.9	Muzyka (1976)
New York	Low salt marsh	4.7- 6.3	210Pb	2.9	Armentano & Woodwell (1975)
New York	Low salt marsh	2.0- 4.2	Particle layer	2.9	Richard (1978)
New York	Low salt marsh	2.5	Historic record	2.9	Flessa et al. (1977)
Delaware	Low salt marsh	5.1- 6.3	Particle layer	3.8	Stearns & McCreary (1957)
Delaware	Low salt marsh	5.0	210Pb	3.8	Lord (1980)
Georgia	Low salt marsh	3-5	137Cs		Hopkinson (unpubl.)
Louisiana	Deltaic plain		127Cs	9.2	Hatton et al. (1983)
(i) Streamside	(levee)				
	a. Salt marsh	13.5			
	b. Intermediate	13.5			
	c. Brackish marsh	14.0			
	d. Freshwater marsh	10.6			
(ii) Inland (backmarsh)			137Cs	9.2	Hatton et al. (1983)
	a. Salt marsh	7.5			
	b. Intermediate	6.4			
	c. Brackish marsh	5.9			
	d. Freshwater marsh	6.5			
Louisiana			Particle layer	9.2	Baumann (1980)
(i) Streamside salt marsh		15.2			
(ii) Inland salt marsh		9.1			
Louisiana	Chenier Plain Low Marsh	4.7	137Cs	9.2	DeLaune (unpubl.)

METHODOLOGY

The objectives of the present study were met in a two-step procedure: (1) interpretation of the present distribution of coastal land categories and their attributes pertinent to sea level rise, and (2) development of a computer model to simulate the future response of the coastal land categories to postulated rates of sea level rise. Both are described in detail below.

Data

To develop a regional/national analysis of U.S. coastal wetland responses to sea level rise, stratified sampling of the continuous U.S. coastline was undertaken for nine regions (Figure 4-3). Selected 7.5-minute quadrangles were characterized as to coastal features, elevation, and development. The quadrangles were selected to capture, to the extent possible, the variation in coastal landscapes within each region. In addition, within each region, important lagoonal and deltaic wetlands were analyzed (Table 4-3). The sites interpreted for the present study are shown for each region of the United States in Figures 4-4 through 4-7. A total of 183 quadrangles were used for the 57 sites depicted. The entire case study data set is presented as Appendix 4-A. Although the sites are representative of the coastal wetlands, they do not constitute a statistical sample from which probabilistic inferences can be made concerning all coastal areas of the contiguous United States.

The data were collected from each 1 km^2 cell registered on the Universal Transverse Mercator (UTM) grid so that re-inventorying would be routine. Of the sixteen categories of coastal types, each is based on the dominant category within the square-kilometer cell. They are summarized in Table 4-4. The type of coastline is defined as one of the following: (1) steep slope, (2) low slope, terraced, (3) deltaic, and (4) low slope, unterraced. The height of low coastal terrace is estimated for each site and region from the literature (e.g., Richards 1962); however, it is not used in the current version of the simulation model. 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 extent to which the cell can be classified as residentially or commercially developed is noted. The extent of freshwater and brackish wetlands cannot be determined at the regional level from topographic maps.

TABLE 4-3
REGIONAL CLASSIFICATION OF COASTAL WETLANDS AND REPRESENTATIVE SAMPLE SITES

Region	Deltaic	Lagoonal
New England	Narragansett Bay (RI)	Barnstable Marsh (MA)
Atlantic	Charleston area (SC) James River/Chesapeake Bay	Sapelo Island (GA)
Gulf Coast	Apalachicola Bay (FL) Mississippi River (LA)	Fort Walton Beach (FL) Galveston Bay (TX)
Pacific		
Temperate	Yaquina (OR)	Coos Bay (OR)
Dry Mediterranean	Santa Ynez River (CA)	Cabrillo NM (CA)
Tropical-Subtropical		Florida Bay

FIGURE 4-3
UNITED STATES COASTAL REGIONS

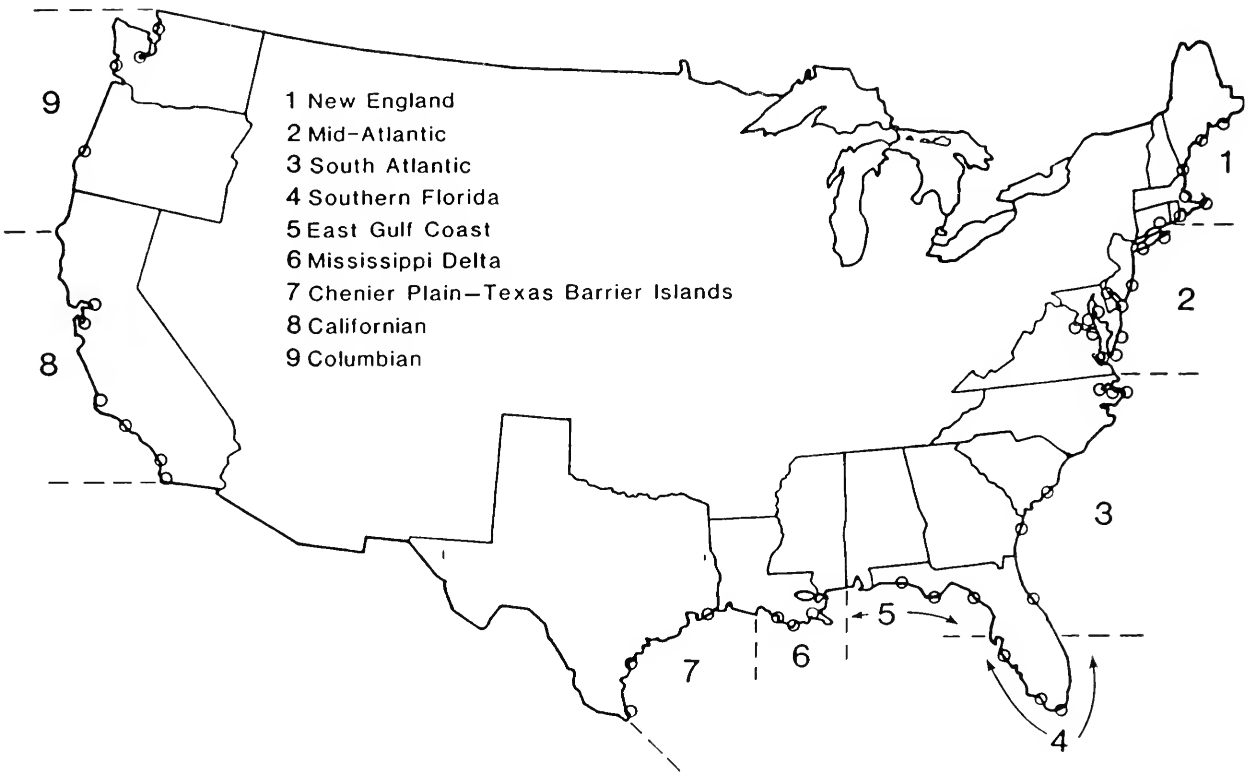


FIGURE 4-4
LOCATION OF STUDY SITES (USGS Quadrangle Maps) IN NEW ENGLAND AND MID-ATLANTIC REGION

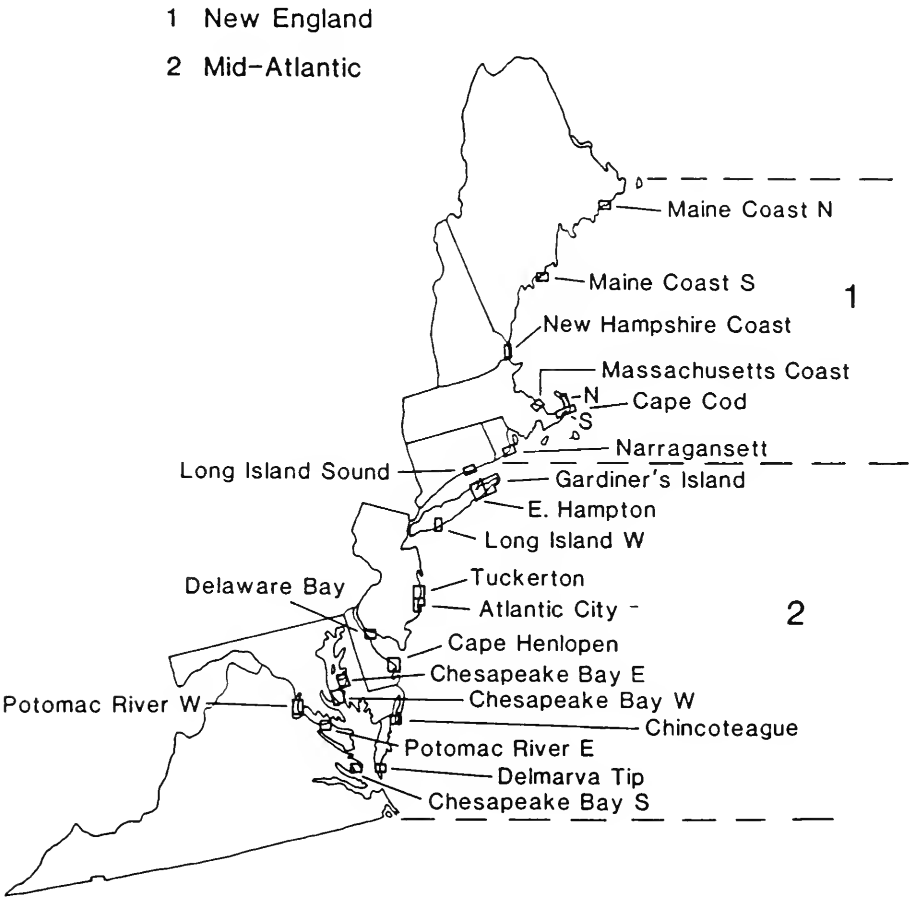


FIGURE 4-5

LOCATION OF STUDY SITES (USGS Quadrangle Maps) IN SOUTH ATLANTIC, SOUTHERN FLORIDA, AND EAST GULF COAST

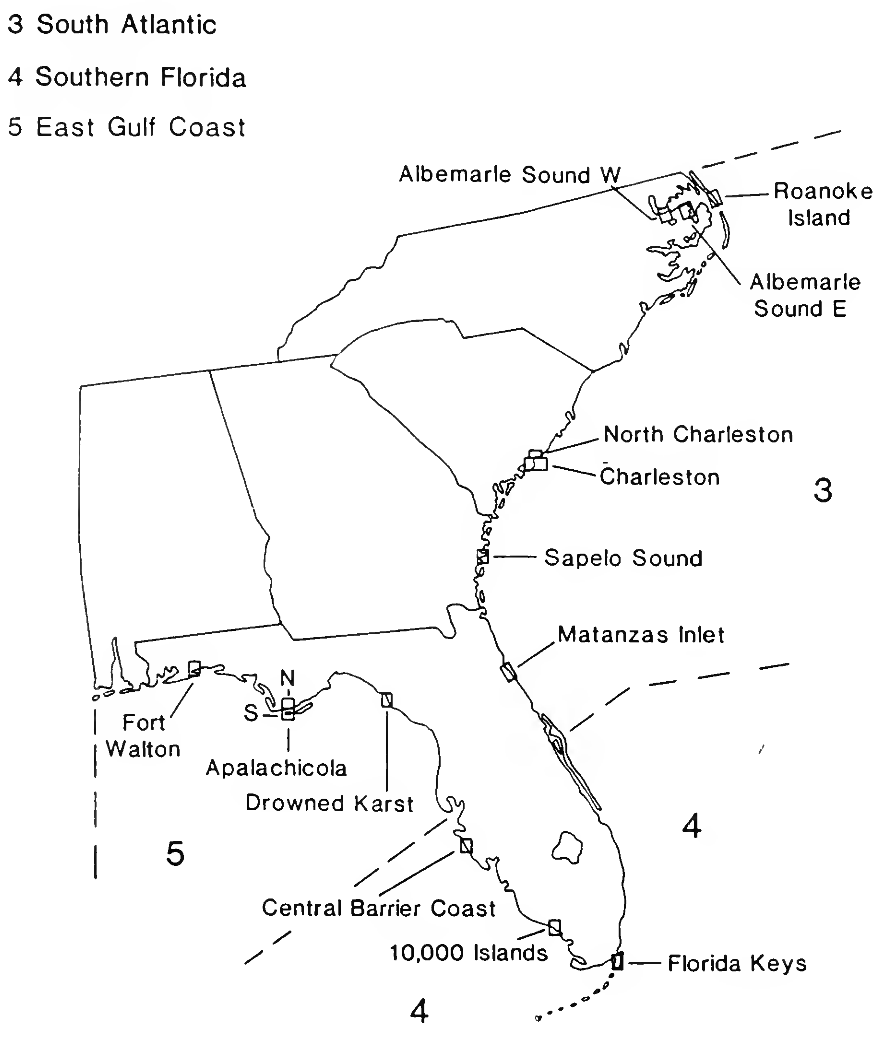


FIGURE 4-6
LOCATION OF STUDY SITES (USGS Quadrangle Maps) IN MISSISSIPPI DELTA AND CHENIER PLAIN-TEXAS BARRIER ISLANDS

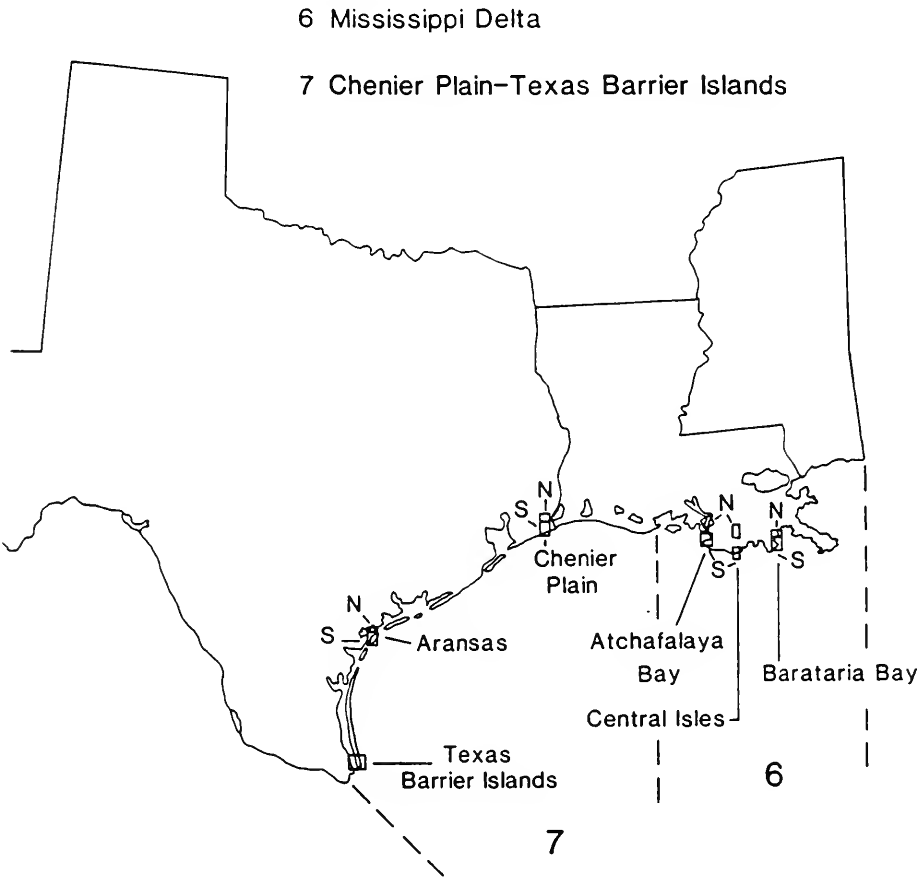


FIGURE 4-7

LOCATION OF STUDY SITES (USGS Quadrangle Maps) IN CALIFORNIAN AND COLUMBIAN PROVINCES

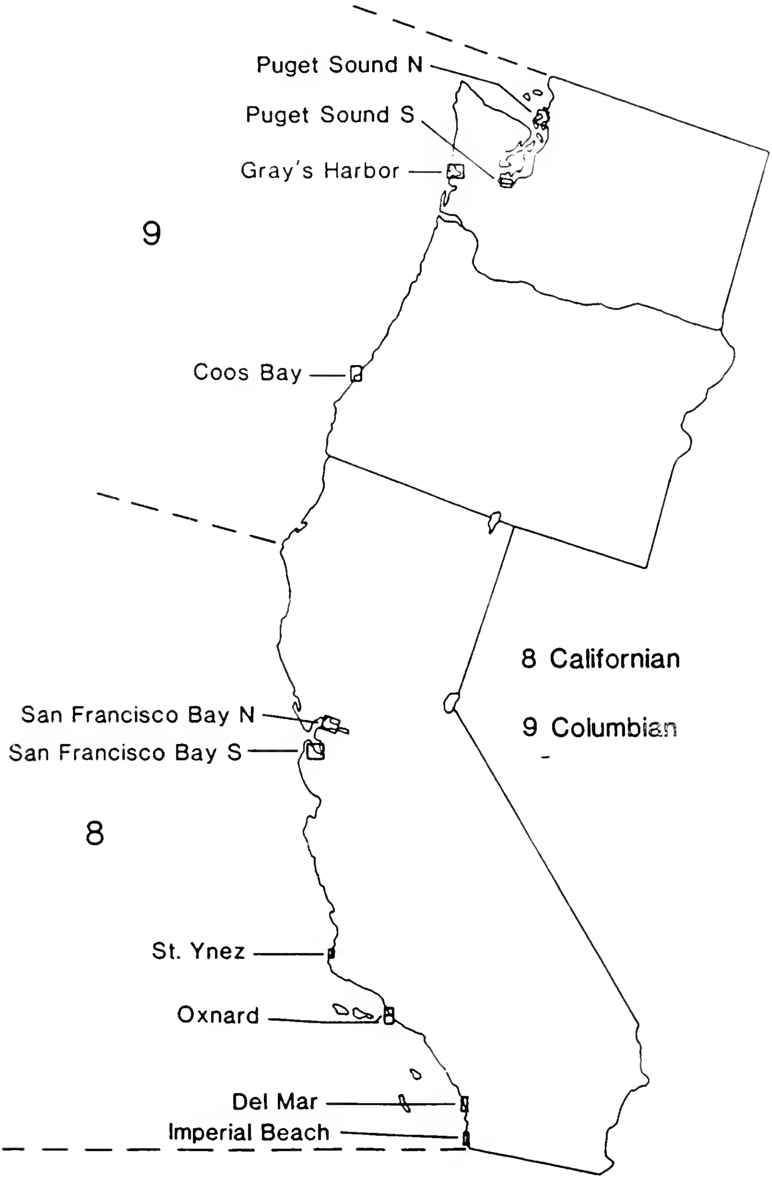


TABLE 4-4
COASTAL LAND CATEGORIES

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

MODELING

Prior Models

A large number of models have been constructed for fresh- and saltwater wetlands (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 the present study.

The SLAMM Model

Description. Because no previous researchers had developed a satisfactory model, it was necessary for us to develop a simulation model suitable for analyzing the impact of sea level rise on coastal wetlands. The model, called SLAMM (Sea Level Affecting Marshes Model), simulates the long-term change in coastal areas due to rising sea level. 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 4-8). These rules embody assumptions of linear, average responses. They 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.

Figure 4-8 summarizes the model. The average elevation for a cell is determined by subtracting the sea level rise for a five-year time step from the previous average elevation for that cell. When the average elevation drops below 3.5 m above mean sea level, undeveloped and developed upland are transferred to undeveloped and developed lowland, respectively. Developed lowland is considered to be "protected lowland" if it incorporates a protective dike or levee (a characteristic noted in the input data) or if the user has chosen the option of having all developed areas protected automatically. Protected lowlands are not permitted to change by the year 2100, even under the scenario of the highest projected sea level rise.

Undeveloped lowlands and developed but unprotected lowlands are subject to inundation when the average elevation is less than the mean high water (MHW) during spring tides (MHWS), which is approximated as half-again as high as MHW. An inundated cell becomes "tidal flat" (actually rocky intertidal, but the two are combined) if the coast is rocky. If the cell is adjacent to open water it becomes exposed beach; otherwise, it can become one of three categories: tidal flat if erosion is greater than low (as determined by the average fetch of the adjacent sheltered water); mangrove swamp if the region is tropical (as indicated by the presence of mangroves in the map area); or salt marsh. High and low salt marsh are not distinguished nor are differences in levee versus back-marsh accretion rates where the latter two have been differentiated in the literature; accretion rates from back marsh areas have been employed because levee marshes occupy relatively small areas.

The average elevation of wetlands is a function of relative sea level and accretion due to sedimentation and accumulation of organic material. As a simplification, accretion is considered to be an approximate function of the areal extent of existing wetlands; extensive wetlands are considered to indicate high sedimentation and accretion rates (Table 4-5). The influence of this assumption has been tested for several locations and is described in the Results section. When the average elevation of a marsh is less than the level of the embayed MHWS tide plus 0.25 m, the wetland is considered to be saltwater; otherwise it is considered freshwater. (The embayed tide is taken from the source map or, if unavailable, is estimated to be two-thirds the oceanic tidal range; it is assumed that tidal ranges that are amplified by embayments will be noted on the map.) Because freshwater and salt marshes cannot be distinguished using topographic maps, this algorithm is applied to the input data as well as being used during the simulation. However, if the cell is initially freshwater marsh and is protected by a dike or levee, the cell remains freshwater marsh regardless of its elevation. In some areas (especially southern Florida and Louisiana), the extent of freshwater marshes may be underestimated significantly because the influence of freshwater discharge and a coastal freshwater lens is not considered. If the area is tropical, the saltwater wetland is considered to be mangrove swamp; otherwise, it is considered to be salt marsh. Table 4-6 illustrates accretion and subsidence rates for the study areas.

If a salt marsh is adjacent to open ocean or if erosion is heavy (as indicated by the average fetch) or if the average elevation is below mean sea level, the cell is converted to tidal flat. If the average elevation is less than embayed mean low water (MLW) and the marsh is adjacent to water, or if the average elevation is below MLW (which is assumed to be lower than embayed MLW)

FIGURE 4-8
SLAMM FLOW CHART SHOWING TRANSFERS AMONG CATEGORIES

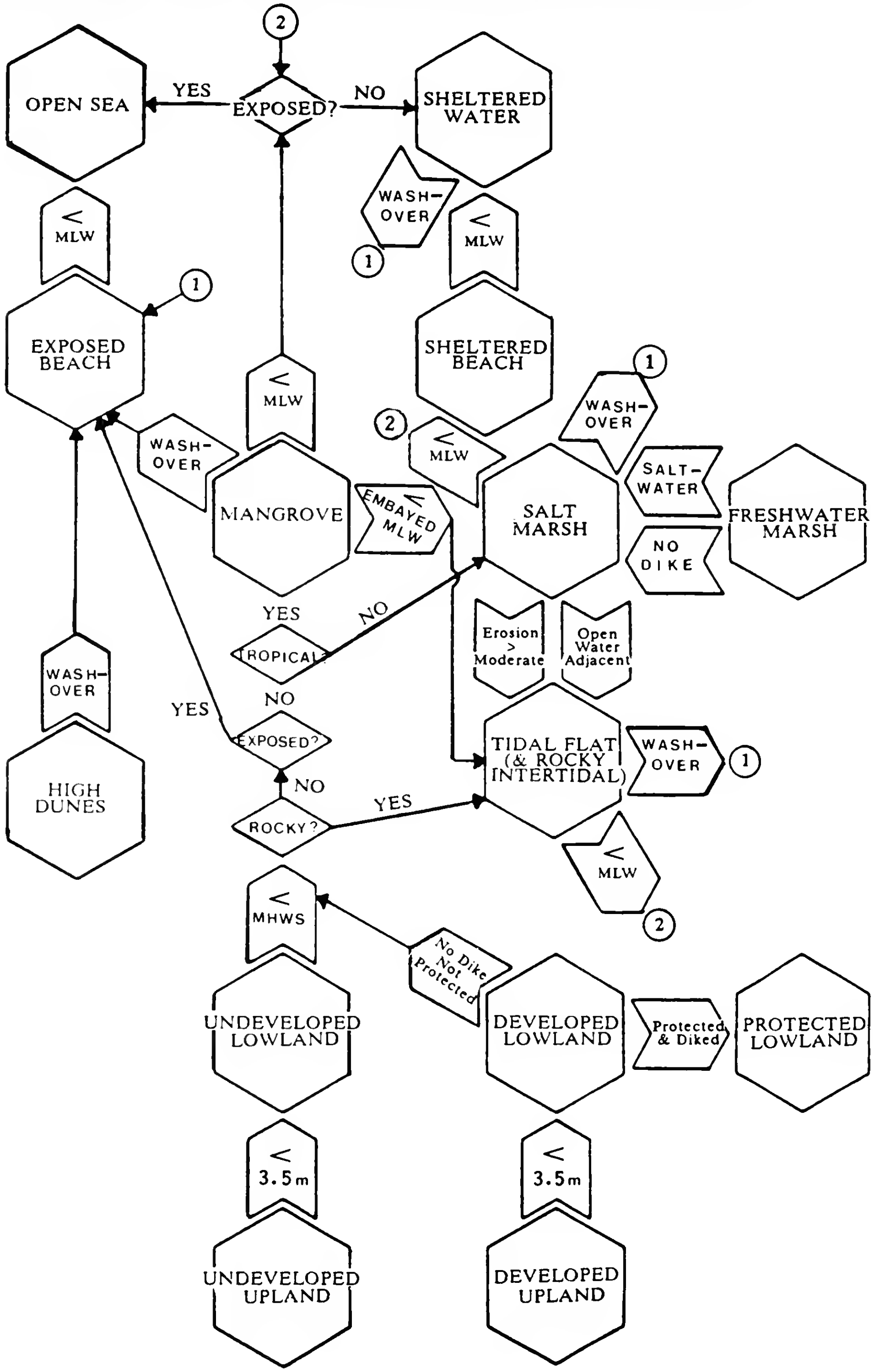


TABLE 4-5
PARAMETERS EMPLOYED

Process	Rate	Comments
Sea Level Rise		
low	1.444 m by 2100	See Chapter 1
high	2.166 m by 2100	See Chapter 1
Accretion of Wetlands		
low	2 mm/yr	Low value reported
moderate	5 mm/yr	Common midrange
high	10 mm/yr	Approx. highest value observed
Sedimentation		
nondeltaic	half of accretion	cf. Bartberger 1976
deltaic	same as accretion	cf. DeLaune et al. 1983
Erosion		
fetch < 1km	none	calibrated and personal observation
1 km < fetch < 3 km	little	
3 km < fetch < 9 km	low	
fetch > 9 km	heavy	

without water adjacent to it), the cell becomes open or sheltered water, depending on its exposure. This algorithm permits the gradual erosion of the edge of an extensive marsh until such time as the entire marsh is inundated. By testing for adjacent water only in the direction of dominant waves for 7 out of 8 cycles (35 out of 40 years), the protection afforded wetlands in the lee of obstructions is modeled reasonably well. As more water occurs in the map area, the qualitative erosion rate increases, mimicking the lateral scour due to increased fetch that has been observed in deteriorating wetlands (Baumann, Day, and Miller 1984).

Mangrove swamp is treated in much the same way as salt marsh except that it can occur on exposed coasts. If the average elevation is less than embayed MLW and there is adjacent water, the cell becomes tidal flat. If the average elevation is less than MLW, the cell becomes open sea or sheltered water, depending on its exposure.

If a cell is tidal flat, its average elevation is a result of sea level rise and sedimentation. If the cell is protected by a dike, it does not change. Otherwise, when the elevation is less than embayed MLW, the cell becomes sheltered water (which can convert to open sea if there is adjacent open sea). If the average elevation is above mean sea level, if erosion is not heavy, and if the coast is not rocky, the cell becomes mangrove swamp or salt marsh.

Undeveloped sheltered beaches become tidal flats if the average elevation is below mean sea level but above embayed MLW; if the average elevation is below embayed MLW, these beaches become sheltered water. If there is essentially no erosion (due to lack of fetch for waves), a sheltered beach is converted to tidal flat. Exposed beaches become open sea when the average elevation becomes less than mean sea level. Developed beaches are treated the same as undeveloped beaches unless they are protected by dikes or the user has chosen the option of protecting all developed areas. It is assumed that fast-rising sea level will not result in significant new dune fields. High dunes become beach when the average elevation becomes less than MHWS.

TABLE 4-6

ASSUMED SUBSIDENCE AND ACCRETION RATES

Location	Accretion Rate (mm/yr) a/ 1975	2025	2050	2075	2100	Subsidence (mm/yr)
Maine Coast N	2	-	-	-	-	0
Maine Coast S	2	-	-	-	-	0
New Hampshire Coast	5	-	2(5)	2	-	0
Massachusetts Coast	2	-	-	-	-	0
Cape Cod N	2	-	-	-	-	0
Cape Cod S	2	-	-	-	-	0
Narragansett	2	-	-	-	-	0
Long Island Sound CN	2	5(2)	5	-	-	0
E. Hampton, NY	2	-	-	-	-	0
Gardiner's Island, NY	2	-	-	-	-	0
Long Island W, NY	5	-	-	-	-	0
Atlantic City, NJ b/	5	-	10(5)	10	2(10)	1.2
Tuckerton, NJ b/	5	-	-	2(5)	2	1.2
Delaware Bay, RI	5	-	-	-	10	2.9
Cape Henlopen, DE	5	-	-	-	2(5)	3.0
Chesapeake E., MD	2	-	-	-	-	2.0
Chesapeake W., MD	2	-	-	-	-	2.2
Potomac River E., VA	2	-	-	-	-	1.8
Potomac River W., MD	2	-	-	-	-	1.6
Chincoteague, VA b/	5	-	-	2(5)	2	1.9
Delmarva, VA	5	-	-	5	2(5)	1.2
Chesapeake Bay S., VA	2	-	-	-	-	2.8
Roanoke Island, NC b/	5	-	2(5)	2	1	1.2
Albemarle E., NC	10	-	-	10	5	0
Albemarle W., NC	5	-	-	5	2(5)	0
N. Charleston, SC	5	-	-	-	5	1.2
Charleston, SC b/	2.5	.62(2.5)	.02(.08)	5(0)	2.5	1.2
Sapelo Sound, FL	10	-	-	-	-	0
Matanzas, FL	5	-	-	-	-	0
Florida Keys	10	-	-	10	2(10)	0
10,000 Islands, FL	10	-	-	-	-	0
Cntrl. Barrier Coast, FL	2	-	-	-	-	0
Drowned Karst, FL	10	-	-	-	-	0
Apalachicola N., FL	10	-	-	-	-	0
Apalachicola S., FL	10	-	-	-	-	0
Fort Walton, FL	2	-	-	-	-	0
Barataria Bay N., LA	10	5(10)	2(5)	2	-	11.0
Barataraia Bay S., LA	10	-	2(10)	2	-	11.0
Central Islands N., LA b/	10	-	-	-	5(10)	4.0
Central Islands S., LA b/	10	-	-	-	5(10)	4.0
Atchafalaya N., LA b/	0	-	25	1(2.5)	1	3.5
Atchafalaya S., LA b/	5	-	-	1(2.5)	1	3.5
Chenier Plain N., TX	2	-	5(2)	5	5(2)	3.5
Chenier Plain S., TX	10	-	-	-	5(10)	3.5
Aransas NWR N., TX	2	-	-	-	-	3.5
Aransas NWR S., TX	5	-	-	2	-	3.5
Texas Barrier Island	2	-	-	-	-	0
Imperial Beach, CA	2	-	-	-	-	0
Del Mar, CA	2	-	-	-	-	0
Oxnard, CA	2	-	-	-	-	0
St. Ynez, CA	2	-	-	-	-	0
SF Bay N., CA	10	5(10)	10	-	-	0
SF Bay S., CA b/	2	5(2)	5	-	-	0
Coos Bay, OR b/	2	-	-	-	-	0
Gray's Harbor, WA b/	2	-	-	-	-	0
Puget Sound N., WA	2	5(2)	5	-	-	0
Puget Sound S., WA	2	-	-	-	-	0

a/ Values in ( ) are for low sea level rise; one value only indicates that the low and high values are the same. A dash means no change.

b/ Development protected.

Tidal flats, marshes, mangrove swamps, sheltered beaches, high dunes, and sheltered water can become exposed beaches by the process of "washover." If an adjacent exposed beach in the direction of the dominant waves is converted to water or tidal flat, the cell in question becomes beach, with an average elevation slightly above sea level to insure that the beach is not immediately inundated and eroded. This mimics the in-place "drowning" of barrier beaches (Leatherman 1983) and their eventual stepwise retreat over back-barrier marshes and lagoons once they are low enough to be subject to washover (Sanders and Kumar 1975, Rampino and Sanders 1980, Buttner 1981). Washover leads to a migrating beach in seven out of eight cycles; inundation during the other cycle results in a breach in the barrier island.

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 intervals of years for a given area and rate of rise in sea level. 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.

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 pocket beaches and marshes and narrow barrier beaches being under-represented; 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 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.

Although the model is intended for regional forecasts it does not treat effects on subsurface freshwater supplies or storm-surge effects.

Application. The use of the model may be best understood through application to a particular site. Because Tuckerton, New Jersey, was used as a case study (Kana et al. 1988 and Chapter 3, this report), it is used as an example here. We simulated the change in square-kilometer cells; three representative cells are emphasized in the following discussion. These are shown in Figure 4-9.

The open-ocean and inland tidal ranges of 3 feet and 2 feet were taken directly from the map. The area was not designated as deltaic, although a small delta is adjacent to the area.

Cell A contains part of a barrier island and adjacent bay and open ocean. Because the barrier island is the dominant element, the cell is encoded as "beach," ignoring the fact that water constitutes almost 40 percent of the area. (The portion of the barrier island immediately to the north does not constitute the dominant element in either of two cells, so both cells are encoded as water.) The average elevation of the island in cell A is estimated to be 1.0 m; with a contour interval of 10 feet and only the dunes shown as exceeding 10 feet, the determination of elevation is admittedly imprecise. Furthermore, the elevation of the dominant category is used, rather than the average elevation for the cell; otherwise, a conflict might arise between the category elevation and the cell elevation used in the simulation.

Cell B is approximately 50 percent marsh and 50 percent developed lowland; it is categorized as marsh. Inspection of the map indicates that this "worst case" occurrence of two equally distributed categories is uncommon. More often cells are dominated by a single category. Furthermore, over large areas, error compensation would be expected. Based on a linear interpolation, the average elevation is assumed to be 0.5 m. It is not possible to tell from the topographic map whether cell B is salt marsh or fresh marsh, but, given the elevation and the tidal range, we assume it would be salt marsh. Although the cell is developed, because it is salt marsh the development is ignored in the simulation (the assumption being that developed marsh is not valuable enough to be protected).

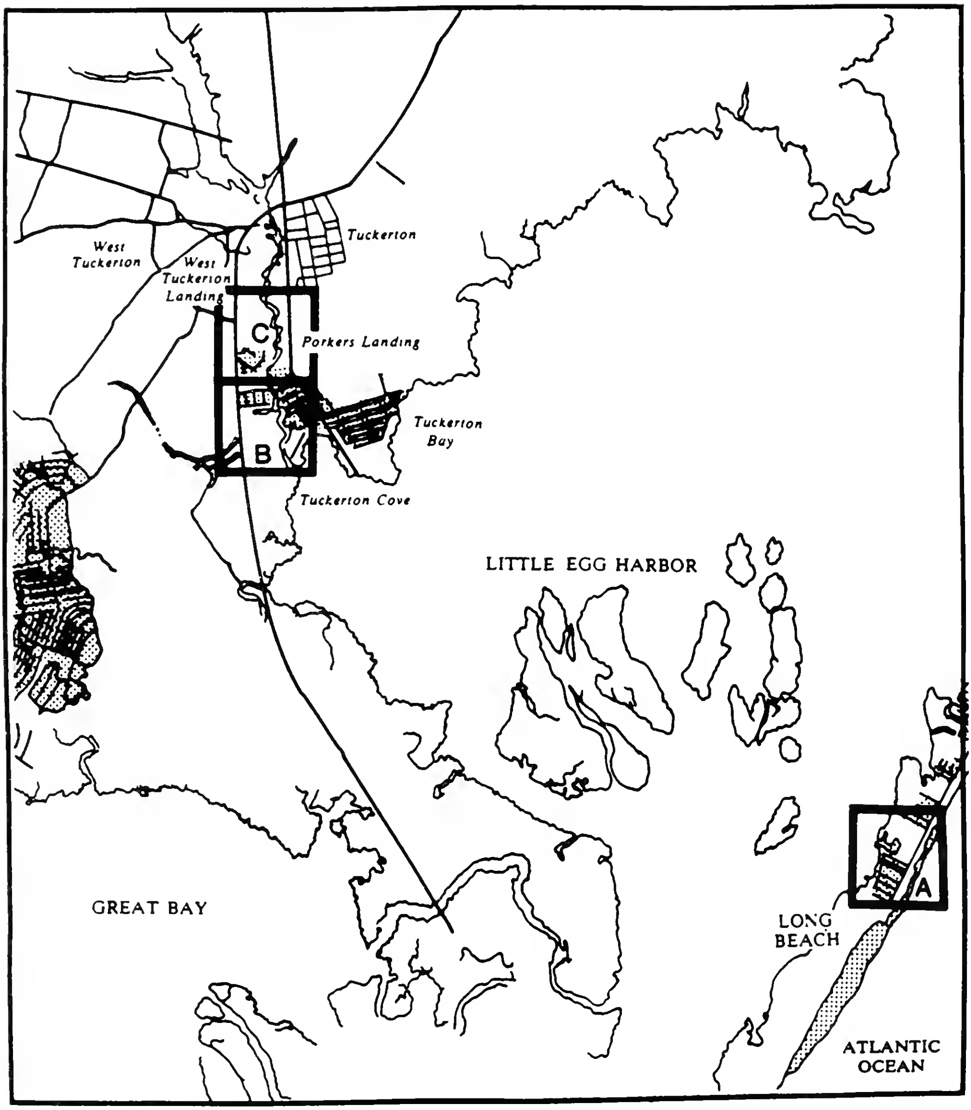
Cell C is partly developed lowland, partly marsh, and partly undeveloped upland; it is categorized as developed lowland. The elevation varies from near sea level to over 20 feet; it is given as 1.0 m.

We begin the simulation with the year 1975. The datum for mean sea level is 0.00 m. Because the percentage of marsh is greater than 5 percent and less than 25 percent, we assumed that accretion would be at 5 mm/yr; because the area is not deltaic, we assumed the sedimentation rate to be half that of marsh accretion (2.5 mm/yr). The rates were assumed to be half the natural rates, due to engineering projects diverting sediment on rivers. It might have been reasonable to change this default and double the rates.

Based on an interpolation for the high scenario, the initial rate of sea level rise would be 5 mm/yr; therefore, by 1980, mean sea level is modeled as 0.03 m above the datum. This rise has no effect on the distribution of cell categories in the Tuckerton area. In fact, not until 2030, when sea level is close to 0.5 m above the 1975 datum, is a change observed (0.3 percent of the upland, which was originally 4.0 m in elevation, is converted to lowland). Meanwhile, by 2000 the rate of sea level rise has increased to 10.44 mm/yr; by 2025 it has increased to 15.72 mm/yr.

In 2035, due to the position of the spring high water level, the fresh marshes are converted to salt marshes, with mean sea level 0.55 m above the 1975 datum. In 2060, with mean sea level at 1.02 m, several changes take place. Undeveloped upland loses 0.1 percent to undeveloped lowland, and 7.3 percent of salt marsh and 0.1 percent of tidal flat are converted to sheltered water. These cells, originally 0.5 m in elevation, are now inundated even at low tide. With wetlands decreasing to below 5 percent of the map area, accretion of marsh drops to 2.0 mm/yr and sedimentation drops to 1.0 mm/yr, mimicking sedimentation further upstream in estuaries rather than along the coast.

FIGURE 4-9
GRAPHIC REPRESENTATION OF USGS MAP OF TUCKERTON, N.J.



In 2070 another 0.1 percent of salt marsh is converted to sheltered water. In 2080, with mean sea level 1.53 m above the 1975 datum, 0.1 percent of undeveloped upland and 0.1 percent of developed upland are converted to undeveloped and developed lowland, respectively; and almost all remaining salt marsh (2.4 percent) and all remaining tidal flat (0.4 percent)—cells that were originally 1.0 m in elevation—are lost to sheltered water. No further changes occur by 2100 (Figures 4-10, 4-11, and 4-12).

FIGURE 4-10

SIMULATION MAP SHOWING RAW DATA FOR TUCKERTON, N.J.

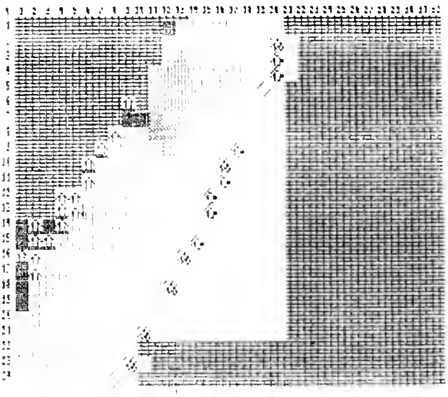


FIGURE 4-11

TUCKERTON, N.J., IN THE YEAR 2050 WITH HIGH SEA LEVEL RISE

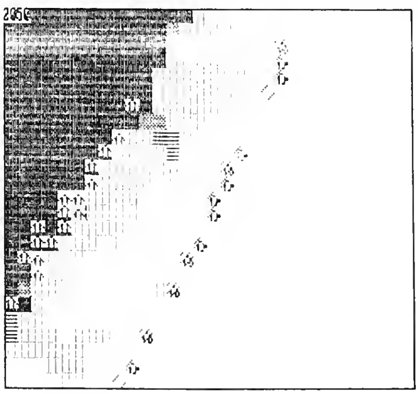
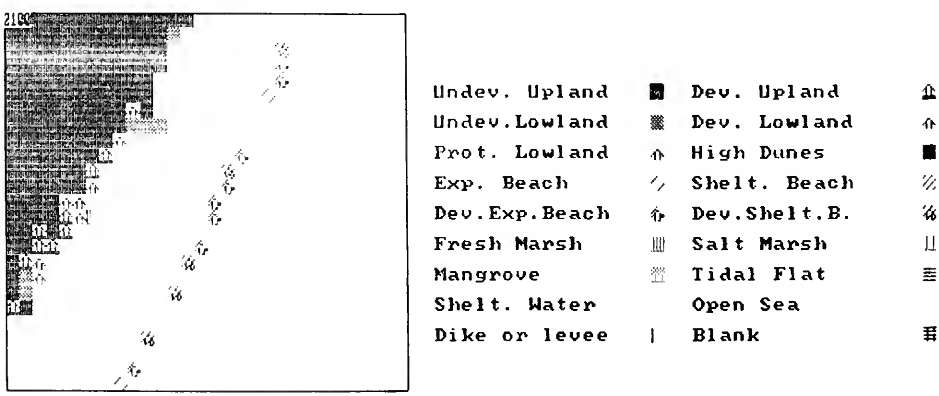


FIGURE 4-12

TUCKERTON, N.J., AT END OF SIMULATION (year 2100) WITH HIGH SEA LEVEL RISE, PROTECTION OF DEVELOPED AREAS, AND SUBSIDENCE EQUAL TO 1.2 mm/yr.



The initial elevation of the exposed beach protected it from inundation. The developed areas were assumed to be protected, so that developed lowland and exposed beaches are not inundated. If the option of not protecting developed areas had been chosen, the pattern would have been quite different: part of the barrier island system would have been breached, resulting in erosion of coastal areas that were previously sheltered from the open sea, and in migration of beaches.

Appendix 4-C describes how to use the program that we used to carry out our simulations.[1]

RESULTS

In this section the general patterns of the response of wetland regions are summarized for the low and high scenarios. The simulation results are given in detail in Appendices 4-A and 4-B. We show percent change in wetland area from current conditions, rather than absolute area, in order to emphasize that our intent is not to predict expected response at specific locations but to describe one class of response, among several that can be hypothesized, that could develop within a generalized regional coastal environment. Thus, although the text refers to specific map designations, interpretation should be applied only to a general coastal environment similar to the one represented by the designation.

New England Region

Under the low scenario, the general pattern of salt marsh response in New England involves expansion onto the limited freshwater areas such as those on Cape Cod, or onto unprotected adjacent undeveloped lowland, dunes, or beach. However, where salt marshes with high capacity for lateral erosion are found adjacent to tidal flats immediately landward of open sea, expansion of the flats onto salt marsh also would occur, thus reducing or eliminating existing marshes. (The model may overestimate this effect because attenuation of wave energy is not considered.) This pattern is revealed even by the year 2050 in New Hampshire. These losses, however, are relatively small and/or partially compensated for by expansion of salt marsh onto adjacent freshwater marsh, so that some salt marsh is preserved.

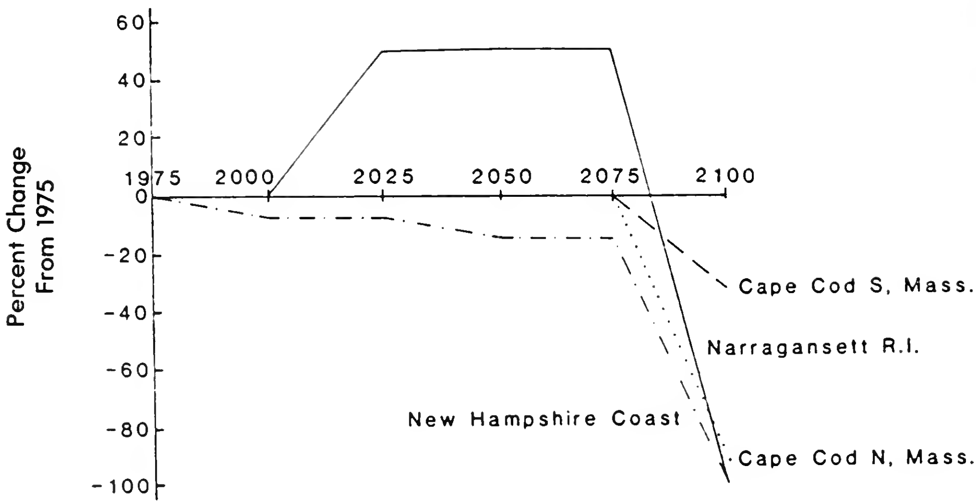
Under the high scenario, however, more rapid rise later would outstrip the adjustment capacity of salt marshes; these would become extensively converted to tidal flats and might be totally lost in some locations where conditions resemble our New Hampshire simulation (Figure 4-13). Even under sheltered conditions, the rise is sufficient to inundate salt marshes in most places with steep slopes and cliffs typical of New England, such as those in Jonesport, Maine, and in Cape Cod, Massachusetts. Thus, for the relatively low accretion rates typical of New England salt marshes and the distribution of land categories found there, a high rate of sea level rise could profoundly reduce the areal distribution of both salt and fresh marshes under conditions stipulated in model simulations.

Mid- and South-Atlantic Region

Further south from Connecticut to New Jersey, extensive low-lying coastal areas are characteristic. The low scenario predicts salt-marsh distributions similar to the 1975 condition; wetlands could even increase as the intertidal zone encroached onto undeveloped lowlands. Susceptible developed lowlands also might be converted to salt marsh unless protected by dikes. The expansion of salt marsh at the expense of adjacent lowland would already be evident by the year 2050 or before.

[1] The SLAMM program operates on IBM personal computers and is available from the authors.

FIGURE 4-13
NEW ENGLAND



Simulated change in wetland area in New England and mid-Atlantic regions. The high sea level rise scenario is shown. Subsidence is modeled as 0 mm/yr.

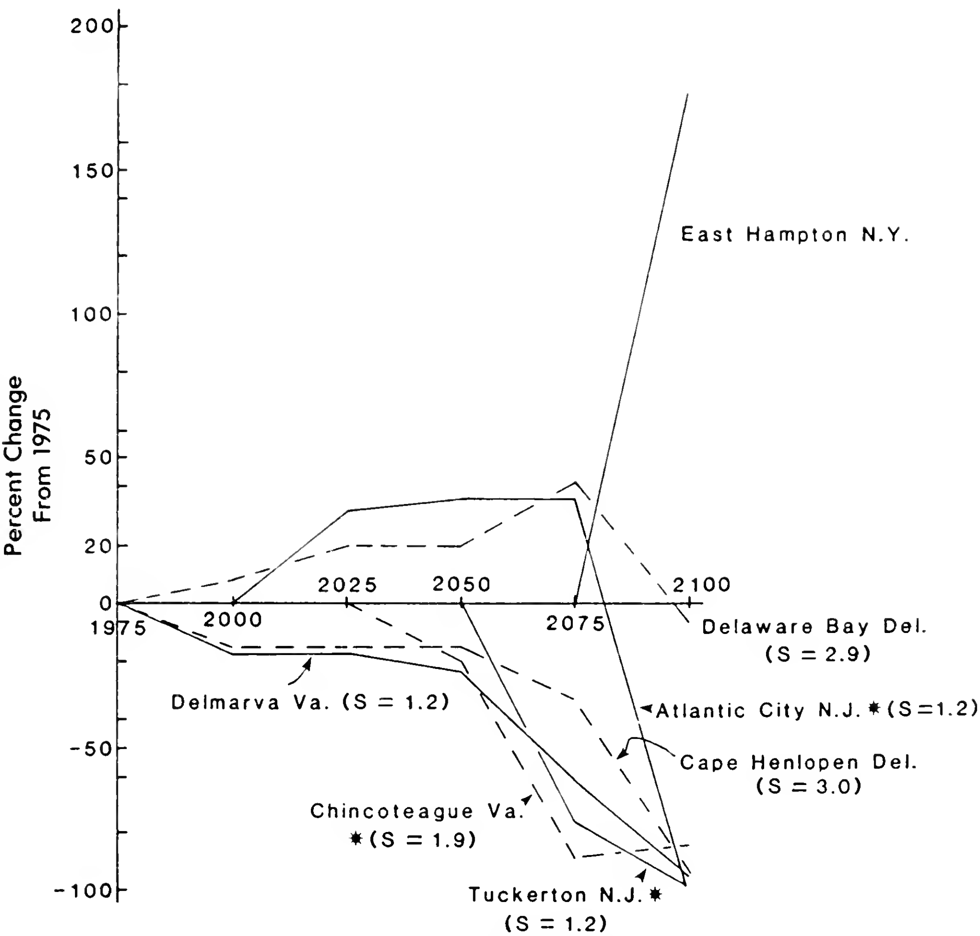
Under the high scenario, salt marsh expansion would accelerate and be more advanced by the year 2050 in certain areas than in the low scenario; but the increased flooding in later decades would inundate exposed seaward salt marsh, thus reducing total marsh area, particularly in the more southerly part of the three-state region (Figure 4-14). On Long Island Sound, however, salt marsh might persist without any loss of area even under the high scenario. However, much of the remaining salt marsh should be recognized as recent and perhaps unstabilized salt marsh developed as a consequence of flooding of lowland nonmarsh areas. Much of the original salt marsh would have been lost to shallow water and tidal flats. Thus marsh properties requiring substantial time to develop might not be evident in many of these newly formed marshes.

In the Maryland-to-Virginia region, a complex pattern of coastal landforms, terraces, and marsh types creates a complex pattern of response. In Delaware, the low scenario reveals the persistence and expansion of marsh as it gains at the expense of undeveloped lowland or fresh marsh until late in the simulation period. But along Chesapeake Bay, where significant subsidence submerges lowland areas and also along parts of the Delmarva Peninsula, tidal flats or sheltered water would replace some salt marsh even by the year 2050. Along the part of Delmarva, Virginia, barrier beaches are breached late in the period, causing the erosion of salt marshes (Figure 4-14).

The high scenario generally predicts acceleration of the processes observed under the low scenario. Delaware salt marshes expand through the year 2050 but losses may or may not occur afterward depending on location. At Bombay Hook accretion is projected to rise to 10 mm/yr, thus reinforcing the maintenance of salt marsh against the sea level rise. At Cape Henlopen lateral erosion increases, causing salt marsh loss. In parts of Virginia, barrier beaches are inundated and breached earlier and salt marsh loss accelerates as these areas decline. Consequently, accretion rate drops, further accelerating salt marsh flooding. Elsewhere (e.g., in Achilles, Virginia) some salt marsh is preserved, even as late as 2100, partially by the spread of

FIGURE 4-14

MID ATLANTIC



Change in wetland areas in mid-Atlantic region in SLAMM simulations. The high scenario is shown. Development is protected only on significantly developed sites. Unless otherwise noted, subsidence (S) is modeled as 0 mm/yr.*

marsh onto adjacent undeveloped lowland late in the simulation period. Overall, however, as expected, a greater net loss of marsh occurs than under the low scenario.

In North Carolina, particularly in and around Albemarle Sound, the abundant marshes would benefit from sea level rise in the low scenario by spreading onto the extensive low terrace (undeveloped lowland) in the first half of the twenty-first century. Thereafter, however, changes vary more clearly with location. At Manteo, for example, wetlands would be completely lost after the year 2075 as seaward wetlands were inundated and landward wetlands were unable to spread to adjacent lowland. Although the high dunes persist through the year 2100, the wetlands behind them are flooded as are those on the inner edge of the Sound. Only part of this loss can be attributed to a stipulated decline in accretion rate from 5 mm/yr to 2 mm/yr in 2100, because the decline began around 2080 before accretion slowed.

Elsewhere on the Sound (e.g., Columbia), however, wetlands continue to expand, under the low scenario, through the end of the simulation period. In contrast, at Plymouth on the west end of the Sound, wetlands are rapidly replaced by sheltered water over the period 2075 to 2100. The difference in behavior at the two sites is related to the presence of adjacent lowland. At Plymouth most wetlands are located adjacent to uplands (higher terraces), whereas further east at Columbia, wetlands are located adjacent to undeveloped lowland (low terrace) which can be readily converted to wetlands as mean sea level rises, thus compensating for some wetland loss to sheltered water.

Even under the high scenario, migration of wetlands onto adjacent undeveloped lowland continues as late as 2075 at such sites as Columbia where abundant lowland is available (Figure 4-15). However, after that period, under the assumption that accretion rates declined to 5 mm/yr between 2075 and 2100, wetland area is significantly reduced as rising seas flood out most lowland sites throughout the area. Elsewhere, where less lowland is available, the wetlands maintain themselves at about the same level as under the low scenario until about 2050. In the second half of the century, however, major losses occur as favorable landward sites for marsh migration become rare. For example, all of the wetlands on Manteo Island are lost to rising seas because no adjacent lowland remains, thus cutting off possible wetland migration.

Wetland behavior at the Charleston, South Carolina, site may not be well simulated by SLAMM because of fine-scale natural and disturbed landscape features that could not be depicted at the scale employed in this study. Charleston harbor is unusual in that the Santee River was diverted into it, causing high sedimentation. In order to maintain this naval port, large amounts of sediments are dredged annually and dumped on the adjacent lowlands. Examination of large-scale maps shows that levees, sea walls, dredge spoil islands, and other alterations of the natural landscape would significantly limit marsh migration. However, because these features are under-represented at the 1 km^2 cell scale, our simulations depict higher marsh migration rates than those estimated by fine-scale studies (Kana, Baca, and Williams 1986 and Chapter 2, this report). Under the high scenario, 75 percent of the existing marshes are lost, but 38 percent of the lowland is converted to marsh. Thus, because the model was developed as a regional-scale model, it is of limited use in simulating small-scale patterns.

Marsh behavior in the Georgia environment resembles that of North Carolina. High accretion rates (10 mm/yr) enable extensive marshlands to maintain themselves against the rising sea level. The protected marshes on the lee side of undeveloped lowlands can expand onto these lowlands in a seaward movement as well as spread landward onto lowlands further west within the sample area. Elsewhere, however, lowlands replace salt marsh so that the net change is quite small under the low scenario.

Similarly, under the high scenario, because of available lowland and an accretion rate which equals or exceeds the sea level rise rate the first 50 years of the simulation, salt marshes could expand modestly in area. At lower accretion rates, losses of salt marsh would occur relatively quickly under the high scenario. Given that the rate of sea level rise by 2100 exceeds even the high accretion rate by over three times, running the scenario into later years would result in a substantial net loss of salt marsh.

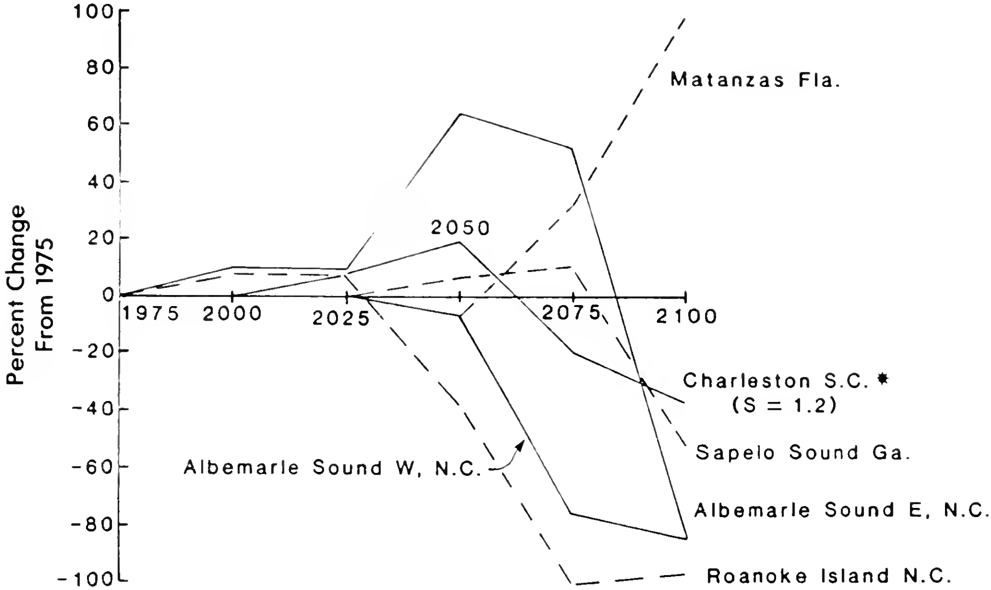
Florida Atlantic and Gulf Coasts

Although the northeastern part of this region is considered part of the South Atlantic region, it is included here because mangroves could become important if the climate warms.

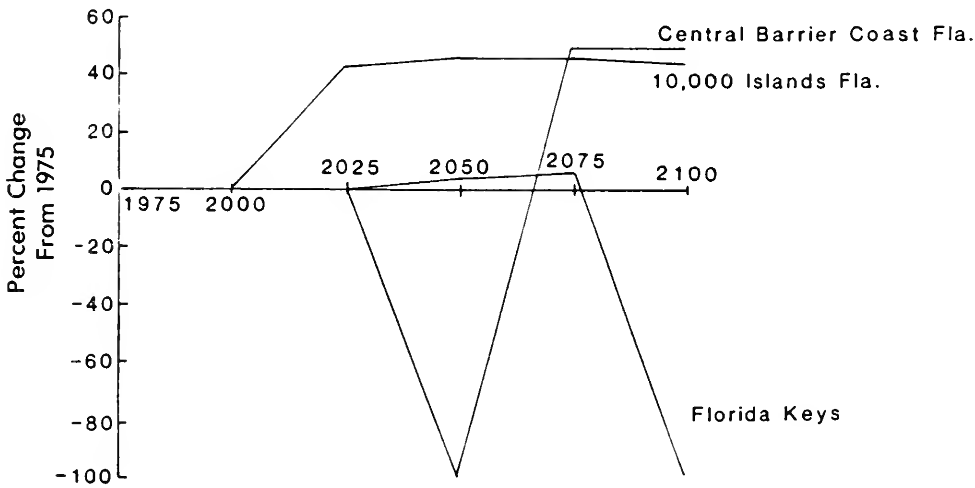
In north Florida (Matanzas), wetlands are lost by the year 2100 under either low or high sea level rise scenarios, probably reflecting the 5 mm/yr accretion rates that are reasonable for this area. Most of the more extensive freshwater marshes here would be lost, but some protected by upland areas would be preserved.

FIGURE 4-15

SOUTH ATLANTIC REGION



SOUTHERN FLORIDA REGION



Changes in wetland area in the South Atlantic and southern Florida regions in SLAMM simulations. The high scenario is shown. Unless otherwise noted, subsidence (S) is 0 mm/yr.

More interesting, however, is the potential for mangroves to expand into the area, replacing undeveloped and developed lowland. Although the northern limit of mangrove distribution in eastern Florida is about 80 km south of the Matanzas area, the mangroves here are poorly developed (Odum et al. 1982). The climatic warming that would generate increased sea level rise also would provide favorable conditions for mangrove expansion beyond the center of species distribution in the United States. Because mangrove swamps are modeled as resistant to lateral erosion, a simulation of the area with mangroves is quite different from one with just marsh.

The potential for mangrove expansion is seen more clearly in the response of the 10,000 Islands region of south Florida. Here, under both scenarios through the late twenty-first century, mangroves could become dominant land categories as they moved inland with the advancing tide, replacing marsh and lowlands.

In the Florida Keys simulations, rapid expansion of mangrove onto areas previously occupied by freshwater marsh in the Everglades is also an artifact of the model. Under the low scenario, the replacement of freshwater marsh by mangrove would not occur until near the end of the simulation period. Before then, limited expansion of mangroves onto undeveloped lowland in the Keys would occur. By 2100, however, the extensive freshwater marsh areas on the mainland adjacent to the Keys are inundated at high tide, assuming no influx of freshwater. Under the high scenario, freshwater marsh areas would be subject to tidal water intrusion and conversion to mangrove swamps by the year 2075 unless significant freshwater discharge would inhibit this trend. However, by the year 2100 mangrove areas would be lost due to complete inundation, and only tidal flats would remain on the higher Keys.

Along the Florida Gulf Coast north of the mangrove zone, wetlands would expand inland under both the low and high scenarios. Substantial marsh would remain even as late as 2100 in the high scenario by virtue of available adjacent lowland. Expansion of salt marsh, however, would peak in the high scenario by about 2075, to be followed by increased submergence on the seaward side, greatly slowing down the net increase in wetland area. Under the low scenario, salt marsh would still be expanding fairly rapidly in the year 2100.

Mississippi Delta

The response pattern for all the Louisiana wetland simulations was remarkably similar for Barataria Bay, Atchafalaya Delta, and the Central Isles Derniere in the Terrebonne Delta. High subsidence rates (11 mm/yr for Barataria Bay; Hatton, DeLaune, and Patrick 1933) are not entirely offset by high accretion rates. Rising seas thus accelerate loss of seaward salt marshes and disequilibrium is introduced into the salt marsh system. By the year 2100, and often even before (e.g., in the Atchafalaya by 2060), the extensive gains in salt marshes are totally flooded by rising seas and converted to sheltered or open water. By that time, the extensive freshwater and brackish marshes would be long gone.

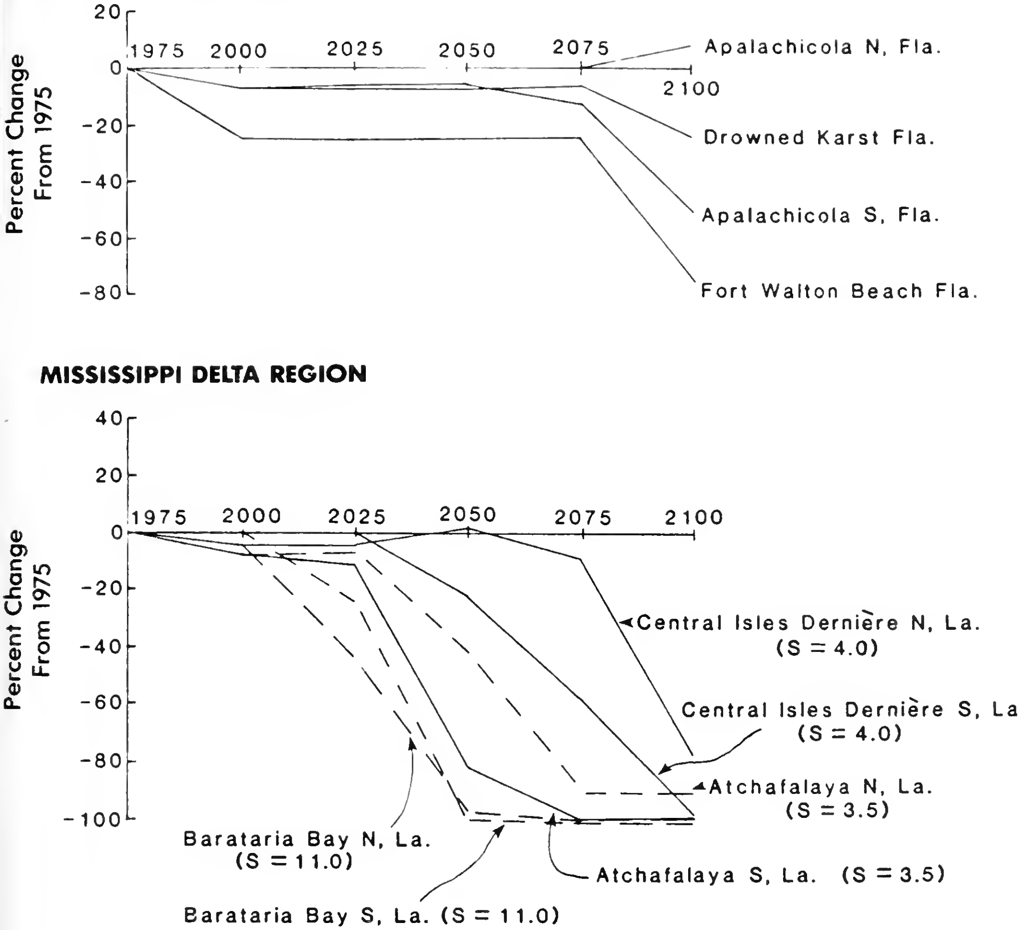
Although the pattern under the high scenario was similar, trends developed at a faster rate. By 2050 most salt marshes were totally inundated (Figure 4-16). Elsewhere the process was a bit slower but the trends were similar. In those cases complete loss of salt marsh was apparent by the year 2075 in the high scenario (Figure 4-16). These rapid losses occurred despite a simulated accretion rate of 10 mm/yr in marshes. The loss rate of salt marshes in the later decades of each scenario can be attributed partly to a lower accretion rate which can be expected as estuarine conditions prevail. However, even with a constant rate of 10 mm/yr, rapid losses of wetlands in coastal Louisiana would result from accelerated sea level rise, as simulated.

Chenier Plain-Texas Barrier Islands

In the sample area considered on the Chenier Plain of Texas, extensive freshwater marshes lie behind lowlands which include small salt marsh areas. Under the low sea level rise scenario, the seafront salt marshes are largely lost to tidal flats by the year 2000, but inland marshes are unaffected. However, in succeeding decades, salt marsh expands onto adjacent freshwater marsh,

FIGURE 4-16

EAST GULF COAST REGION

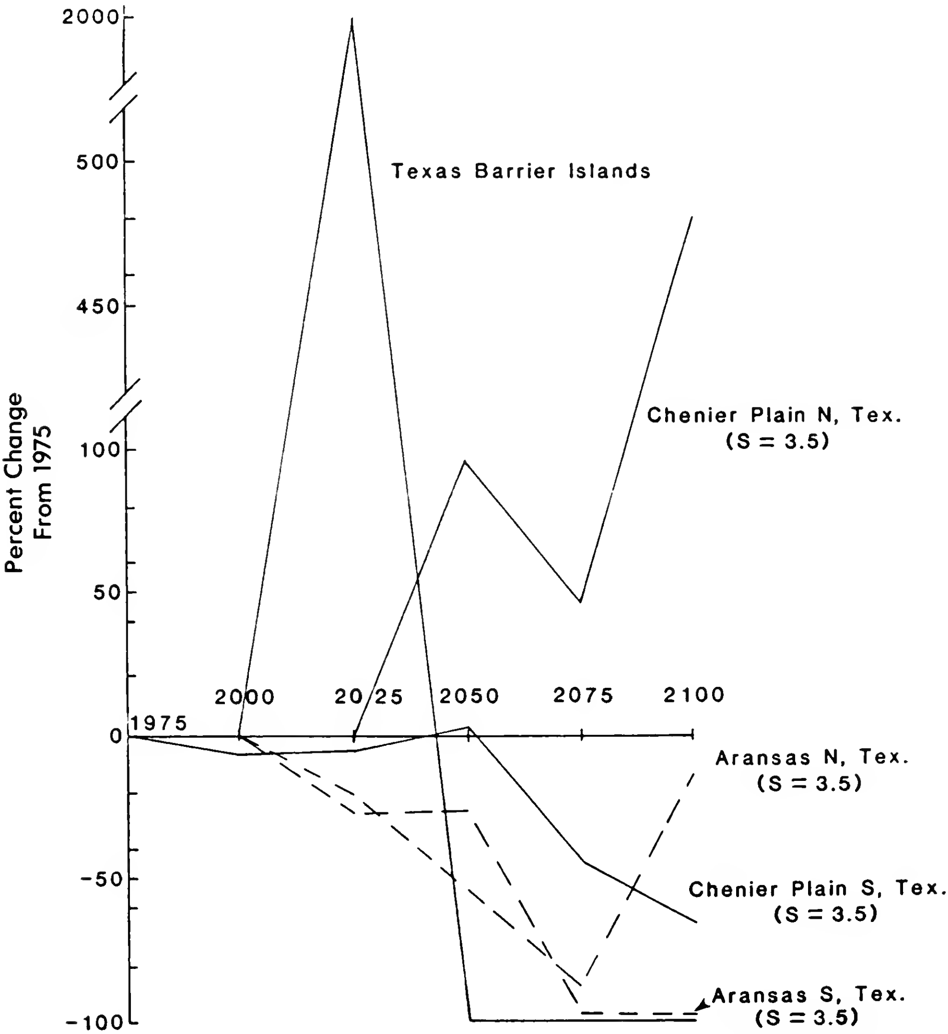


Changes in wetland area in the east Gulf Coast and Mississippi Delta regions in SLAMM simulations. The high scenario is shown. Development is protected only on significantly developed sites. Unless otherwise noted, subsidence (S) is 0 mm/yr.*

thus reducing its area. By 2050, this trend is only slightly developed; but by 2100, salt marsh has expanded onto more than half of the original freshwater marsh. However, simultaneous movement of marsh onto adjacent undeveloped lowland helps reduce the net marsh loss to about one-half the original area. Further south, however, as around Aransas Wildlife Refuge, freshwater marshes are more extensively flooded and over 90 percent may be lost by 2100 in the low scenario. Also in this location, all marshes may be entirely lost by the end of the simulation period, although earlier they held constant or even expanded relative to the 1975 condition. A similar pattern holds for the Texas Barrier Islands region.

At some sites marshes would expand significantly by the year 2050, spreading onto adjacent undeveloped lowland (Figure 4-17). Generally, however, by the end of the simulation period, these gains have been lost where barrier islands that protect marshes have been breached, or have washed over onto the back-barrier marshes. Most of these regions have become open sea by this time. Yet elsewhere, where tidal fluxes are dampened as in the Chenier Plain North sample area, salt marshes continue to expand through the end of the twenty-first century. In such protected situations, the full effects of sea level rise are delayed relative to more exposed situations.

FIGURE 4-17
CHENIER PLAIN-TEXAS BARRIER ISLANDS



Changes in wetland area in Texan study sites according to SLAMM high-scenario simulations. Unless otherwise noted, subsidence (S) is 0 mm/yr.

Californian Region

South of San Francisco Bay, most coastal wetlands in California are so small as to be under-represented at the regional scale used in this study. Thus, at the 1 km^2 cell level, no salt marsh appears as a dominant land category except at Oxnard. Here, marsh is lost by the end of the simulation period through formation of tidal flats and eventually total submergence of some cells in both scenarios (Figures 4-18). Elsewhere in southern California, freshwater marshes may persist where they are located in sheltered or protected locations (e.g., Imperial Beach). Salt marsh could persist under both scenarios under unprotected situations (such as Del Mar) so long as adjacent lowland or freshwater marsh could be converted. That the potential for marsh establishment and spread may be limited by abrupt topographic change is seen at Santa Ynez, where no marsh is developed at any time under either scenario.

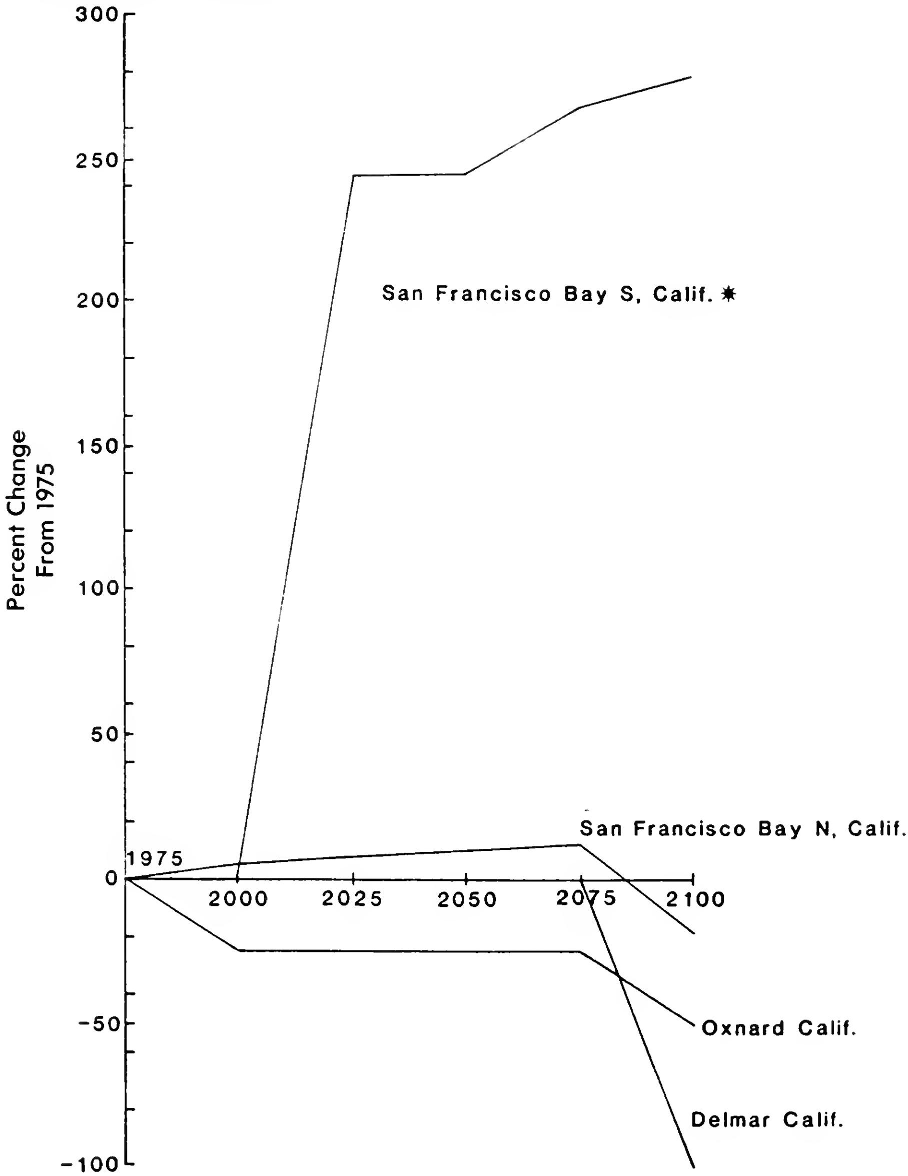
In San Francisco Bay the presence of large marshlands, many severely modified by human activities, presents a different situation. A large percentage of remaining marshlands in the Bay area has been associated with levees at one time or another and many of these no longer function as typical salt marshes. But the remaining 10-20 percent of the salt marshes still open to tidal exchange provide a starting point for the expansion of salt marsh onto adjacent lowland and freshwater marsh. However, where any of these areas are protected by levees, salt marsh migration is not possible. Thus, protected marshes may persist while salt marsh expands significantly onto other unprotected lowlands.

Even where accretion is considered to be zero, protection will permit persistence of the marshes. Some losses may occur as a result of rising waters, but this may be offset by marsh migration onto unprotected lowlands. This is seen under the low scenario for both simulations. In the south Bay area, even under the high scenario, salt marshes increase over the entire simulation period, primarily through expansion into lowland areas already near sea level through subsidence due to groundwater withdrawal (Figures 4-18). At the north Bay site, the same situation holds well into the second half of the twenty-first century; but by the end of the simulation period, flooding begins to exceed the continued spread of salt marsh and a net decrease occurs. However, the loss, compared to the 1975 condition, is only about 39 percent of the total marsh area because of the protection afforded by levees.

Columbian Region

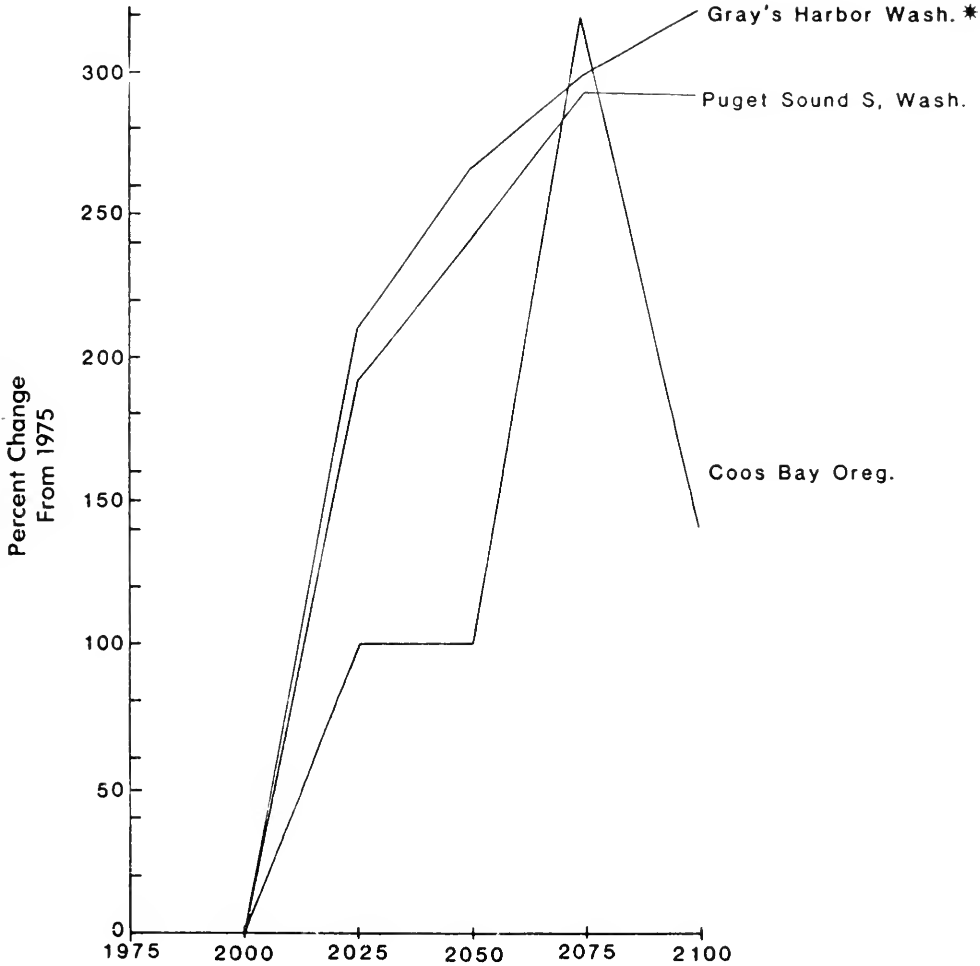
Although coastal topography in the Columbian region limits wetland area and would be expected to do so if sea level rise accelerated, simulations of sites with significant wetlands suggest that for low and high sea level rise scenarios, salt marsh area would expand (Figure 4-19). Expansion would be seen both along the coast in bays and harbors as well as under conditions similar to those of the northern and southern ends of Puget Sound. In fact, under both scenarios at all sites examined, salt marsh would begin expanding early in the simulation period and continue for the most part until 2100, even in the high scenario; however, the total areas involved are small. Only under conditions such as those found at Coos Bay would rising seas begin to exceed the spread of salt marsh, and this reversal would develop only in the last quarter of the twenty-first century (Figure 4-19). At that time undeveloped lowland for colonization by salt marsh becomes limited. Elsewhere, where important undeveloped lowland areas remain which could convert to salt marsh, marsh areas continue to expand, sometimes rapidly, as in our simulation of Puget Sound North. Here, in both scenarios, salt marshes are still expanding significantly as of 2100, but more rapidly in the high scenario because of adjacent undeveloped lowland. However, the more rapid expansion of salt marsh also means more rapid decrease in lowland availability, suggesting that conditions soon would become limiting for further salt marsh expansion here as well. For all our simulations in the Columbian region, wetland areas in the next century would exceed present areas due to the adjacent low terrace; because of the rapid rise in sea level this would not be a continuation of the present tendency of tidal marshes in this region to prograde under twentieth-century conditions (Seliskar and Gallagher 1973).

FIGURE 4-18
CALIFORNIAN REGION



Changes in wetland area in Californian study sites according to SLAMM high-scenario simulations. Development is protected only on significantly developed sites. Subsidence is modeled as 0 mm/yr.*

FIGURE 4-19
COLUMBIAN REGION



Changes in wetland area in Columbian study sites according to SLAMM high-scenario simulations. Development is protected only on significantly developed sites. Subsidence is modeled as 0 mm/yr.*

DISCUSSION

Effects of Alternate Assumptions

Geodynamic changes in elevation of land relative to "global" sea level are a function of glacial isostatic rebound affecting large portions of continents, regional adjustments to plate tectonics, subregional isostatic adjustments to sedimentary loading, and local subsidence due to withdrawal of groundwater and oil and compaction of sediments. Because relative sea level at any particular tidal gauge is also affected by barometric pressure, wind direction, and coastal currents, at least 35 years of data are needed to separate the various components of local sea level to detect a 1 mm/yr trend with 95 percent confidence (IAPSO 1985). The average rate of glacial isostatic submergence for the East Coast is 0.6 mm/yr (IAPSO 1985), which would mean that the simulation would be advanced by approximately three years over a hundred-year period compared with a 0.0 value for subsidence. If a value of 1.2 mm/yr is used, based on Hicks et al. (1983), the simulation is advanced by six years over a hundred-year period.

Simulation of sea level response at Bombay Hook, Delaware, shows how subsidence assumptions affect wetland response. If subsidence is considered as negligible (held to 0.0 in computer runs), only a slightly different outcome results by the year 2100 than if subsidence is considered to be 2.9 mm/yr (Table 4-7). Under the low scenario, higher subsidence results in a slightly larger wetland area because conversion of lowland occurs. Marsh area expands at the expense of undeveloped lowland by virtue of its 5 mm/yr accretion rate beginning around the turn of the century. However, subsidence assumptions make no difference through 2050.

TABLE 4-7

PERCENT MARSH FOR DIFFERENT MODEL CONDITIONS; DELAWARE BAY: TOTAL AREA = 30,800 ha

	Low				High			
	A = 5		A = Variable		A = 5		A = Variable	
Year	S = 0	S = 2.9	S = 0	S = 2.9	S = 0	S = 2.9	S = 9	S = 2.9
2050	29.2	29.2	29.2	29.2	29.2	29.2	29.2	29.2
2100	34.0	34.7	34.0	34.7	30.5	22.7	39.2	30.2

A = Accretion Rate in mm/yr; S = Subsidence Rate in mm/yr

In the Gulf Coast, average subsidence ranges from 0.0 and 1.5 mm/yr (Holdahl and Morrison 1974). Subsidence is essentially zero for most of the Gulf Coast areas simulated, except for the northern Texas Coast, where a subsidence value of 3.5 mm/yr was used, and for the Mississippi Delta, where values of 3.5 to 11 mm/year were used. Because the tidal range is 0.3 m along the Texas Coast, a 3.5 mm/yr subsidence doubles the rate of change in coastal features compared to the default of 0.0. The results of these alternative values are shown in Table 4-8.

As expected, holding accretion rate constant, rather than allowing it to increase as marshes expand, has an impact similar to that of introducing a small subsidence rate (Table 4-7). The net effect is loss of most wetlands that would have been gained under the higher accretion rate by the year 2100. However, the total wetland area was nearly equal under the two conditions. Differences are more striking under the high scenario. Here the increase in accretion to 10 mm/yr, which began in 2075, enables salt marsh expansion. In contrast, if the accretion rate is held constant, marsh never accumulates beyond its original area in 2075, and fewer areas are suitable for marsh expansion. Therefore, by the year 2100 the marsh area was reduced to 30.5 percent. In contrast, the total area of wetlands with rising accretion but no subsidence equalled about 39 percent.

TABLE 4-8

CHANGES IN WETLAND AREAS BETWEEN 1975 AND 2100 a/ (all areas in 10^3 hectares)

Region	1975 Marsh Area	Low Scenario			High Scenario		
		Lost	Gained	Net	Lost	Gained	Net
New England	6.0	0.2	0	-0.2	3.8	0	-3.8
Mid-Atlantic	45.4	17.7	8.9	-8.8	45.5	6.7	-38.8
South Atlantic	91.3	26.1	30.2	4.1	70.5	21.2	-49.3
Florida (subtropical)	59.8	0.2	17.4	17.2	24.1	16.0	-8.1
NE Gulf Coast	73.6	6.4	1.3	-5.1	21.6	2.4	-19.2
Mississippi Delta	150.9	121.1	0	-121.1	146.0	0	-146.0
Chenier Plain TX	29.9	10.9	6.8	-4.1	31.5	6.5	-25.0
Californian Prov.	26.5	9.1	8.9	-0.2	9.5	10.2	4.7
Columbian Prov.	1.2	0.1	11.6	11.5	0.3	12.4	12.1
TOTAL IN SAMPLE b/	484.6	191.8	85.1	-106.7	352.8	76.4	-272.4

a/ The projections are not interpretable as statistically valid estimates of regional trends.

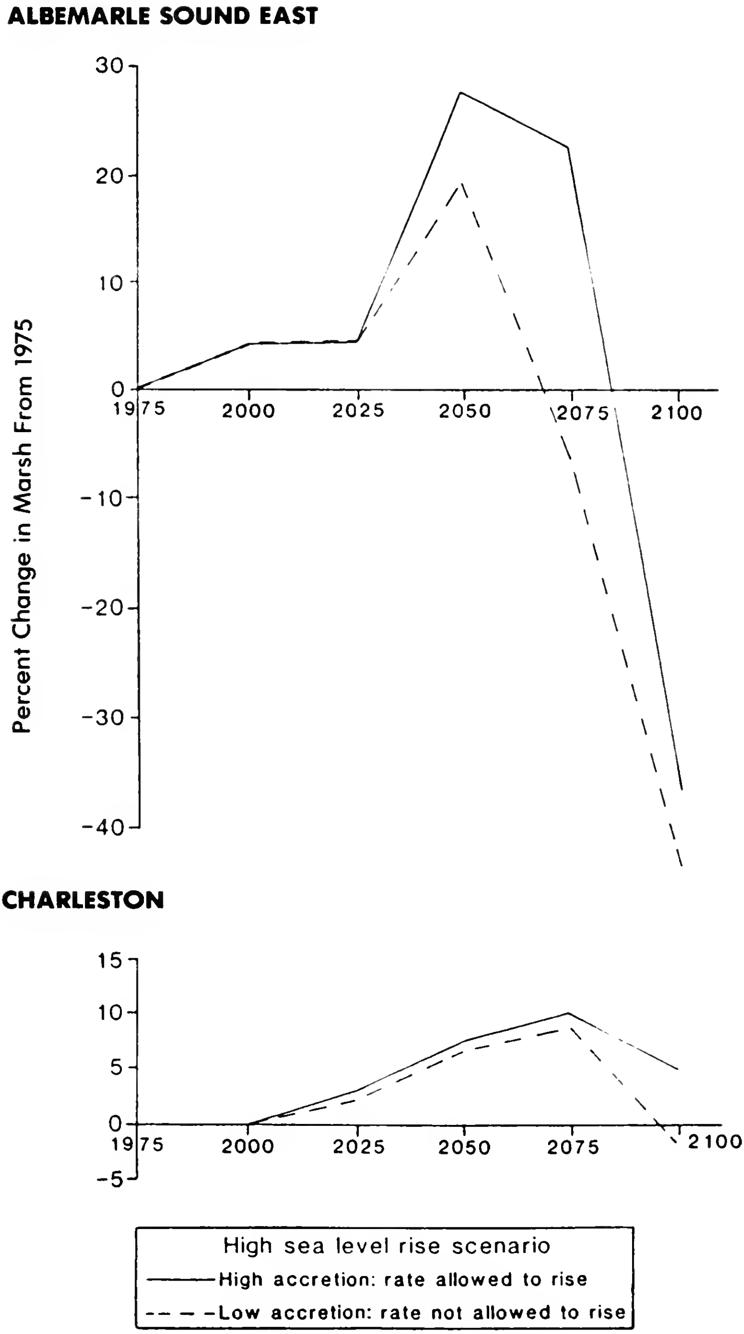
b/ The number of cells in particular regions were not based on underlying population. Thus, the percent reduction of sample does not necessarily reflect reductions in U.S. wetlands.

When accretion rate is held constant and a subsidence rate of 2.9 mm/yr is assumed, conditions are least favorable for maintenance of marshland (Table 4-7). Under the low scenario, total wetland area is reduced to 22.7 percent by the year 2100, one-third less than without subsidence. Inland marsh would have disappeared by 2100, but its area is unchanged from assumptions of constant accretion without subsidence through the year 2075. Marsh areas react somewhat similarly under both scenarios, but with subsidence, areas peak by 2075 instead of continuing to expand, and then decline suddenly to the final level as inundation accelerates. Thus the cumulative effect of subsidence becomes most apparent only late in the scenario period.

The importance of accretion rate was examined in the Albemarle Sound East simulations by comparing varying accretion rates with a constant accretion rate of 5 mm/yr (Figure 4-20). The high accretion rate allows marshes to be maintained through the year 2050 rather than the year 2000 under a lower accretion rate. By 2050, despite the lower accretion rate, salt marsh initially expands for the next 25 or 30 years. Later, rising waters rapidly inundate the salt marshes, eliminating them completely by the year 2095. In contrast, the 10 mm/yr accretion rate allows greater persistence of marshes through the year 2085.

Shortly thereafter, however, the exponentially increasing rise in sea level drowns over 90 percent of the marshes, leaving a situation only marginally improved over conditions prevailing under assumptions of a lower accretion rate. Although the importance of accretion in maintaining marsh elevation against rising seas is seen, an accelerating rise in sea level allows accretion rate to provide only a temporary means for maintaining coastal marshlands.

FIGURE 4-20



The effect of alternative accretion-rate assumptions on changes in wetland area at Albemarle Sound East, North Carolina, and Charleston, South Carolina.

Model Comparisons with Site Assessments

There are few opportunities for validation of our regional model of coastal response to sea level rise. Knowing that the model has an accuracy definable at a particular level would be of great help in interpreting the findings of the study. One approach to validation, although an imperfect one, is to compare model results with detailed studies of local sites. Two such studies are available—a study of the impact of sea level rise on wetlands in Tuckerton, New Jersey, by Kana et al. (1988 and Chapter 3, this report), and in Charleston, South Carolina, by Kana, Baca, and Williams (1986 and Chapter 2, this report). However, it must be recognized that true validation cannot be obtained because of the radically different approaches being compared. Thus, our simulations for Charleston suggest that a greater capacity for marsh migration exists than fine-scale analysis suggests. As stated above, fine-scale disturbances and landscape complexity, which limit marsh migration, could not be simulated using a square kilometer grid. The New Jersey site, however, with greater landscape homogeneity on a coarser scale, provides a quasivalidation of the SLAMM model.

Several of the major differences in methodology of the regional model and site-specific approaches should be understood before making comparisons. First of all, the model approach operates at a much larger geographic scale and consequent loss of local scale accuracy, in keeping with the major objectives of the study. Thus, for example, high and low salt marsh are not distinguished in the model as they are in the site studies. The 1 km^2 cell which forms the spatial unit of the model is defined only by the predominant land category type present. Therefore, in areas where salt marsh may be an important but secondary land category, it will be underrepresented in the regional analysis. Similarly, where salt marsh predominates, it could be overrepresented as the only category present, and if conditions for migration are favorable, an overestimate of migration results. In the comparisons to follow, this latter situation is believed to be more significant than the former.

The data limitations in the modeling approach are defined by the accuracy and timeliness of the USGS 7 and 1/2 minute (and occasionally 15 minute) quadrangle topographic map series. Necessarily, then, a set of generalized properties results. This is most apparent with elevation because the quadrangle series frequently presents elevational contours at five- or ten-foot intervals, which are quite coarse for subdividing coastal land categories. Consequently, subtle differences which show up in a detailed study as a loss or gain of one category or another are not recognized in the regional analysis.

Freshwater and saltwater marshes are not distinguishable based on the USGS maps. Therefore, the raw data recognizes only "marsh," and our model used an algorithm based on elevation with respect to spring high tide to differentiate the two types.

Other aspects affect both regional and local interpretations. These include limited data on subsidence rates and accretion rates as well as on actual marsh migration rates, and lack of any empirical knowledge of coastal land responses to sea level rise at a rate as rapid as that projected for the next century.

The major response at the New Jersey wetland site to the low scenario through 2075 is the replacement of high salt marsh with low salt marsh (Kana et al. 1988 and Chapter 3, this report). Also projected is the loss of over half the transition marsh in the Tuckerton area, but an increase of the same area in the Great Bay Boulevard area. However, at both locations no change in overall wetland area is projected under the low scenario. The conversion of high to low salt marsh noted by Kana et al. would not be detected in our model; furthermore, because the distinction between saltwater 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 New Jersey and South Carolina studies would occur within the framework of our general freshwater marsh category. We project a 9 percent decline in total wetland area by 2075, growing rapidly to a 75 percent decline by the year 2100. For the year

2075, Kana et al. project a slight increase in the total marsh area, whereas we project a 9 percent decline. However, as late as 2045 we project a 1.0 percent decline in wetland area, a figure not significantly different from theirs 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 86 percent decline in salt marshes of the Tuckerton area by 2075, compared to a loss of 75 percent by 2075 and a loss of 99 percent 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.

FUTURE RESEARCH NEEDS

Although the implementation of the SLAMM model has provided a useful analysis of probable coastal wetland responses to accelerated sea level rise, increased accuracy, reliability, and credibility would follow from additional refinement and study. We recommend that the following steps be implemented:

(1) *Increase the resolution by using a 0.25 km^2 or 0.125 km^2 grid cell for most areas.* This would avoid the under- or over-representation of categories such as marshes and would permit the elevation of the dominant category to coincide more closely with the average cell elevation. The reliability of results would be significantly increased through these more realistic estimates of the distributions of the major categories.

(2) *Obtain statistically unbiased samples of sufficient size for quantitative inferences.* To do this, a method for stratified random sampling within each region must be developed which takes into account variation in wetland types and coastal topography. With such a method, large-scale changes could be estimated for specific regions, with a level of accuracy sufficient to guide policymaking at the regional level.

(3) *Distinguish among wetland types*, including freshwater, transitional, and high and low salt marshes, using the Fish and Wildlife Service habitat classification maps. This would provide a better basis for understanding changing ecological relationships and their implications for future conservation and resource management.

(4) *Analyze the change in the boundary between wetland and open sea.* Although wetland loss is recognized as deleterious to fisheries and other marine resources, the relationship is not linear. Recent model analysis using a 1 km^2 cell grid (Browder, Bartley, and Davis 1985) shows that as the total "interface" of a coastal marsh (area of marsh surface exposed to tidal water) changes as marsh shoreline disintegrates or becomes increasingly indented, nutrient exchange increases to a point and then declines rapidly, affecting the coastal fishery. An analysis of the changing marsh area exposed to tidal waters could be made from the database and SLAMM model used in the present study; such an analysis would help diagnose the changing resource values of the wetlands.

(5) *Validate the model,* using historic data on changes in coastal wetlands, beaches, and lowlands, accompanying anomalously large subsidence in areas such as the Mississippi Delta in Louisiana, Galveston and Houston, Texas, and San Jose, California.

(6) *Use data for remote sensing.* This would make it possible to more accurately characterize existing vegetation types. Transect studies could be used to characterize the relationship between vegetation type, frequency of flooding, and elevation, as described by Kana et al.

CONCLUSION

Regional patterns of wetland distribution and the potential for loss or gain of wetlands from sea level rise during the next century depend on two principal factors: (1) the tidal range within which wetlands can occur and (2) the extent of the lowest Pleistocene terrace (often found at approximately five feet 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.

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. Furthermore, in many 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. However, marshes will be lost in areas that have high coastal dunes or that lack the low terrace.

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. The southern Everglades will also disappear.

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 has 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 the marshes will decline precipitously. A notable exception to this pattern is in 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 area early in the next century.

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 through 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.

Aggregating the individual case studies provides a convenient way to detect commonalities in wetland response trends throughout the diverse U.S. regions. However, 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 assured. 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.

The percent change in wetland area at each study site is given in Appendix 4-B. These regional data have been summarized in Table 4-8, shown earlier. The aggregated data illustrate the clear trend toward diminished wetlands in the next century as an overall response to increased sea level rise (Table 4-8).

Nationally, the 57 sites selected for study include 485,000 ha of coastal wetlands. Under the high scenario, about 73 percent (192,000 ha) of the sample wetlands would be lost by 2100. However, formation of new wetlands reduced the loss to 56 percent of the 1975 wetland area. Under the low scenario, about 40 percent of the 1975 wetlands would be inundated, but new wetlands extended over 85,100 ha, leaving a net reduction by 2100 of 107,000 ha or 22 percent 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.

Wetland decline occurred at case study sites from all regions under high scenario conditions except for the relatively small wetland areas considered in the Californian and Columbian provinces. However, in San Francisco Bay, which contains by far the largest area of wetlands, both major losses and gains occurred, depending on local conditions and whether or not wetlands were allowed to migrate. Also, the complex shoreline of Puget Sound probably was not adequately characterized by the selected case studies.

Further east, relatively large wetland losses predominated everywhere under the high scenario. New England and Mississippi Delta study areas lost much, or nearly all, of 1975 wetlands with no compensating gains of new wetlands. Elsewhere along the Atlantic and Gulf Coasts, small-to-low landward gains fell well short of the 1975 wetland losses. Trends under the low scenario were similar for most regions, showing substantial but smaller wetland losses. Clear exceptions occurred, however, in the south Atlantic and in subtropical Florida. In both regions, gains in certain study areas balance significant losses in other areas; thus, values averaged over these regions impart little information.

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 next century. Over extensive areas of the United States, however, virtually all wetlands may be lost by 2100 if adjacent lowlands are developed and protected, instead of being reserved for wetland migration.

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APPENDIX 4-A

COASTAL SITES USED IN MODEL

(See page 138 for explanation of abbreviations and key to column entries)

SITE	MEAN Tide Range Ocn/Ild (ft)*	C	D	E	LOCATION N	LOCATION W	Total Area
NEW ENGLAND							
Maine Coast N	12/	1	1	4	44/37/30	67/45/00	28,000
Maine Coast S	9/	1			44/00/00	69/30/00	28,000
New Hampshire	7/	3	1	4	43/07/30	50/52/30	27,500
Mass. Coast	9.5/	1	1	4	42/00/00	70/45/00	26,600
Cape Cod N	6.6/9.6	3	2	1	42/00/00	70/05/00	35,000
Cape Cod S	6.6/9.8	3		4	41/47/00	70/22/30	72,200
Narragansett	3.2/	1		3	41/30/00	71/37/30	64,000
MID-ATLANTIC							
Long Island South CN	/4.0	2	1	4	41/22/30	72/30/00	27,300
E Hampton NY	2.5/2.4	5	2		41/07/30	72/22/30	55,000
Gardiner's Island NY	2.5/2.4	5	2		46/07/30	72/07/30	34,200
Long Is W NY	3.0/1.2	5	2	4	40/45/00	73/30/00	9,900
Atlantic City NJ	3.3/1.8	5	2	4	39/30/00	74/30/00	40,000
Tuckerton NJ	3.3/1.8	5	2	4	39/45/00	74/22/30	100,000
Delaware Bay RI	/5.8	3	1 3		39/22/30	75/37/30	30,800
Cape Henlopen DE	4.2/0.6	5	2		38/52/30	75/15/00	45,000
Chesapeake E MD	/1.1	4	1		38/45/00	76/22/30	52,500
Chesapeake W	/1.1	4	1		38/30/00	76/37/30	55,000
Potomac Riv. E	2.1/	2			38/15/00	77/00/00	30,800
Potomac Riv. W	/1.4	4	1		38/37/30	77/22/30	55,000
Chincoteague VA	3.6/1.7	2	2		38/00/00	75/30/00	33,000
Delmarva S VA	3.8/2.7	2	2		37/15/00	76/00/00	26,600
Chesapeake Bay S VA	/2.4	2	3		37/22/30	76/30/00	30,800

COASTAL SITES USED IN MODEL (Continued)

SITE	AREA (ha) Marsh: Fresh	Marsh: Salt	Marsh: Mangr.	Beach: Undeveloped Exp.	Beach: Undeveloped Shelt.	Beach: Developed Exp.	Beach: Developed Shelt.	Beach: High Dunes	Beach: Tidal Flat
NEW ENGLAND									
Maine Coast N	0	112	0	0	504	0	112	0	0
Maine Coast S	0	0	0	0	0	0	0	0	0
New Hampshire	0	1,513	0	110	0	193	0	0	193
Mass. Coast	0	0	0	0	904	0	0	0	0
Cape Cod N	0	1,400	0	0	0	0	0	0	210
Cape Cod S	217	2,527	0	289	289	0	0	0	73
Narragansett	192	0	0	128	0	1,280	0	0	0
MID-ATLANTIC									
Long Island South CN	0	1,010	0	0	0	0	0	0	0
E Hampton NY	110	110	0	0	110	0	0	0	0
Gardiner's Island NY	103	0	0	205	103	0	0	0	0
Long Is W NY	1,505	505	0	1,297	0	0	0	0	0
Atlantic City NJ	0	9,000	0	600	400	1,280	1,200	0	280
Tuckerton NJ	2,400	7,500	0	200	0	1,100	200	0	0
Delaware Bay RI	185	7,300	0	0	92	0	0	0	0
Cape Henlopen DE	3,600	1,800	0	180	90	180	90	180	0
Chesapeake E MD	0	105	0	0	105	0	0	0	0
Chesapeake W	0	220	0	0	0	0	0	0	0
Potomac Riv. E	0	0	0	0	92	0	92	0	0
Potomac Riv. W	825	275	0	0	0	0	0	0	0
Chincoteague VA	297	4,092	0	1,716	1,118	0	792	0	0
Delmarva S VA	1,889	2,208	0	3,804	0	0	0	0	1,702
Chesapeake Bay S VA	0	400	0	0	0	0	0	0	585

COASTAL SITES USED IN MODEL (Continued)

SITE	AREA (ha)						
	Lowland			Upland		Water	
		Developed					
	Undev.	Unpro.	Prot.	Undev.	Dev.	Shelt.	Open
NEW ENGLAND							
Maine Coast N	112	0	0	15,288	196	11,704	0
Maine Coast S	0	0	0	9,492	112	1,092	17,304
New Hampshire	6,793	6,105	0	5,308	193	2,310	4,813
Mass. Coast	0	0	0	12,502	1,197	11,997	0
Cape Cod N	105	210	0	10,605	1,190	10,885	10,395
Cape Cod S	217	2,310	0	27,689	4,693	20,577	13,140
Narragansett	0	128	0	6,208	576	1,408	55,296
MID-ATLANTIC							
Long Island South CN	601	1,092	0	17,199	601	6,798	0
E Hampton NY	2,310	605	0	21,615	1,980	22,000	6,215
Gardiner's Island NY	1,094	308	0	3,694	1,402	14,090	13,201
Long Is W NY	0	1,703	0	99	1,000	0	3,802
Atlantic City NJ	3,400	1,800	0	4,480	0	4,600	12,880
Tuckerton NJ	600	700	0	14,000	1,000	27,400	44,900
Delaware Bay RI	3,111	92	0	9,702	893	9,394	0
Cape Henlopen DE	3,015	720	90	14,490	990	11,790	7,695
Chesapeake E MD	15,908	683	0	315	0	35,385	0
Chesapeake W	825	1,100	0	32,780	1,925	18,205	0
Potomac Riv. E	585	0	0	14,692	308	15,000	0
Potomac Riv. W	220	0	0	37,510	2,475	13,695	0
Chincoteague VA	693	0	0	4,884	0	9,108	'10,197
Delmarva S VA	1,011	0	0	5,107	106	1,490	9,310
Chesapeake Bay S VA	8,901	585	986	585	400	18,295	0

COASTAL SITES USED IN MODEL (Continued)

SITE	MEAN Tide Range Ocn/Ild (ft)*	C	D	E	LOCATION N	LOCATION W	Total Area
SOUTH ATLANTIC							
Roanoke Is VA	2/ .5	5	2	4	36/00/00	75/45/00	57,500
Albemarle E. NC	/ .5	3	3		36/00/00	76/15/00	57,500
Albemarle W. NC	/ .5	3	3		36/00/00	76/45/00	46,000
N. Charleston SC	5.2/4.4	4	1		33/00/00	80/07/30	34,500
Charleston SC	5.2/5.3	4	1		32/53/30	80/07/30	99,000
Sapelo Sound FL	6.9/7.2	5	2		31/37/30	81/22/30	57,500
Matanzas FL	4.0/0.5	5	2		29/45/00	81/22/30	40,000
SOUTH FLORIDA							
Florida Keys	1.5/1.0	3	2		25/22/30	80/30/00	62,500
10,000 Is. FL	2.0/ to 3.5	3	2		26/00/00	81/30/00	65,000
Cntrl Barrier Coast FL	1.1/ to 2.1	5		2	27/22/30	82/37/30	62,500
EAST GULF COAST							
Drowned Karst FL	2.0/	3			29/22/30	83/00/00	52,800
Apalachicola North FL	1.6/	4	1		30/00/00	85/07/30	19,600
Apalachicola South FL	1.6/	4	1		29/52/30	85/07/30	62,500
Fort Walton FL	neg/0.8	5	2		30/37/30	86/45/00	48,000
MISSISSIPPI DELTA							
Barataria Bay North LA	1.0/.30	4	1	1	29/30/00	90/15/00	45,600
Barataria Bay South LA	1.0/.30	4	1	1	29/15/00	90/15/00	60,000

COASTAL SITES USED IN MODEL (Continued)

SITE	AREA (ha)								
	Marsh			Beach					
				Undeveloped		Developed		High	Tidal
	Fresh	Salt	Mangr.	Exp.	Shelt.	Exp.	Shelt.	Dunes	Flat
SOUTH ATLANTIC									
Roanoke Is VA	1,495	3,278	0	115	115	0	0	2,013	0
Albemarle E. NC	20,298	4,773	0	173	0	0	0	0	0
Albemarle W. NC	3,910	1,196	0	0	0	0	0	0	0
N. Charleston SC	3,312	4,899	0	0	104	0	0	0	0
Charleston SC	4,500	18,700	0	700	0	400	100	0	400
Sapelo Sound FL	115	21,103	0	518	288	0	0	0	2,013
Matanzas FL	2,800	80	800	200	0	0	0	200	0
SOUTH FLORIDA									
Florida Keys	16,813	0	6,438	0	0	0	0	0	0
10,000 Is. FL	12,415	5,200	18,785	0	0	0	0	0	0
Cntrl Barrier Coast FL	0	0	125	500	0	1,000	313	0	0
EAST GULF COAST									
Drowned Karst FL	26,506	2,218	0	0	0	0	0	0	0
Apalachicola North FL	16,992	0	0	0	0	0	0	0	0
Apalachicola South FL	23,813	3,688	0	0	0	0	0	0	0
Fort Walton FL	288	96	0	1,392	96	192	0	0	0
MISSISSIPPI DELTA									
Barataria Bay North LA	10,716	8,482	0	0	0	0	0	0	0
Barataria Bay South LA	28,680	11,280	0	0	0	0	0	0	0

COASTAL SITES USED IN MODEL (Continued)

SITE	AREA (ha)						
	Lowland			Upland		Water	
		Developed					
	Undev.	Unpro.	Prot.	Undev.	Dev.	Shelt.	Open
SOUTH ATLANTIC							
Roanoke Is VA	3,105	518	0	575	0	27,313	18,975
Albemarle E. NC	17,883	115	0	0	0	14,203	0
Albemarle W. NC	6,900	322	0	20,884	92	12,696	0
N. Charleston SC	3,692	483	0	16,905	4,313	794	0
Charleston SC	9,900	7,700	200	37,800	7,300	5,200	7,100
Sapelo Sound FL	8,223	0	0	4,600	173	2,073	17,825
Matanzas FL	4,400	1,080	0	11,400	680	0	18,280
SOUTH FLORIDA							
Florida Keys	1,563	500	0	0	0	22,375	14,813
10,000 Is. FL	15,990	780	0	0	0	0	11,830
Cntrl Barrier Coast FL	375	1,313	0	29,375	6,188	4,188	19,125
EAST GULF COAST							
Drowned Karst FL	3,115	0	0	12,197	0	0	8,818
Apalachiocola North FL	1,509	196	0	902	0	0	0
Apalachicola South FL	6,875	375	0	1,813	500	22,000	3,375
Fort Walton FL	0	288	0	31,104	3,312	5,904	5,280
MISSISSIPPI DELTA							
Barataria Bay North LA	0	410	0	91	0	7,387	18,286
Barataria Bay South LA	0	0	0	0	0	20,040	0

COASTAL SITES USED IN MODEL (Continued)

SITE	MEAN Tide Range Ocn/Ild (ft)*	C	D	E	LOCATION N	LOCATION W	Total Area
MISSISSIPPI DELTA (cont)							
Central Is N LA	1.0/.25	4	1	1	29/37/30	90/52/30	32,500
Central Is S LA	1.0/.25	4	1	1	29/15/00	90/52/30	27,600
Atchafalaya North LA	1.0/.25 to to 1.5/0.5	4	1		29/52/30	91/37/30	33,600
Atchafalaya South LA	1.0/.25 to to 1.5/0.5	4	1		29/45/00	91/37/30	60,000
CHENIER PLAIN-TEXAS BARRIER IS							
Chenier Plain N TX	1.0/	3	2	1	29/52/30	94/22/30	31,200
Chenier Plain S TX	1.0/	3	2	1	29/45/00	94/22/30	60,000
Aransas NWR North TX	1.0/.25	5	2		28/22/30	97/00/00	37,500
Aransas NWR South TX	1.0/.25	5	2		28/15/00	97/00/00	62,500
TX Barrier Is.	1.0/ .5	5	2		26/30/00	97/22/30	80,000
CALIFORNIAN							
Imperial Beach CA	4.0/00	1		1/3	32/45/00	117/07/30	13,300
Del Mar CA	4.0/	1	1/2		33/07/30	117/22/30	27,500
Oxnard CA	4.0/	1			34/15/00	119/15/0	48,300
St. Ynes CA	4.0/	1	1		34/45/00	120/37/30	9,800
SF Bay N CA		3	1/3	1/3	38/15/00	122/07/30	82,500
SF Bay S CA	/3-5	3	1/3	1	37/37/30	122/15/00	80,000
COLUMBIAN							
Coos Bay OR	/5-6	5	2		43/30/00	124/22/30	42,000
Gray's Harbor WA	6-10/7	5	1		47/07/30	124/15/00	85,000
Puget Sound N	/5	3	3		48/37/30	122/37/30	45,000
Puget Sound S	/10	3	3		47/7/30	122/52/30	17,000

COASTAL SITES USED IN MODEL (Continued)

SITE	AREA (ha)								
	Marsh			Beach					
				Undeveloped		Developed		High	Tidal
	Fresh	Salt	Mangr.	Exp.	Shelt.	Exp.	Shelt.	Dunes	Fla
MISSISSIPPI DELTA (cont)									
Central Is N LA	23,790	1,300	0	0	0	0	0	0	0
Central Is S LA	18,106	110	304	0	0	0	0	0	0
Atchafalaya North LA	9,307	706	0	0	0	0	0	0	0
Atchafalaya South LA	33,600	4,500	0	0	0	0	0	0	0
CHENIER PLAIN-TEXAS BARRIER IS									
Chenier Plain N TX	811	0	0	0	0	0	0	0	0
Chenier Plain S TX	20,400	1,380	0	480	120	0	0	0	0
Aransas NWR North TX	600	300	0	0	113	0	0	0	0
Aransas NWR South TX	2,688	3,688	0	688	1,125	0	0	625	0
TX Barrier Is.	80	0	0	1,600	23,680	0	0	880	0
CALIFORNIAN									
Imperial Beach CA	106	0	0	0	904	0	106	0	0
Del Mar CA	193	0	0	0	0	0	0	0	303
Oxnard CA	290	97	0	0	0	0	0	483	97
St. Ynes CA	0	0	0	0	0	0	0	0	0
SF Bay N CA	3,630	19,965	0	0	413	0	0	0	0
SF Bay S CA	560	1,680	0	0	5,600	0	0	0	0
COLUMBIAN									
Coos Bay OR	0	210	0	504	2,184	0	210	1,806	0
Gray's Harbor WA	170	595	0	340	11,220	680	1,020	595	0
Puget Sound N	0	0	0	0	4,995	0	90	0	0
Puget Sound S	0	204	0	0	595	0	102	0	0

COASTAL SITES USED IN MODEL (Continued)

SITE	AREA (ha)						
	Lowland			Upland		Water	
		Developed					
	Undev.	Unpro.	Prot.	Undev.	Dev.	Shelt.	Open
MISSISSIPPI DELTA (cont)							
Central Is N LA	3,510	2,503	0	0	0	0	1,398
Central Is S LA	0	0	0	110	0	0	8,998
Atchafalaya North LA	13,003	2,688	16,13	3,091	504	2,688	0
Atchafalaya South LA	3,000	180	120	120	0	1,920	16,620
CHENIER PLAIN-TEXAS BARRIER IS							
Chenier Plain N TX	16,411	94	4,711	6,396	2,402	406	0
Chenier Plain S TX	12,000	0	4,200	600	0	1,500	19,320
Aransas NWR North TX	4,500	0	788	23,700	0	7,500	0
Aransas NWR South TX	18,125	188	813	4,313	0	21,375	8,875
TX Barrier Is.	19,200	160	2,080	3,520	0	20,000	8,720
CALIFORNIA							
Imperial Beach CA	904	1,503	106	3,298	1,995	2,594	1,796
Del Mar CA	303	193	0	13,008	2,695	0	10,808
Oxnard CA	1,497	1,594	290	29,511	918	0	13,524
St. Ynes CA	196	0	0	5,802	0	0	3,802
SF Bay N CA	4,125	1,403	5,775	32,918	1,403	12,870	0
SF Bay S CA	7,120	4,080	15,200	30,720	5,520	9,520	0
COLUMBIAN							
Coos Bay OR	1,386	294	210	20,286	2,520	1,680	10,710
Gray's Harbor WA	2,890	3,570	170	48,280	1,105	7,565	6,715
Puget Sound N	7,515	90	3,510	14,085	1,305	13,410	0
Puget Sound S	493	0	595	13,396	306	1,202	0

LEGEND FOR APPENDIX 4-A

ABBREVIATIONS:

N - North

S - South

Mangr - Mangrove

Dev - Developed

Undev - Undeveloped

Exp - Exposed

Shelt - Sheltered

Unprot = Unprotected

Prot = Protected

Ocn = Ocean

Ild = Inland

* Blanks indicate lack of ocean or inland tides

KEY:

C - Coastal Line Type

1. Steep
2. Low Slope, Terraced
3. Low Slope, Unterraced
4. Deltaic
5. Barrier Islands/Dunes

D = Wetland Types

1. Deltaic
2. Lagoonal
3. Estuarine

E = Engineering Structures

1. Levee
2. Seawall
3. Breakwater
4. Mosquito Ditches

APPENDIX 4-B

CHANGE IN WETLAND AREA (100 Ha) from 1975 to 2100 AT EACH STUDY SITE

Location	LOW		HIGH	
	Lost	Gained	Lost	Gained
NEW ENGLAND				
Maine Coast N	0	0	1	0
Maine Coast S	0	0	0	0
New Hampshire Coast	2	0	14	0
Mass. Coast	0	0	0	0
Cape Cod N	0	0	12	0
Cape Cod S	0	0	9	0
Narragansett RI	0	0	2	0
MID-ATLANTIC				
Long Island Sound CN	0	4	6	6
E. Hampton NY	1	5	2	5
Gardiner's Island NY	0	4	1	1
Long Island W NY	0	11	19	0
Atlantic City NJ	8	31	90	0
Tuckerton NJ	74	0	96	0
Delaware Bay DE	0	29	60	49
Cape Henlopen DE	18	0	50	0
Chesapeake E MD	1	0	1	0
Chesapeake W MD	2	3	2	0
Potomac River E VA	0	1	1	0
Potomac River W MD	6	0	6	0
Chincoteague VA	41	1	42	3
Delmarva VA	25	0	41	1
Chesapeake Bay S VA	1	0	1	0
SOUTH ATLANTIC				
Roanoke Island NC	48	0	48	2
Albemarle W NC	41	0	48	5
N Charleston SC	0	21	52	36
Charleston SC	116	65	172	87
Sapelo Sound GA	1	24	165	55
Matanzas FL	8	14	8	37
SOUTHERN FLORIDA				
Florida Keys	1	15	236	1
10,000 Is. FL	0	159	4	159
Cntrl. Barrier Coast FL	1	0	1	0
MISSISSIPPI DELTA				
Barataria Bay N LA	192	0	192	0
Barataria Bay S LA	400	0	400	0
Central Is. N LA	154	0	210	0
Central Is. S LA	185	0	185	0
Atchafalaya N LA	91	0	92	0
Atchatalaya S LA	381	0	381	0

CHANGE IN WETLAND AREA (Continued)

Location	LOW		HIGH	
	Lost	Gained	Lost	Gained
CHENIER PLAIN—TEXAS BARRIER ISLAND				
Chenier Plain N TX	3	14	5	32
Chenier Plain S TX	34	52	132	18
Aransas NWR N TX	8	2	5	15
Aransas NWR S TX	63	0	63	0
TX Barrier Is.	1	0	1	0
CALIFORNIA				
Imperial Beach CA	0	0	0	0
Del Mar CA	0	0	2	0
Oxnard CA	1	0	2	0
St. Ynez CA	0	0	0	0
SF Bay N CA	89	25	85	31
SF Bay S CA	1	64	6	71
COLUMBIA				
Coos Bay OR	0	5	2	3
Gray's Harbor WA	1	23	1	25
Puget Sound N WA	0	82	0	90
Puget Sound S WA	0	6	0	6

APPENDIX 4-C

HOW TO USE THE SLAMM COMPUTER PROGRAM

The IBM PC-executable code is SLAMM.COM, so the model is called by entering "SLAMM" in response to the system prompt. The model responds with SIMULATION OPTIONS, which provides defaults for the few parameters required by the model (Figure 4-C-1). In order to change a parameter, the user types the first letter of the desired choice, and then picks the appropriate first letter from among the choices provided. Because we want to use the defaults, we type "C" to continue; "Q" is used to quit the model. The next screen provides OUTPUT OPTIONS with defaults (Figure 4-C-2). We type "T" to change the time step for plotting maps; then we enter "50" in order to increase the interval from 25 years (the default) to 50 years. (The model actually plots those years divisible by the specified number without a remainder; so to plot only the year 2050 in addition to the initial and final years, which are always plotted, the user types "2050.") We also type "P" to plot the input data on the screen so that it can be edited.

FIGURE 4-C-1

OPTIONS AVAILABLE FOR SLAMM SIMULATIONS

```
                    SIMULATION OPTIONS

Initial year = 1975
Last year = 2100
Rate of sea level rise = High (2.166 m by 2100)
Subsidence rate for region = 1.20 mm/yr
Decrease sediment with engineering projects on rivers = TRUE
Protect developed areas = TRUE
Waves from the east
Continue
Quit
```

FIGURE 4-C-2

OPTIONS AVAILABLE FOR SLAMM OUTPUT

```
                    OUTPUT OPTIONS

Dump input data to printer = FALSE
Plot input data on screen = FALSE
Legend = FALSE
Automatically print maps = TRUE
Time step for plotting map = 25.0
Summarize output = TRUE
Continue
```

The model will then request the name of the input data file. Files having the default extension ".DAT" are those that have been prepared and saved by SLAMM; other extensions, such as ".PRT" for files prepared by Lotus 123, must be given by the user. We enter "NJTUCKER" to use the file that has already been edited for Tuckerton, New Jersey, on the default disk drive.

The legend is then plotted on the screen (Figure 4-C-3). It will remain until a key is pressed. If a hard copy is desired, the IBM PrtSc key should be used; remember that GRAPHICS or another screen dump program must have been invoked before calling SLAMM if graphics are to be sent to the printer. The data in the specified file are then plotted on the screen (Figure 4-C-4). The coordinates are used in editing the data and should be noted by the user. The screen is exited by pressing any key, such as the space bar. If the user chooses to edit the data, the X and Y coordinates must be entered (Figure 4-C-5).

FIGURE 4-C-3
KEY TO SYMBOLS FOR CATEGORIES USED IN SLAMM SIMULATIONS

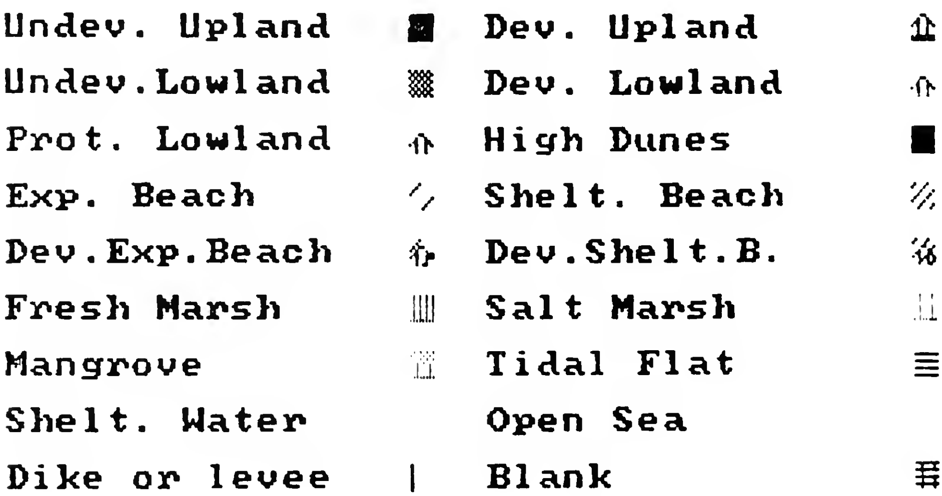


FIGURE 4-C-4

SIMULATION MAP SHOWING RAW DATA FOR TUCKERTON, N.J.

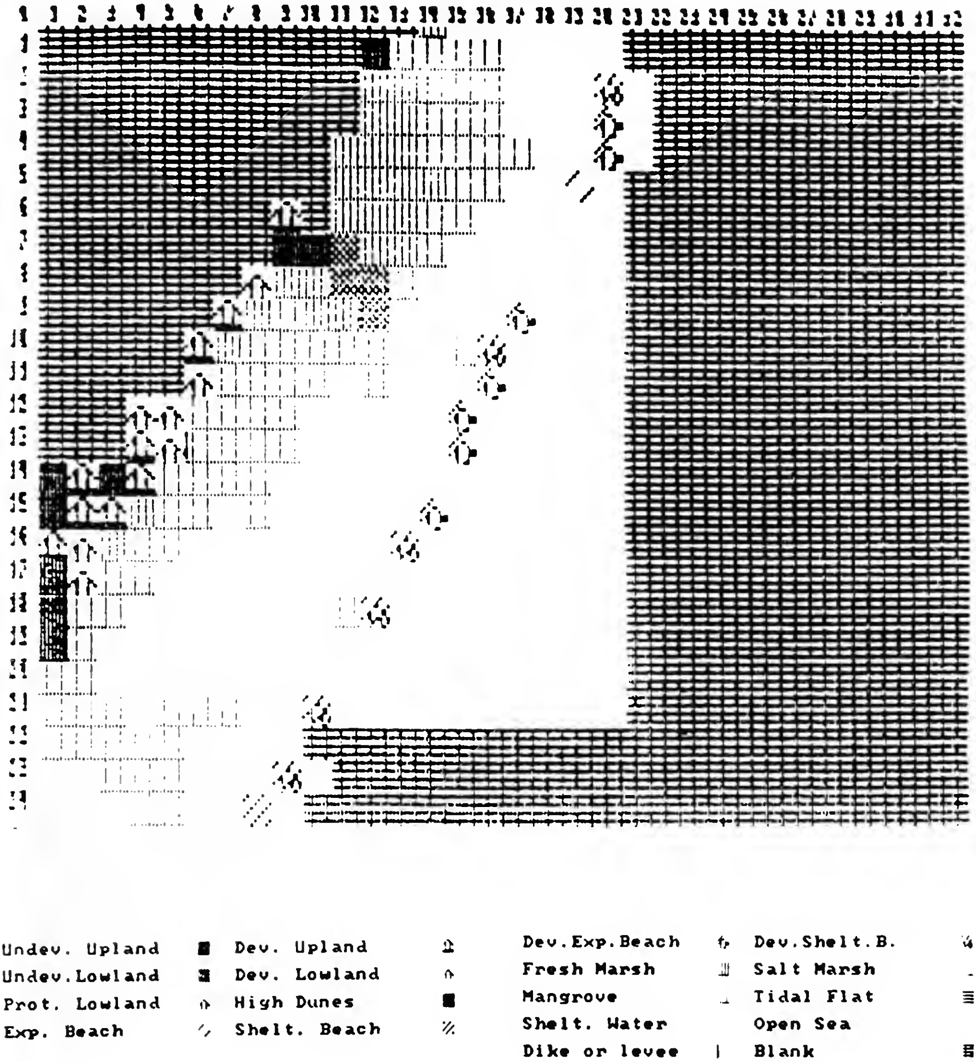


FIGURE 4-C-5

INITIAL DISPLAY FOR EDITING CELLS IN SLAMM SIMULATIONS

Do you wish to edit ? (Y/N) Y
X coordinate:
9

Y coordinate:
23

In editing the data, the characteristics of the indicated cell are displayed along with EDIT OPTIONS (Figure 4-C-6). The user then chooses the desired option, such as "D" to change the dominant category. We then choose "9" to change the cell from Developed Sheltered Beach to Developed Exposed Beach (Figure 4-C-7). Other changes may be made until the user types "C" to continue (Figure 4-C-8), at which time the map is again displayed.

FIGURE 4-C-6
OPTIONS FOR EDITING RAW DATA BEFORE SIMULATING SEA LEVEL RISE

```
9.23. Dev.Shelt.B. Elev. = 1.00
Protected by dike or levee = FALSE Developed = TRUE

              EDIT OPTIONS

Dominant cell category
Average elevation
Protected by dike or levee
Residential or commercial development
Edit another cell (without plotting)
Continue
```

FIGURE 4-C-7
CELL CATEGORIES AVAILABLE FOR EDITING RAW DATA USED IN SLAMM

```
Residential or commercial development
Edit another cell (without plotting)
Continue

Cell categories
 1  Undev. Upland
 2  Dev. Upland
 3  Undev. Lowland
 4  Dev. Lowland
 5  Prot. Lowland
 6  High Dunes
 7  Exp. Beach
 8  Shelt. Beach
 9  Dev. Exp. Beach
10  Dev. Shelt. B
11  Fresh Marsh
12  Salt Marsh
13  Mangrove
14  Tidal Flat
15  Shelt. Water
16  Open Sea

Choose number:
9
```

FIGURE 4-C-8
DISPLAY AFTER EDITING DOMINANT CELL CATEGORY AND EDIT OPTIONS

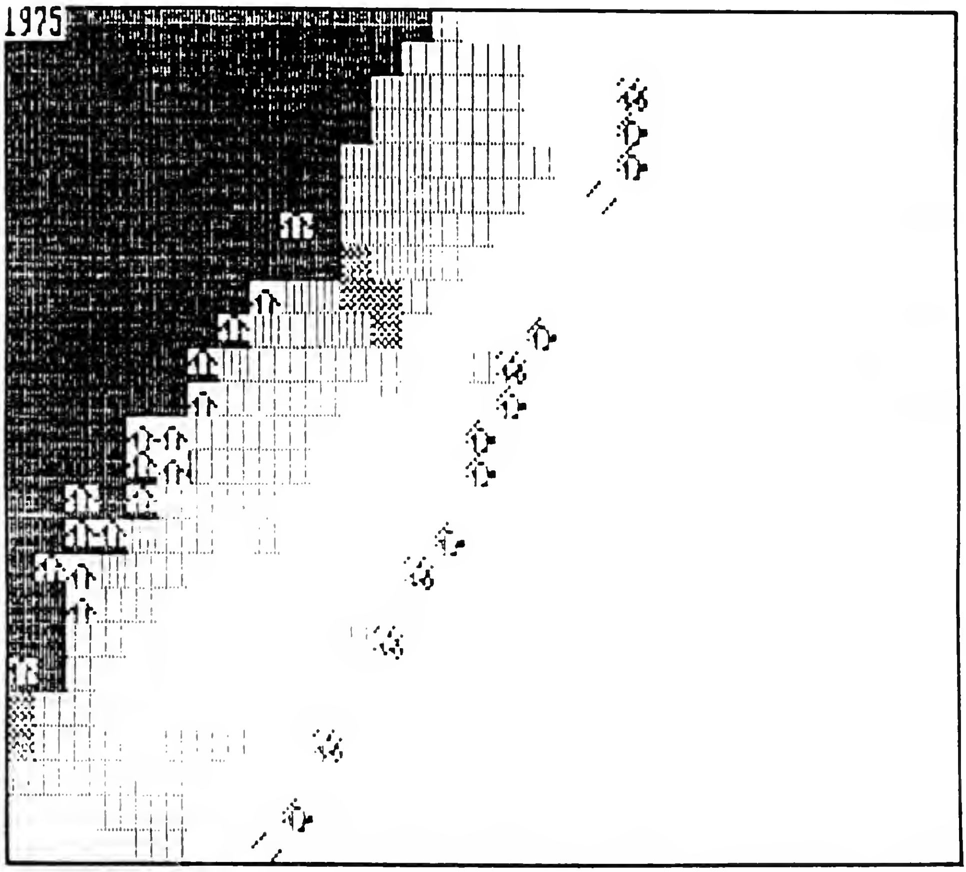
```
9.23. Dev.Shelt.B. Elev. = 1.00
Protected by dike or levee = FALSE
Developed = TRUE

              EDIT OPTIONS

Dominant cell category
Average elevation
Protected by dike or levee
Residential or commercial development
Edit another cell (without plotting)
Continue
```

When finished with editing and displaying the updated map, the user is given the opportunity to save the data under the same file name or under a new name. We will press the return key because we do not wish to save the change permanently. The model seems to pause for a few seconds while it converts the blank cells to water, lowland, or upland, depending on the categories of the adjacent cells. A summary of the initial conditions is then printed. Note: it is assumed that a printer using Epson/IBM printer protocol is connected and ready to receive output.

The next display is a map of the categories at the initial time step (Figure 4-C-9). However, it may differ from the input data if there were conflicts between the categories and the other characteristics for any of the cells. To ensure that the initial conditions are consistent for the site, SLAMM applies all the transfer algorithms at the beginning of the simulation before incrementing sea level. For example, the beach cell south of cell A was converted from sheltered beach to exposed beach because it is adjacent to open sea. The conditions and distribution of

FIGURE 4-C-9

SIMULATION MAP OF TUCKERTON, N.J., AT INITIAL TIME STEP



the categories are again summarized (Figure 4-C-10). The conditions include the present sea level with respect to the initial datum, the instantaneous rate of sea level rise, the subsidence rate (which is constant for a simulation), and the marsh accretion and subtidal sedimentation rates (which may vary as the percentage of wetlands varies).

FIGURE 4-C-10

INITIAL CONDITIONS AND ABUNDANCE OF EACH LAND CATEGORY AT TUCKERTON, N.J.

```
1975 File: NJTUCKER
Mean sea level = 0.00 m
Rate of sea level rise = 0.00 mm/yr
Subsidence rate for region = 1.20 mm/yr
Accretion rate for wetlands = 0.00 mm/yr
Sedimentation rate for subtidal areas = 0.00 mm/yr
Decrease sediment with engineering projects on rivers = TRUE
Protect developed areas = TRUE
Waves from the east
Undev. Upland  14.0%
Dev. Upland     1.0%
Undev. Lowland  0.6%
Dev. Lowland    0.7%
Prot. Lowland   0.0%
High Dunes      0.0%
Exp. Beach      0.1%
Shelt. Beach    0.1%
Dev. Exp. Beach 0.7%
Dev. Shelt. B   0.6%
Fresh Marsh     2.5%
Salt Marsh      7.4%
Mangrove        0.0%
Tidal Flat      0.0%
Shelt. Water   27.4%
Open Sea       44.9%
```

Regardless of the interval chosen for plotting the map output, summary output is provided on the printer at a 25-year interval. The next screen display is of the updated map following the chosen interval, in this case 50 years (Figure 4-C-11). Note that all the freshwater marsh has been converted to salt marsh but that no wetland has yet been lost. The cell just west of cell B has been converted from upland to lowland, and several of the lowland cells have been converted to tidal flat.

Again, summary output is sent to the printer, and the next updated map is plotted, in this case for the year 2100 (Figure 4-C-12). Regardless of plotting interval, the final map is plotted so that the user can see the terminal conditions in graphic form. Unlike the intermediate maps, which remain only as long as required to print and to compute new conditions, the final map remains on the screen until a key is pressed.

FIGURE 4-C-11

TUCKERTON, N.J., IN THE YEAR 2050 WITH HIGH SEA LEVEL RISE.

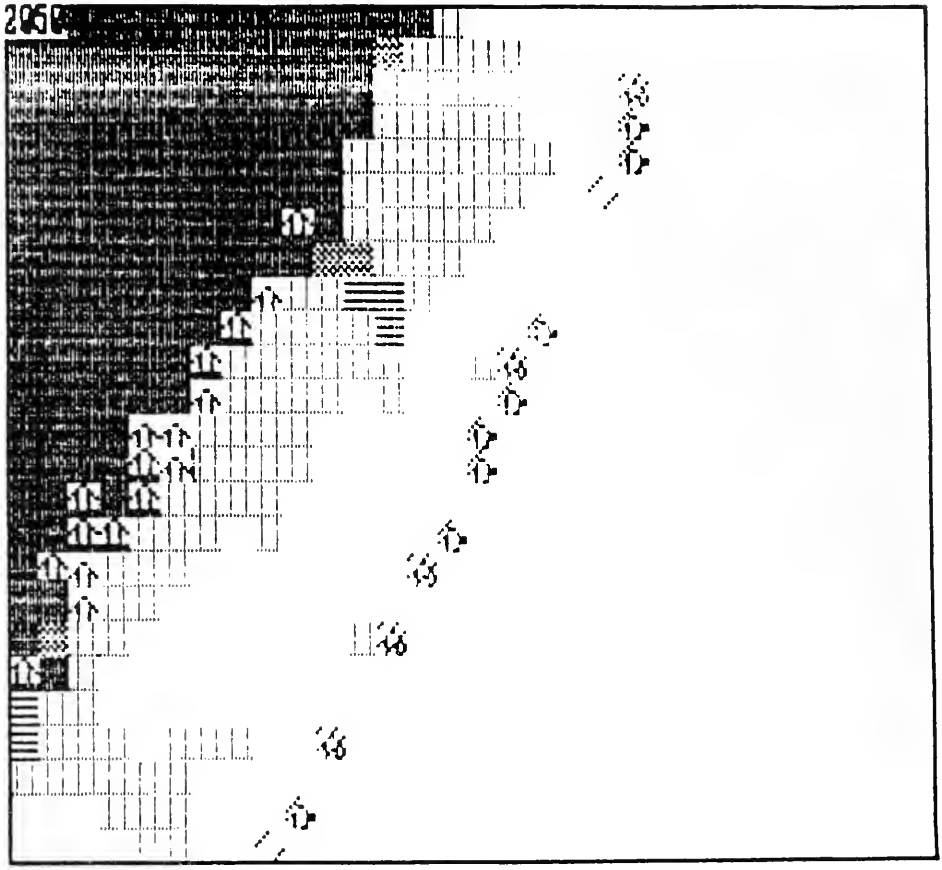
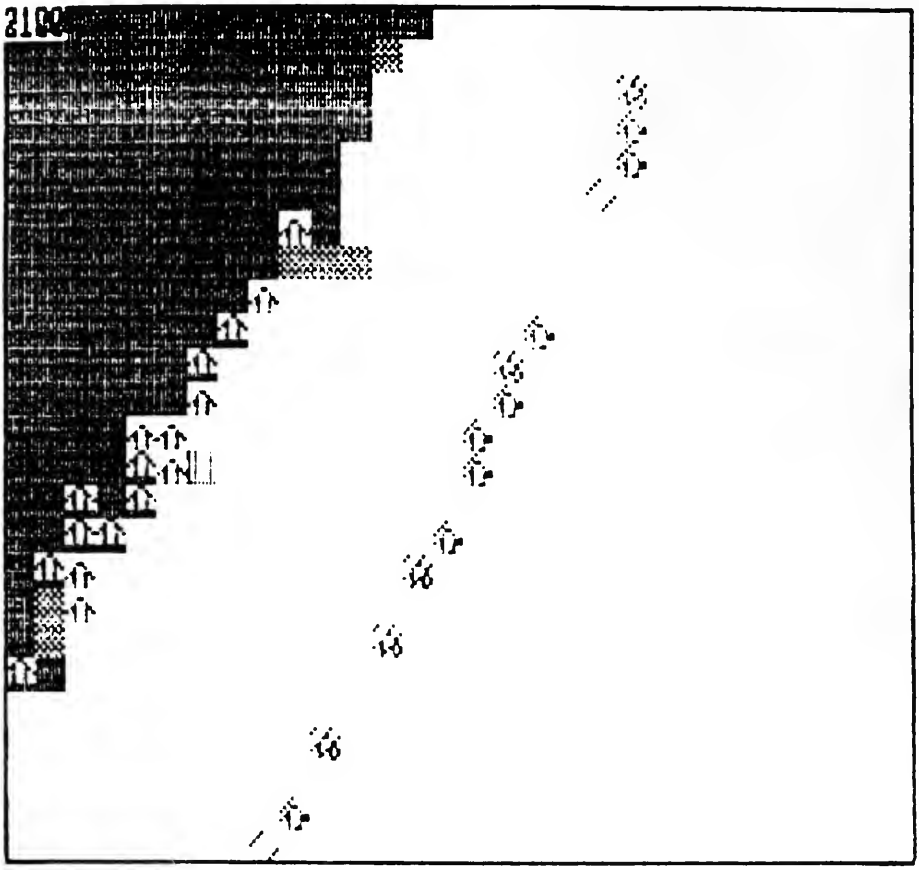


FIGURE 4-C-12

TUCKERTON, N.J., AT END OF SIMULATION (YEAR 2100) WITH HIGH SEA LEVEL RISE, PROTECTION OF DEVELOPED AREAS, AND SUBSIDENCE EQUAL TO 1.2 MM/YR.



Finally, a summary table of percent changes in wetland areas at 5-year intervals is printed (Table 4-C-1). Types of wetlands are not differentiated in the summary because the model should not be used to interpret detailed changes between freshwater and saltwater types (see Assumptions). In this example only 1% of the original wetlands remains by the year 2085, with most of the loss occurring between 2055 and 2060. The lack of lowland areas precludes new wetlands, and thus the column showing hectares gained is uniformly 0; however, in other areas this column would help indicate possible wetland migration, which could then be accepted or discounted in the interpretation of the results.

TABLE 4-C-1

SUMMARY OF CHANGES IN WETLAND AREA FOR TUCKERTON, N.J., UNDER THE HIGH SCENARIO

	Hectares	Percent	HA Lost	HA Gained
1975	9900	9.9	0	0
1980	9900	9.9	0	0
1985	9900	9.9	0	0
1990	9900	9.9	0	0
1995	9900	9.9	0	0
2000	9900	9.9	0	0
2005	9900	9.9	0	0
2010	9900	9.9	0	0
2015	9900	9.9	0	0
2020	9900	9.9	0	0
2025	9900	9.9	0	0
2030	9900	9.9	0	0
2035	9900	9.9	0	0
2040	9900	9.9	0	0
2045	9900	9.9	0	0
2050	9900	9.9	0	0
2055	9900	9.9	0	0
2060	2600	2.6	7300	0
2065	2600	2.6	0	0
2070	2500	2.5	100	0
2075	2500	2.5	0	0
2080	100	0.1	2400	0
2085	100	0.1	0	0
2090	100	0.1	0	0
2095	100	0.1	0	0
2100	100	0.1	0	0