United States
Environmental Protection
Agency

Office of Policy
Planning and Evaluation
Washington, DC 20460

May 1986
EPA 230-10-85-014

EPA

Potential Impacts of Sea Level Rise On Wetlands Around Charleston, South Carolina

Library of Congress Cataloging-in-Publication Data
Kana, Timothy W., 1949-
Potential impacts of sea level rise on wetlands
around Charleston, South Carolina.

Bibliography: p.
1. Wetland conservation--South Carolina--Charleston.
2. Wetlands--South Carolina--Charleston. 3. Sea Level--
South Carolina--Charleston. 4. Greenhouse effect, Atmospheric.
I. Baca, Bart J. II. Willliams, Mark L. III. Title.
QH76.5.S67K36 1986 333.91'815'09757915 86-29309

POTENTIAL IMPACTS OF SEA LEVEL RISE ON WETLANDS AROUND CHARLESTON, SOUTH CAROLINA

Prepared by
Timothy W. Kana, Bart J. Baca
and Mark L. Williams

Coastal Science & Engineering, Inc.
P.O. Box 8056
Columbia, South Carolina 29202

This document has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use. Please send comments to James G. Titus (PM-220), Strategic Studies Staff, U.S. Environmental Protection Agency, Washington, D.C. 20460.

SUMMARY

Recent reports by the National Academy of Sciences (NAS) and others have concluded that increasing concentrations of carbon dioxide and other gases released by human activities are likely to warm the earth a few degrees Celsius in the next century. Such a warming could raise sea level by expanding ocean water, melting mountain glaciers, and eventually causing polar glaciers to slide into the oceans. Unfortunately, it is not yet possible to accurately predict future sea level. Estimates for the year 2025 range from five to twenty-one inches above current sea level, while estimates of the rise by 2100 range from two to eleven feet. While the timing and magnitude of the future rise in sea level is uncertain, there is an emerging scientific consensus that a significant rise is likely.

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

These decisions also require an understanding of the consequences of sea level rise and of the potential costs and benefits of adopting measures that can forestall those consequences. To further this understanding, EPA has initiated studies of the impacts of sea level rise on economic development in Charleston, South Carolina, and Galveston, Texas; on municipal drainage facilities; on salinity of surface and ground water; and on beach erosion on coastal barrier islands.

This study examines the potential impact of alternative sea level rise scenarios on wetlands in the area of Charleston, South Carolina. Because economic development in coastal areas can have long-term impacts on the viability of wetland ecosystems, and because sea level rise would cause these ecosystems to migrate inland, wetland protection strategies constitute a class of decisions that may depend on sea level rise. The purpose of this report is to enhance our knowledge of the possible impacts of the rise in sea level projected by previous reports. Because of the uncertainty associated with these forecasts, additional analysis will be needed to determine what changes in existing wetland protection strategies, if any, may be appropriate.

In this report, a team of wetland scientists describes surveys of twelve wetland transects in the Charleston area and presents estimates of the ability of these wetlands to keep pace with rising sea level. Also presented are estimates of the shifts in wetland communities and of the net loss of marsh acreage associated with three possible scenarios of sea level rise for the year 2075, all of which are well within the range of estimates reported in previous studies: (1) current trends of 1 foot per century along the Atlantic Coast; (2) the NAS estimate of a 2-1/3 foot global rise in sea level; and (3) a high scenario of a 4-1/2 foot global rise. Because sea level is rising about 8 inches per century more rapidly along the Atlantic coast than worldwide, these scenarios imply rises of 2.9 and 5.2 feet, respectively, by 2075 in the Charleston area.

CONCLUSIONS

1. Sea level rise could become a significant cause of wetland loss in the Charleston area. If current trends continue for the next century, economic development will destroy less than 0.5 percent of the area's wetlands, and those losses would be more than offset by natural creation of wetlands. Projected sea level rise, however, could result in the loss of between 50 and 90 percent of the area's marsh in the next century.

2. The National Academy of Sciences' estimate of sea level rise (2.9 feet) implies that Charleston could lose 50 percent of its marsh by 2075. The area of high marsh would decline from 2300 to 700 acres, while the area of low marsh would decline from 5400 to 3200 acres.

3. The high scenario (5.2 feet) implies that Charleston could lose 80 percent of its marsh by 2075 if human activities do not interfere. As with the NAS estimate, the high marsh would decline from 2300 to 700 acres; low marsh, however, would decline from 5400 to 900 acres.

4. The impact of sea level rise on coastal wetlands will ultimately depend on whether developed areas immediately inland of the marsh are protected from rising sea level by levees and bulkheads. The above estimates are based on the assumption that new wetlands will be created as inland areas are flooded. However, new wetlands can only be created if areas just inland of the marsh are undeveloped. If these areas are developed and protected with levees and bulkheads as the sea rises, no additional wetlands will be created; thus, the net loss will be greater. The high scenario (5.2 feet) would imply a loss of all high marsh and all but 750 acres of low marsh. Because development in the Charleston area is generally at least three feet above the high marsh, constructing these barriers would not increase the loss of marsh by 2075 for the NAS scenario (2.9 feet), although some transition wetlands would be lost.

5. Factors not considered in this report could increase or decrease the vulnerability of wetlands to a rise in sea level. The estimates in this report are based on the assumptions that the rate of vertical marsh growth and the shape and position of marsh profiles remain unchanged. More extensive study could improve upon these assumptions and take into account such factors as impacts of global warming on peat formation, reworking of sediment, and oxidation of peat due to marsh drowning.

6. Other communities with similar types of marsh can obtain inexpensive first-order estimates of future wetland loss. The data in this report, along with information on tidal ranges, can be used by those who need only a rough indication of the vulnerability of wetlands to rising sea level.

7. Assessments should be undertaken of how to mitigate loss of wetlands from sea level rise. Although the most substantial losses of wetlands are at least 50 years away, today's coastal development may largely determine the success with which wetlands adjust to rising sea level in the future.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to several people who provided assistance to this study.

The research was completed with the assistance of several people at Coastal Science and Engineering, Inc., including S. Jonathan Siah, who prepared the tide probability analysis; Bill Eiser, Mark Jordana, and Mike Bise, who assisted in the field; and Tom Ballouy, who helped identify the marsh species. Graphics for the report were prepared under the supervision of Starnell Perez with the assistance of Jerry Cole, Steve Loy, Harriet Gilkerson, and Cindi Fehrs.

Report production services were provided by staff at EPA, RPI, Inc., and ICF Incorporated: Joan O'Callaghan of EPA and Susan MacMillan of ICF provided editing contributions; and finally, the manuscript was prepared by Diana Sangster of RPI and Margo Brown of ICF Incorporated.

Discussions with Miles O. Hayes, President of RPI, Inc., were beneficial to the authors in preparing this report. David Flemer, Alan Hirsch, Howard Marshall, and Gregory Peck of the Environmental Protection Agency reviewed the draft and provided substantive comments. Carroll Cordes and Edward Pendleton of the U.S. Fish and Wildlife Service's National Coastal Ecosystems Team and Joy Zedler of San Diego State University also made useful suggestions. Finally, James G. Titus of EPA provided overall guidance for the study and wrote portions of the final report.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Increasing atmospheric concentrations of carbon dioxide, methane, and other "greenhouse" gases are expected to raise the earth's average temperature a few degrees centigrade in the next century. Such a warming could cause sea level to rise a few feet by expanding ocean waters, melting mountain glaciers, and perhaps causing polar glaciers to melt or slide into the oceans. Because most coastal wetlands are within a few feet of mean sea level, a rise in water levels could cause a major loss of these ecosystems.

This study examines the potential impact of future sea level rise on coastal wetlands in the area of Charleston, South Carolina, for the year 2075. The report builds upon previous EPA studies that had assessed the potential physical and economic impacts of sea level rise on the Charleston area. We surveyed twelve wetland transects to determine elevations of particular parts of the marsh, frequency of flooding, and vegetation at various elevations. From these transects, we developed a composite transect representing an average profile of the area. Using this information and estimates of the sediment provided by nearby rivers, we then estimated the shifts in wetland communities and net loss of marsh acreage associated with three possible scenarios of sea level rise for the year 2075: (1) the current trend, which implies a rise of 24 cm (0.8 ft); (2) the National Academy of Sciences estimate, which implies a rise of 87 cm (2.9 ft); and (3) a high scenario rise of 159 cm (5.2 ft).

This report presents background information concerning global warming and future sea level rise, the ecological balance of coastal wetlands; and the potential transformation of these ecosystems as sea level rises. Next, it examines the wetlands in the Charleston study area and describes a field study in which we developed wetland transects. Finally, it discusses the potential impact of future sea level rise on Charleston's wetlands, and suggests ways to improve our ability to predict the impact of sea level rise on other coastal wetlands.

FUTURE SEA LEVEL RISE AND ITS IMPLICATIONS

Global Warming and a Rising Sea

A planet's temperature is determined by the amount of sunlight it receives, the amount of sunlight it reflects, and the extent to which its atmosphere retains heat. When sunlight strikes the earth, it warms the surface, which then radiates the heat as infrared radiation. However, water vapor, carbon dioxide, and other gases in the atmosphere absorb some of the energy, rather than allowing it to pass undeterred through the atmosphere to space. Because the atmosphere traps heat and warms the earth in a manner somewhat analogous to the glass panels of a greenhouse, this phenomenon is generally known as the "greenhouse effect."

Since the industrial revolution, the combustion of fossil fuels, deforestation, and cement manufacture have released enough CO_2 into the atmosphere to raise CO_2 concentrations by 20 percent (Keeling, Bacastow, and Whorf 1982). Review panels of the National Academy of Sciences have concluded that a doubling of atmospheric CO_2 expected in the next century, would warm the earth 1.5°-4.5°C (3°-8°F). Increasing concentrations of methane, chlorofluorocarbons, nitrous oxide, and other trace gases could roughly double the warming from CO_2 alone (Lacis et al. 1981; Ramanathan et al. 1985).

A global warming of a few degrees could be expected to raise sea level for several reasons. Increasing atmospheric temperatures would cause seawater to warm and expand. Mountain glaciers, which have retreated in the last century, could melt more rapidly. Glaciers in Antarctica and Greenland could melt along the fringes, and portions of them could slide into the oceans. Although a complete disintegration of the West Antarctic Ice Sheet would raise sea level six meters, it is unlikely to occur in the next century (Meier et al. 1985).

In 1983, two independent reports estimated sea level rise in the next century. The National Academy of Sciences report Changing Climate estimates that worldwide sea level will rise 70 cm (2-1/3 ft) in the next century, ignoring the impact of the global warming on Antarctica (Revelle 1983). The Environmental Protection Agency report Projecting Future Sea Level Rise states that the uncertainties regarding the factors that could influence sea level rise are so numerous that a single estimate of sea level rise is impossible (Hoffman, Keyes, and Titus, 1983). Instead, it specified high and low estimates for all the factors that could influence sea level and estimates resulting high, medium, and low scenarios. As Table 1 shows, the EPA report estimates that sea level will rise between 38 and 212 cm by 2075, with the likely range falling between 91 and 136 cm (3 and 5 ft), compared with a global rise of 10 to 15 cm (4 to 6 in) in the last century. Because most of the coast is subsiding, sea level rise along the Atlantic coast has been 15 to 20 cm per century higher than the worldwide average; this subsidence trend is expected to continue into the future.

Ecological Balance of Wetlands

Recent attention concerning rising sea level has been focused on the fate of economic development in coastal areas. However, the area facing the most

TABLE 1

SCENARIOS OF FUTURE SEA LEVEL RISE: 1980-2100
(centimeters)

	2000	2025	2050	2075	2080	2100
Current Trends in Sea Level Rise						
Global	2.0-3.0	4.5-6.8	7.0-10.5	9.5-14.3	10-15	12.0-18.0
East Coast	6	13.5	21	28.5	30	36
EPA Scenarios - (Global Sea Level Rise)						
High	17.1	54.9	116.7	211.5	-	345.0
Mid-range high	13.2	39.3	78.9	136.8	-	216.6
Mid-range low	8.8	26.2	52.6	91.2	-	144.4
Low	4.8	13.0	23.0	38.0	-	56.2
NAS Estimate (Global Sea Level Rise--excluding Antarctic contribution)	-	-	-	-	70.0	-

SOURCES: (1) John S. Hoffman, D. Keyes, and J.G. Titus, Projecting Future Sea Level Rise, U.S. EPA, 1983; (2) R. Revelle, "Probable Future Change in Sea Level Resulting from Increased Atmospheric Carbon Dioxide," in Changing Climate, Washington, D.C.: National Academy Press, 1983; (3) Hicks, S.D., H.A. DeBaugh, and L.E. Hickman, Sea Level Variations for the United States 1855-1980, Rockville, Maryland: National Ocean Service, 1983.

immediate consequences would be intertidal wetlands. Lying between the sea and the land, this zone will experience the direct effects of changing sea levels, tidal inundation, and storm surges.

The intertidal wetlands contain productive habitats, including marshes, tidal flats, and beaches, which are essential to estuarine food webs. The distribution of the wetlands is sensitively balanced for existing tidal conditions, wave energy, daily flooding duration, sedimentation rates (and types), and climate. Their elevation in relation to mean sea level is critical to determining the boundaries of a habitat and the plants within it, because elevation affects the frequency, depth, and duration of flooding and soil salinity. For example, some marsh plants require frequent (daily) flooding, while others adapt to irregular or infrequent flooding (Teal 1958). Along the U.S. East Coast, the terms "low marsh" and "high marsh" are often used to distinguish between zones (Teal 1958; Odum and Fanning 1973) that are flooded at least daily and zones flooded less than daily but at least every 15 days. Areas flooded monthly or less are known as transition wetlands.

Regularly flooded marsh in the southeast United States is dominated by stands of smooth cordgrass (Spartina alterniflora), which may at first appear to lack zoning. However, work by Teal (1958), Valiela, Teal, and Deuser (1978), and others indicates total biomass varies considerably within the low marsh, ranging from zones of tall S. alterniflora along active creek banks to stunted or short S. alterniflora stands away from creeks and drainage channels. The tall S. alterniflora may be caused by a combination of factors, including more nutrients, a higher tolerance for the reductions in oxygen that result from subtle increases in elevation along levees (DeLaune, Smith, and Patrick, 1983); and differences in drainage created by variations in the porosity of sediment. The zone where S. alterniflora grows is thought by many to be limited in elevation to mean high water. This is probably too broad a simplification according to Redfield (1972), who emphasized that the upper boundary of the low marsh is, at best, indistinct.

High marsh, in contrast, consists of a variety of species. These include Salicornia spp. (glassworts), Distichlis spicata (spikegrass), Juncus spp. (black needlerush), Spartina patens (salt-marsh hay), and Borrichia *frutescens* (sea ox-eye). Teal (1958) reports that *Juncus* marsh tends to be found at a slightly higher elevation than the *Salicornia/Distichlis* marsh.

The high marsh can also be distinguished from low marsh on the basis of sediment type, compaction, and water content. High-marsh substrate tends to be firmer and dryer and to have a higher sand content. Low-marsh substrate seldom has more than 10 percent sand (except where barrier-island washover deposits introduce an "artificial" supply) and is often composed of very soft mud. Infrequent flooding, prolonged drying conditions, and irregular rainfall within the high marsh also produce wide variations in salinity. In some cases, salt pannes form, creating barren zones. But at the other extreme, frequent freshwater runoff may allow less salt-tolerant species, such as cattails, to flourish close to the salt-tolerant vegetation. These factors contribute to species diversity in the transition zone that lies between *S. alterniflora* and terrestrial vegetation.

By most reports, low marsh dominates the intertidal areas along the southeast (Turner 1976), but the exact breakdown can vary considerably from place to place. Wilson (1962) reported *S. alterniflora* composes up to 28 percent of the marsh in North Carolina, whereas Gallagher, Reimold, and Thompson (1972) report for one estuary in Georgia that the same species covers 94 percent of the "marsh" area. Low marsh is thought by many to have a substantially higher rate of primary productivity than high marsh (Turner 1976). Data presented in Odum and Fanning (1973) for Georgia marshes support this notion. However, Nixon (1982) presents data for New England marshes that indicate above-ground biomass production in high marshes comparable to that of low marshes. Some data from Gulf Coast marshes also support this view (Pendleton 1984).

Potential Transformation of Wetlands

The late Holocene (last several thousand years) trend has been one of gradual infilling and loss of water areas (Schubel 1972). During the past century, however, sedimentation and peat formation have kept pace with rising sea level over much of the East Coast (e.g., Ward and Domeracki 1978; Duc 1981; Boesch et al. 1983). Thus, apart from the filling necessary to build the city of Charleston, the zonation of wetland habitats has remained fairly constant. Changes in the rate of sea level rise or sedimentation, however, would disrupt the present ecological balance.

If sediment is deposited more rapidly, low marsh will flood less frequently and become high marsh or upper transition wetlands, which seems to be occurring at the mouths of some estuaries where sediment is plentiful. The subtropical climate of the southeastern United States produces high weathering rates, which provide large fluxes of sediment to the coastal area. Excess supplies of sediment trapped in estuaries have virtually buried wetlands around portions of the Chesapeake, such as the Gunpowder River, where a colonial port is now landlocked.

If sea level rises more rapidly in the future, increased flooding may cause marginal zones close to present low tide to be under water too long each day to allow marshes to flourish. To maintain the distribution of their habitats, wetlands must shift along the coastal profile--moving upward, to keep pace with rising sea levels (unless sedimentation rates are high). Total marsh acreage can only remain constant if slopes and substrate are uniform above and below the wetlands, and inundation is unimpeded by human activities such as the construction of bulkheads. Titus, Henderson, and Teal (1984), however, point out that there is generally less land immediately above wetland elevation than at wetland elevation. Therefore, significant changes in the habitats and a reduction in the area they cover will generally occur with accelerated sea level rise. Moreover, increasing development along the coast is likely to block much of the natural adjustment in some areas.

Louisiana is an extreme example. Human interference with natural sediment processes and relative sea level rise are resulting in the drowning of 100 sq km of wetlands every year (Gagliano, Meyer Arendt, and Wicker 1981; Nummedal 1982). There is virtually no ground to which the wetlands can migrate. Thus, wetlands are converting to open water; high-marsh zones are being replaced by low marsh, or tidal flats; and saltwater intrusion is converting freshwater swamps and marsh to brackish marsh and open water.

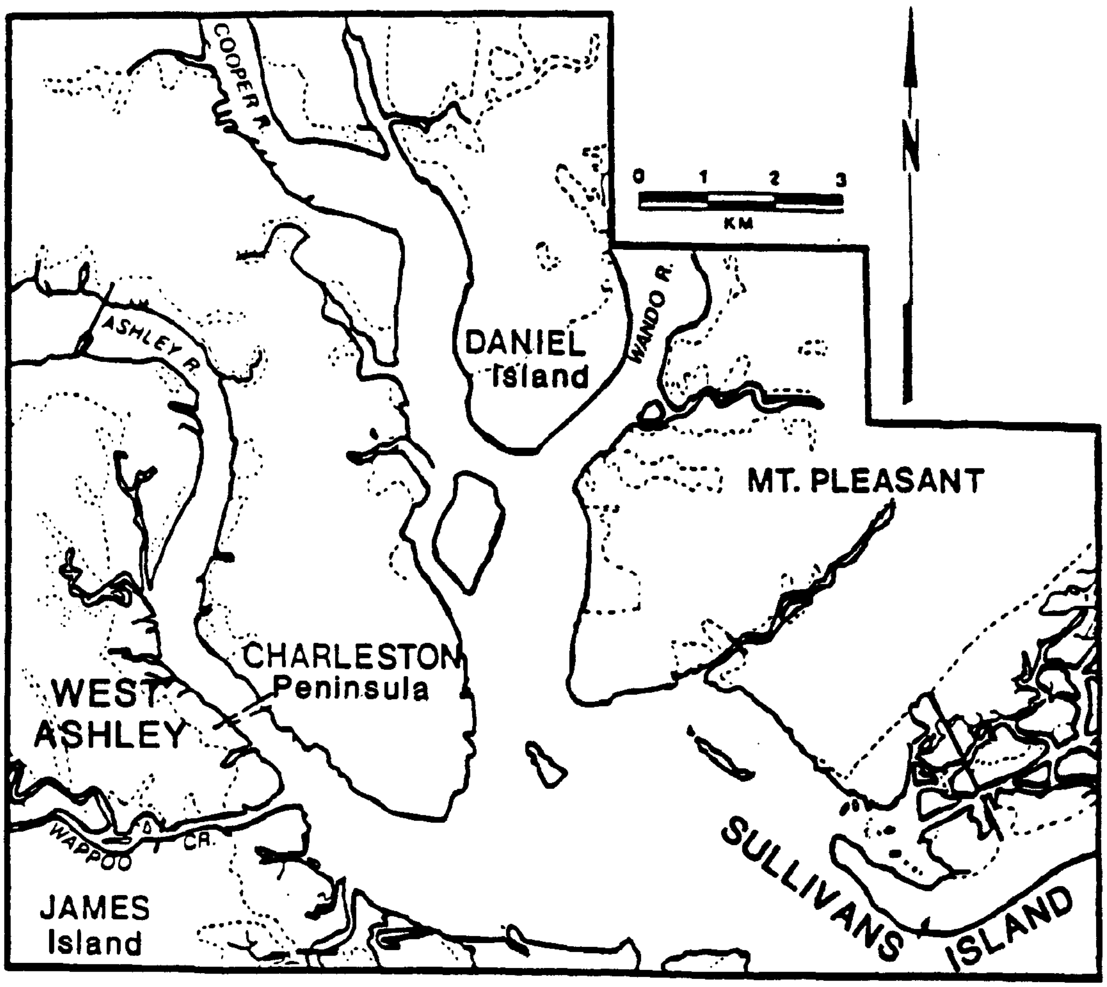
COASTAL HABITATS OF THE CHARLESTON STUDY AREA

As shown in Figure 1, the case study area, stretching across 45,500 acres, is separated by the three major tidal rivers that converge at the port city: the Ashley, Cooper, and Wando Rivers. In addition, it covers five land areas:

- West Ashley, which is primarily a low-density residential area with expansive boundary marsh;
- Charleston Peninsula, which contains the bulkheaded historic district built partly on landfill;
- Daniel Island, which is an artificially embanked dredge spoil island;
- Mount Pleasant, which derives geologically from ancient barrier island deposits oriented parallel to the coast; and
- Sullivans Island, which is an accreting barrier island at the harbor entrance.

FIGURE 1

CHARLESTON STUDY AREA



Six discrete habitats are found in the Charleston area, distinguished by their elevation in relation to sea level and, thus, by how often they are flooded (Figure 2):

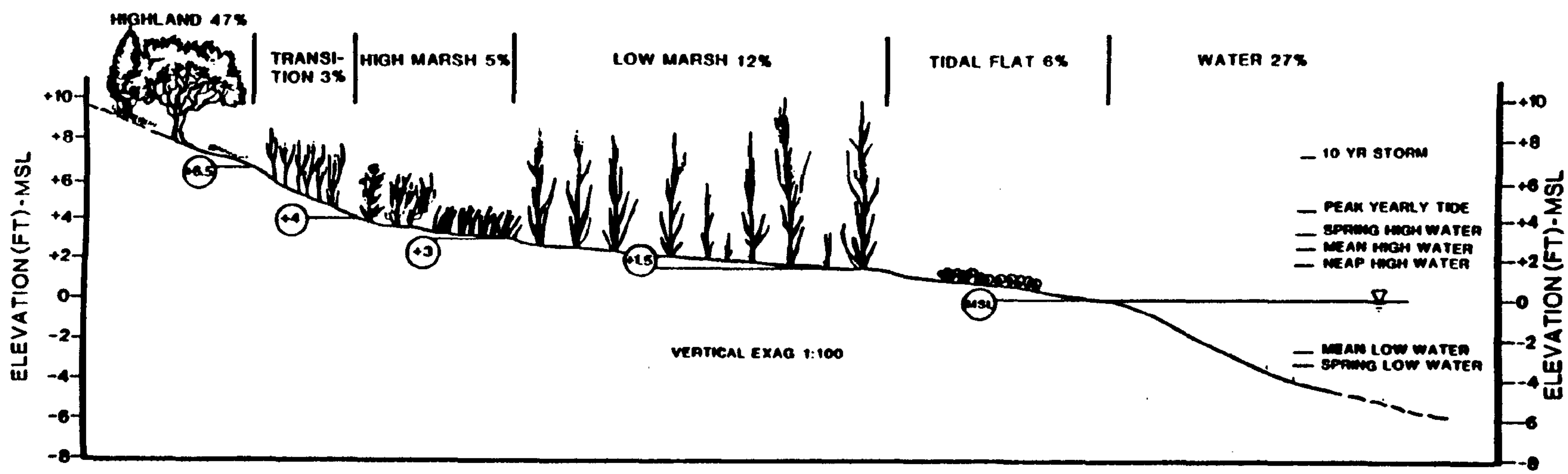
highland	-	flooded rarely (47 percent of study area)
transition wetlands	-	flooding may range from biweekly to annually (3 percent)
high marshes	-	flooding may range from daily to biweekly (5 percent)
low marshes	-	flooded once or twice daily (12 percent)
tidal flats	-	flooded up to half of the day (16 percent)
water	-	flooded more than half of the day (27 percent)

This flooding, in turn, controls the kinds of plant species that can survive in an area. In Charleston, the present upper limit of salt-tolerant plants is approximately 1.8-2.0 m (6.0-6.5 ft) above mean sea level (Scott, Thebeau, and Kana 1981). This elevation also represents the effective lower limit of human development, except in areas where wetlands have been destroyed. The zone below this elevation (delineated on the basis of vegetation types) is referred to as a critical area under South Carolina Coastal Zone Management laws and is strictly regulated (U.S. Department of Commerce 1979).

The distribution of coastal environments around Charleston is balanced for tides occurring twice each day. However, the actual upper limit of salt-tolerant species is considerably above mean high water. Because of the lunar cycle and other astronomic or climatic events, higher tides than average occur periodically. Spring tides occur approximately fortnightly in

FIGURE 2

COASTAL WETLAND HABITATS



conjunction with the new and full moons. The statistical average of these, referred to as mean spring high water, has an elevation of 1.0 m (3.1 ft) above mean sea level in Charleston (U.S. Department of Commerce 1981).

Less frequent tidal flooding occurs annually at even higher elevations ranging upwards of 1.5 m (5.0 ft) above mean sea level. In a South Carolina marsh near the case study area, the flooding of marginal highland occurred at elevations of 4-6 ft above mean sea level (approximately 2.0-2.5 ft above normal). The peak astronomic tide that was responsible for the flooding included an estimated wind setup of 0.5-1.0 ft under 7-9 m/s (13-17 mph) northeast winds.

The Charleston area has a complex morphology. Besides the three tidal rivers that converge in the area, numerous channels dissect it, exhibiting dendritic drainage patterns typical of drowned coastal plain shorelines.

To help provide an understanding of these ecosystems, Figures 3-6 illustrate various marshes in South Carolina. Figure 3 is an oblique aerial

FIGURE 3

BACK BARRIER WETLANDS AND TIDAL CREEK NEAR KIAWAH ISLAND

Photo by M.O. Hayes.

photograph of a back-barrier, tidal creek/marsh/mud-flat system near Kiawah Island, approximately 20 km south of Charleston. It shows a typical drainage pattern and a recently abandoned, horseshoe-shaped infilling with mud.

Throughout the area, highlands are typically less than 5 m (16 ft) above mean sea level. With a mean tidal range of 1.6 m (5.2 ft), a broad area along the coastal edge is flooded twice each day. The natural portions of Charleston Harbor are dominated by fringing salt marshes from several meters to over one kilometer wide.

The upper limit of the marsh can usually be distinguished by an abrupt transition from upland vegetation to marsh species tolerant of occasional salt-water flooding. On topographic maps of Charleston, this break is often about 1.5 m (+5 ft) above mean sea level. The ground photo in Figure 4 shows

FIGURE 4

TRANSITION FROM HIGHLAND TO MARSH: KIAWAH ISLAND

Photo by M.L. Williams, May 16, 1984.

such an abrupt transition along the back side of Kiawah Island, just south of the case study area. Highland terrestrial vegetation appears on the left side of the photo and the marsh is on the right. The detritus seen in the foreground has been washed up by extreme high tide.

The photos in Figures 5 and 6 illustrate typical horizontal and vertical division of these intertidal environments. The most extensive intertidal mud flats around Charleston generally occur in the sheltered zone directly behind the barrier islands. They are thought to represent areas with lower sedimentation rates (Hayes and Kana 1976) away from major tidal channels or sediment sources. Looking seaward, Figure 5 is an oblique aerial photo of the

FIGURE 5

MARSH TIDAL FLAT SYSTEM BEHIND ISLE OF PALMS

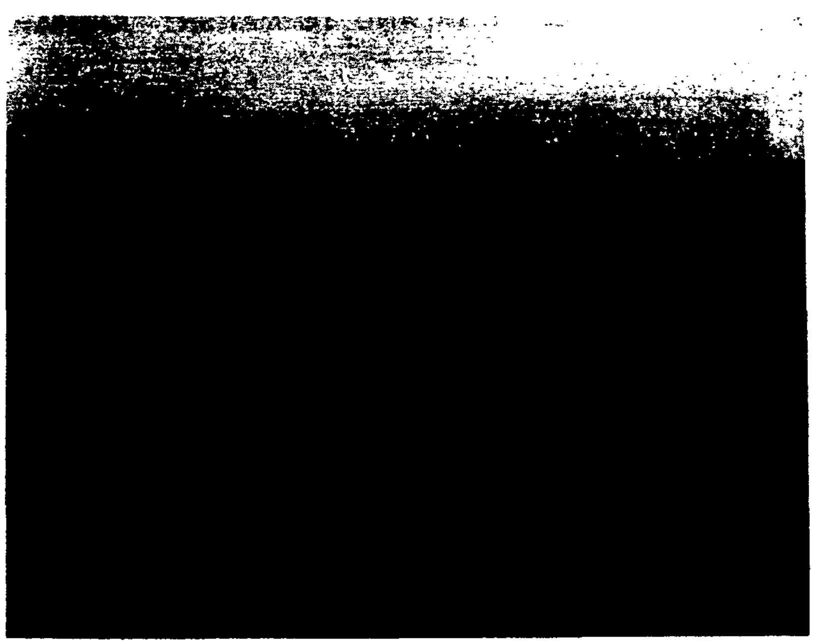


Photo by T.W. Kana, February 1981.

marsh/tidal-flat system behind Isle of Palms (upper right) and Dewees Island, just outside of the Charleston study area. The inlet shown is Dewees Inlet. Note the mud flat and circular oyster mounds in the foreground near marsh and tidal channels.

The photo in Figure 6 was taken at low tide. It shows the vertical transition from marsh to oyster flats along a tidal creek in the Charleston

FIGURE 6

TRANSITION FROM MARSH TO OYSTER FLAT

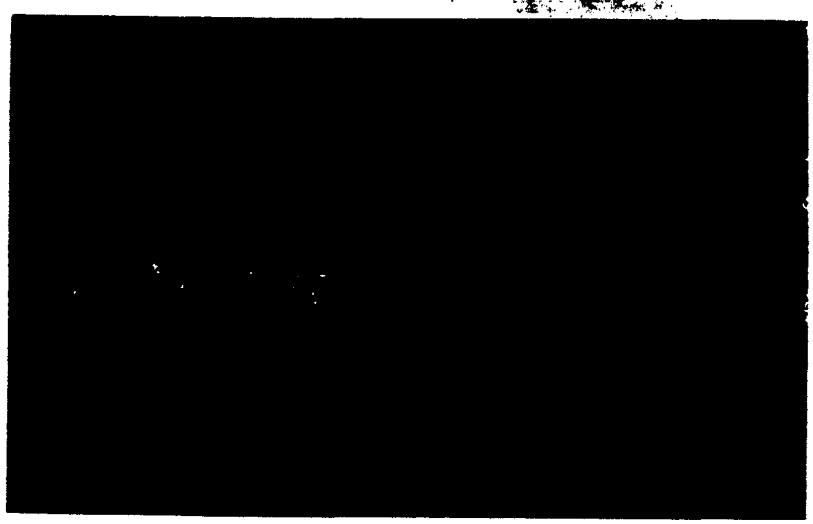


Photo by L.C. Thebeau, April 1981.

case study area. Where the waterfront is developed (Figure 7), the transition from marsh or tidal creeks to highland can be very distinct because of the presence of shore-protection structures, such as vertical bulkheads and riprap. This aerial view was taken 50 km (31 mi) north of the case study area.

FIGURE 7

A DEVELOPED SOUTH CAROLINA COASTAL BARRIER

Photo by T.W. Kana, February 1981.

Much of the Charleston shoreline has accreted (advanced seaward and upward) during the past 40 years (Kana et al. 1984). Marshes accrete through the settling of fine-grained sediment on the marsh surface, as cordgrass (Spartina alterniflora) and other species baffle the flow adjacent to tidal creeks. Marsh sedimentation has generally been able to keep up with or exceed recent sea level rises along this area of the eastern U.S. shoreline (Ward and Domeracki 1978). Much of the sediment into the Charleston area has derived from suspended sediment originating primarily from the Cooper River, which carries the diverted flow of the Santee River (U.S. Army Corps of Engineers, unpublished general design memorandum). However, the recent rediversion will reduce sediment input, which could slow the rate of marsh accretion in the future.

WETLANDS TRANSECTS: METHOD AND RESULTS

To determine how an accelerated rise in sea level would affect the wetlands of Charleston, one needs to know the portions of land at particular elevations and the plant species found at those elevations. To characterize the study area, we randomly selected and analyzed twelve transects (sample cross sections, each running along a line extending from the upland to the water). This section explains how the data from each transect was collected and analyzed, presents the results from each transect, and shows how we created a composite transect based on those results.

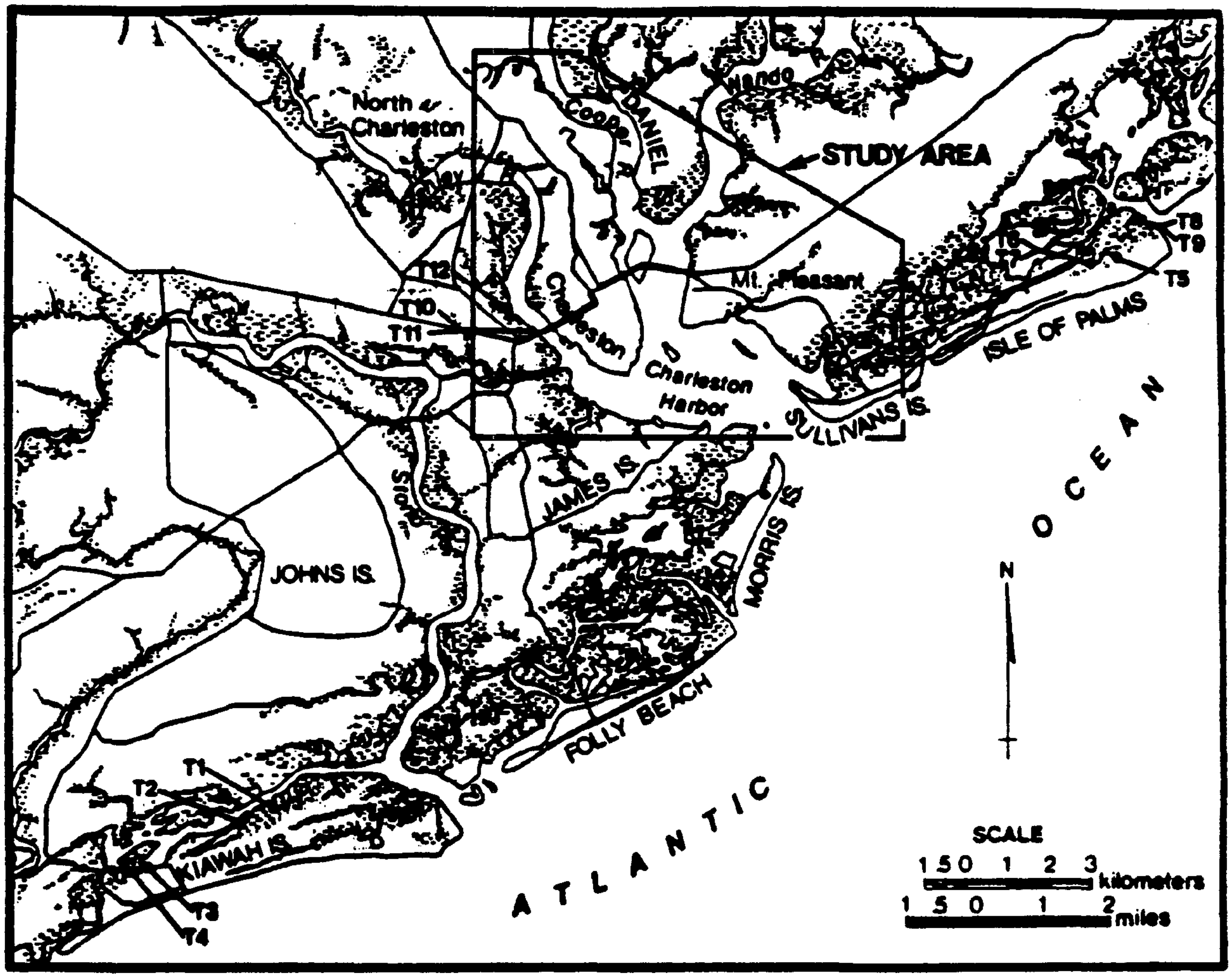
Data Collection and Analysis

For budgetary and logistical reasons, we had to use representative transects near, but not necessarily within, the study area. For example, a limiting criterion was nearness to convenient places where reliable elevations, or benchmarks, had already been established. The marshes behind Kiawah Island and Isle of Palms are similar to the marshes behind Sullivans Island, but are more accessible. As Figure 8 shows, all the transects were within 20 km (12 mi) of the study area.

Each transect began at a benchmark located on high ground near a marsh's boundary, and ended at a tidal creek or mud flat, or after covering 300 m (1,000 ft)--whichever came first. The length of the transects was limited because of the difficulty of wading through very soft muds. Although this procedure may have biased the sample somewhat, logistics prevented a more rigorous survey.

FIGURE 8

LOCATIONS OF STUDY AREA AND TWELVE TRANSECTS



For each transect, we measured elevation and distance from a benchmark using a rod and level. Data points were surveyed wherever there was a noticeable break in slope or change in species. The average distance between points was about 7.5 m (25 ft). Along each transect we collected and tagged samples of species for laboratory typing and verification, noting such information as the elevation of the boundaries between different species. By measuring the length of the transect that a species covered and dividing it by the transect's total length, we computed percentages for the distribution of each species along a transect.

National Geodetic Vertical Datum (NGVD) is the reference level we used for all transects. This datum, derived from the so called 1929 measure of mean sea level, is about 13 cm (0.4 ft) lower than the mean sea level of Charleston today (Ebersole 1982) and therefore does not include sea level rise during the past 50 years. We used the 1929 mean sea level because it is the most widely applied measure of sea level and is used on most published maps. In addition, there is no agreement on an absolute measure of today's sea level since it has to be computed after a period of tidal records become available for analysis.

Results of Individual Transects

Table 2 summarizes the results of the twelve transects. It presents the principal species observed along each transect, their "modal"--or most common--elevations, the percentage of each transect they covered, and the length of each transect. For example, in transect number 6, *Borrichia frutescens* was found at a modal elevation of 118 cm (3.86 ft) above mean sea level and covered 40 percent of the transect, or about 37 m (120 ft).

Because species often overlapped, the sums of the percentages exceed 100. In addition, to omit any marginal plants that exist at transition zones, a modal elevation differs slightly from the arithmetic or weighted mean.

Appendix A contains plots of the profiles of each transect, showing the modal elevations of the substrate and zonation of plant species found there.

TABLE 2

MODAL ELEVATIONS AND PERCENTAGE OF TRANSECT COVERED BY PRINCIPAL SPECIES
(in feet at mean sea level)

Modal Elevations (percent of transect covered)

SPECIES	1	2	3	4	5	6	7	8	9	10	11	12
Batis maritima	-	-	3.13(4)	-	3.20(61)	3.04(14)	-	-	-	-	-	-
Borrichia frutescens	3.90(1)	4.34(33)	4.98(3)	3.48(7)	3.60(14)	3.86(40)	3.17(6)	3.82(27)	3.54(29)	4.94(1)	4.10(9)	-
Distichlis spicata	-	-	-	-	3.52(10)	-	3.20(4)	3.70(23)	3.29(15)	3.80(9)	3.95(35)	3.54(7)
Juncus roemerianus	3.40(1)	-	-	5.34(5)	3.63(2)	3.48(7)	-	-	-	-	5.45(1)	-
Limonium carolinianum	3.27(80)	-	3.07(1)	3.76(1)	3.14(68)	3.04(14)	3.01(4)	3.89(28)	4.35(1)	-	-	-
Polygonum setaceum	-	-	-	-	-	-	-	-	-	5.72(1)	5.45(1)	3.32(7)
Salicornia virginica	3.42(1)	3.38(31)	3.06(9)	3.49(37)	3.12(77)	3.30(34)	3.10(9)	3.30(18)	3.14(31)	-	-	-
Spartina alterniflora	3.27(1)	2.12(75)	2.45(99)	2.05(85)	2.55(78)	-(11)	1.95(62)	2.79(57)	2.71(70)	3.50(99)	3.40(97)	2.65(97)
Spartina patens	-	-	5.35(1)	-	-	-	-	-	-	-	-	-
Spartina cynosuroides	-	-	-	2.51(72)	-	-	-	-	-	-	-	-
Suaeda linearis	-	-	-	-	-	3.61(34)	3.11(4)	4.00(7)	3.22(5)	-	-	-
Transect Length (in feet)	189	51	440	353	933	300	421	387	232	700	588	402

Composite Transect

To model the scenarios of future sea level rise, we had to develop a composite transect from the data in Table 2. Thus, for each species, one modal elevation was estimated from the various elevations in Table 2. Similarly, the percent of each transect covered by an individual species was used to estimate an average percent coverage for all transects (Table 3).

This information allowed us to choose for our composite the five species that dominated the high and low marshes in all the transects: Spartina alterniflora, Salicornia virginica, Limonium carolinium, Distichlis spicata, and Borrichia frutescens. We call these the indicator species. Figure 9 shows the modal elevations for these five species, for two other salt-tolerant plants found in the transects (Juncus roemerianus and Spartina patens), and for a species found in tidal flats and under water (Crassotrea virginica). The primary zone where each species occurs is indicated by the shaded area; occasional species occurrence outside the primary zone is indicated by the unshaded, dashed-line boxes. Figure 9 also outlines the boundaries for the six habitats and indicates the estimated percentage of the study area that each covers.

While this profile is by no means precise, it gives some insight into the expected habitat for a given elevation and the tolerances various species have for flooding. For example, it establishes the general lower limit of marsh for Charleston, where it is presumed that too frequent flooding kills low-marsh species and transforms the marsh to unvegetated mud flats.

The low-marsh plant Spartina alterniflora was the most dominant species, making up 69 percent of the composite transect. Its modal elevation was 75 cm (2.45 ft) above mean sea level (MSL), or 5 cm (0.15 ft) below mean high water

TABLE 3

SUMMARY STATISTICS FOR ELEVATIONS OF MARSH PLANT SPECIES

SPECIES	Weighted Mean (feet above mean sea level)	Standard Deviation (± ft)	Modal Elevation*	Percent Occurrence Composite
Batis maritima	-	-	3.17	7
Borrichia frutescens	3.76	.53	3.16**	14**
Distichlis spicata	3.71	.27	3.71**	9**
Juncus roemerianus	-	-	4.17	1
Limonium carolinianum	3.38	.46	3.38**	16**
Polygonum setaceum	-	-	3.32	1
Salicornia virginica	3.18	.20	3.16**	21**
Spartina alterniflora	2.59	.59	2.45**	69**
Spartina patens	-	-	5.35	≥ 1
Spartina cynosuroides	-	-	2.51	6
Sueada linearis	-	-	3.59	4

* Excludes anomalous values in some cases and observations covering less than 2 percent of transect.

** Recommended indicator species.

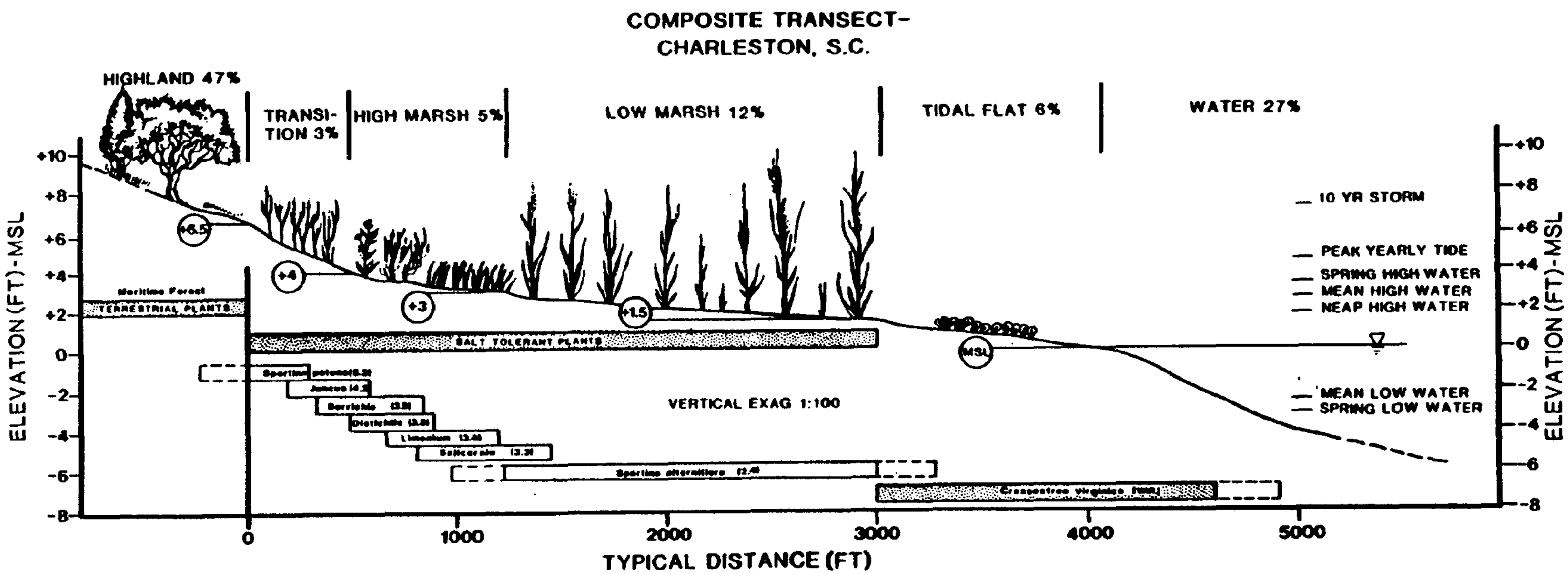


Figure 9. Composite wetlands transect for Charleston illustrating the approximate percent occurrence and modal elevation for key indicator species or habitats based on results of 12 surveyed transects. Minor species have been omitted.

as measured from the 1929 MSL datum. Thus, it would be reasonable to assume that today's low-marsh S. alterniflora prefers elevations close to the limit of the neap tide. For Charleston, this is about 15 cm (0.5 ft) below mean high water. Figure 9 shows that S. alterniflora extends beyond the limits of low marsh into both high marsh and tidal flat; however, this species occurs primarily at low-marsh elevations.

The other indicator species are generally considered to be high-marsh species. These include Distichlis spicata, Borrichia frutescens, Limonium carolinianum and Salicornia virginica. Spartina patens, while having been found to coexist with Distichlis spicata in Maryland and North Carolina marshes (E.C. Pendleton, personal communication, December 1984), is uncommon at elevations less than 122 cm (4 ft) above mean sea level in Charleston (Scott, Thebeau, and Kana 1981). The variance in these observations may be related to the significant difference in tidal range between central South Carolina and North Carolina.

As illustrated in Figure 5 in the previous section, large portions of the back-barrier environments of Charleston consist of tidal flats at lower elevations than the surrounding marsh. Oyster mounds were found at a wide range of elevations along tidal creek bands, but over tidal flats most were common at 30-46 cm (1.0-1.5 ft) above mean sea level.

Area Estimates

Two sources of information were available for land area estimates: United States Geological Survey (USGS) 7.5-minute quadrangles and digitized computer maps prepared in an earlier EPA-sponsored case study (Kana et al. 1984). Using topographic and contour maps, we estimated the number of acres of each habitat in each of the divisions of the Charleston area (see Figure 1). For budgetary reasons, we could not rigorously calculate areas using a computerized planimeter. This level of precision would be questionable anyway, in light of the imprecision of USGS topographic maps in delineating marshes and tidal flats near mean water levels.

Our results were graphically determined and spot-checked by a second investigator to ensure they were consistent to within ±15 percent for each measurement. Thus, the error limits for the overall study area are estimated to be a maximum of ±15 percent by subenvironment. (Because the standard error of a sum is less than the sum of individual standard errors, the errors are likely to be less. Unfortunately, we had no way of rigorously testing these results within the time and budget constraints of the project.)

Tidal-flat areas were estimated using aerial photos and shaded patterns shown on USGS topographic sheets. The marsh was initially lumped together (high and low marsh) to determine representative areas for each Charleston community. The total number of acres for this zone was divided into high- and low-marsh areas by applying the typical percentage of each along the composite transect (70 percent low marsh and 30 percent high marsh). The transition zone areas were estimated from the digitized computer maps.

WETLAND SCENARIOS FOR THE CHARLESTON AREA: MODELING AND RESULTS

After establishing the basic relationships among elevation, wetland habitats, and occurrence of species for Charleston, the next steps in our analysis were to develop a conceptual model for changes in saltwater wetlands under an accelerated rise in sea level and to apply the model to the case study area.

Scenario Modeling

Based on an earlier study sponsored by EPA (Barth and Titus 1984), we chose three scenarios of future sea level rise:

- a baseline scenario, with an average annual rise of 2.5 mm (.1 in), based on current sea-level trends in the Charleston area (Hicks, DeBaugh, and Hickman 1983);
- a low scenario with an average annual rise of 9.2 mm (.36 in), based on the National Academy of Sciences estimate of a worldwide rise of 70 cm (2.3 ft) in the next century and the EPA mid-low scenario; because sea level is rising faster in Charleston than globally, this scenario implies a rise in the Charleston area of 87 cm (2.9 ft) by 2075;
- a high scenario, with an average annual rise of 17.0 mm (.67 in), based on EPA's mid-range high scenario; because of local subsidence trends, this scenario implies a rise of 159 cm (5.2 ft) by 2075 in the Charleston area.

To be consistent with the previous study, we projected the scenarios to the year 2075--95 years after the baseline date of 1980 used to determine "present" conditions.

The model for future wetland zonation also accounted for sedimentation and peat formation, which partially offset the impact of sea level rise by raising the land surface. Sedimentation rates are highly variable within East Coast marsh/tidal-flat systems, with published values ranging from 2 to 18 mm (.08 to .71 in) per year (Redfield 1972; Hatton, DeLaune, and Patrick 1983). Ward and Domeracki (1978) established markers in an intertidal marsh 20 km (12 mi) south of the Charleston case study area and measured sedimentation rates of 4-6 mm (.16-.24 in) per year. Hatton, DeLaune, and Patrick (1983) reported comparable values (3-5 mm per year) for Georgia marshes. Although the rate of marsh accretion will depend on proximity to tidal channels (sediment sources) and density of plants (baffling effect and detritus), we believe the published rate of 4-6 mm per year is reasonably representative for the case study area (Ward and Domeracki 1978). Thus, for purposes of modeling, we assumed a sedimentation rate of 5 mm per year. Obviously, the actual rate will vary across any wetland transect, so this assumed value represents an average. Lacking sufficient quantitative data and considering the broad application of our model, we found it was more feasible to apply a constant rate for the entire study area.

As shown in Table 4, the combined sea level rise scenarios and sedimentation rates yield a positive change in substrate elevation for the baseline and a negative change for the low and high scenarios. The positive change for baseline conditicns follows the recent trend of marsh accretion in Charleston.

TABLE 4

SEA LEVEL RISE SCENARIOS TO THE YEAR 2075

Scenario	Sea Level Rise by 2075	Average Annual Rise	Annual Sedimentation Rate	Annual Net Substrate Change
Baseline	+23.8 cm (0.78 ft)	2.5 mm	5 mm	+2.5 mm
Low	+87.0 cm (2.85 ft)	9.2 mm	5 mm	-4.2 mm
High	+159.2 cm (5.22 ft)	17.0 mm	5 mm	-12.0 mm

For each of these three scenarios, we considered four alternatives for protecting against the rising sea: no protection, complete protection, and two intermediate protection options. Protective options consist of bulkheads, dikes, or seawalls constructed at the upper limit of wetlands (S.C. Coastal

Council critical area line). Figure 10 illustrates the various options. If all property above today's wetlands are protected with a wall, for example, the wetlands will be squeezed between the wall and the sea. Table 5 illustrates the intermediate protection options, whose economic implications were estimated by Gibbs (1984).

For our modeling, we used the composite habitat elevations we derived from the twelve transects (see Figure 9). The cutoff elevation for highland around Charleston was assumed to be 200 cm (6.5 ft) above mean sea level. In general, land above this elevation around Charleston is free of yearly flooding dominated by terrestrial (freshwater) vegetation. Although terrestrial vegetation occurs at lower elevations that are impounded between dikes or ridges, this information is less relevant for sea level rise modeling. The zone of concern is the area bordering tidal waterways, where slopes are assumed to rise continuously without intermediate depressions.

The transition zone is defined as a salt-tolerant area between predominant, high-marsh species and terrestrial vegetation. This area is above the limit of fortnightly (spring) tides but is generally subject to tidal and minor-storm flooding several times each year. If storm frequency remains constant, it is reasonable to assume that storm tides will shift upward by the amount of sea level rise (Titus et al. 1984). However, most climatologists expect the greenhouse warming to alter storm patterns significantly. Nevertheless, because no predictions are available, we assumed that storm patterns will remain the same.

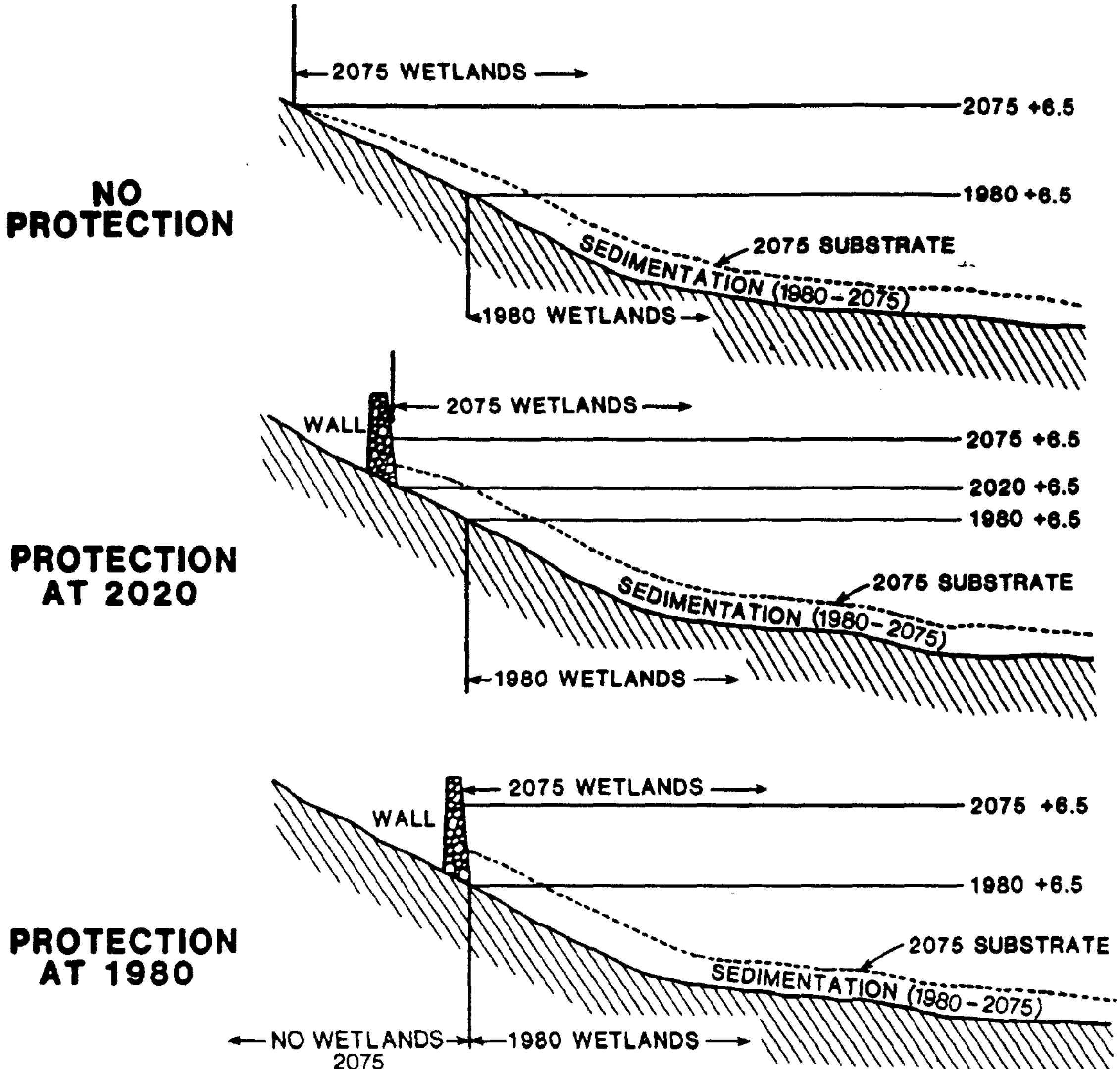


FIGURE 10. If people build walls to protect property from rising sea level, the marsh will be squeezed between the wall and the sea. Sketches show only the upper part of the wetlands which would be affected by shore-protection structures. Mean sea level is off the diagram to the right.

TABLE 5

SHORE-PROTECTION SCENARIOS

Area	Without Anticipating Sea Level Rise	With Anticipating Sea Level Rise
Low Scenario		
Peninsula	Protection after 2050	Protection after 2030
West Ashley/James Island	Protection after 2050	Protect half of area after 2050
Mt. Pleasant	None	Protection after 1990
Sullivans Island	None	None
High Scenario		
Peninsula	Protection after 2020	Protection after 2010
West Ashley/James Island	Protection after 2020	Protect half of area after 2030
Mt. Pleasant	Protection after 2050	Protection after 1990
Sullivans Island	None	None

Note: In West Ashley/James Island, less protection is necessary if sea level rise is anticipated, because more of the low-lying areas are subject to an orderly abandonment. Our high scenario was called "medium" by Gibbs.

Source: Gibbs 1984.

High marsh is defined here by a narrow elevation range of 90 to 120 cm (3 to 4 ft) above mean sea level, and low marsh ranges from 45 to 90 cm (1.5 to 3.0 ft) above mean sea level. This delineation follows the results of surveyed transects and species zonation described earlier. The lower limit of the marsh was estimated from the typical transition to mud flats. Sheltered tidal flats actually occur between mean low water and mean high water but were found to be more common in Charleston in the elevation range of 0-46 cm (0-1.5 ft) above mean sea level. This somewhat arbitrary division was also based on the contours available on USGS maps, which enabled estimates of zone areas within the case study region.

Scenario Results

Based on the shore-protection alternatives for the five suburbs around Charleston, we computed area distributions under the baseline, low, and high scenarios. Figure 10 illustrates shore-protection scenarios and their effects on the wetland transect. Our basic assumption was that the wetland habitats' advance toward land ends at 200 cm (6.5 ft) above mean sea level. Dikes or bulkheads would be constructed under certain protection scenarios at that elevation on the date in question to prevent further inundation.

Because the results are fairly detailed for the five separate subareas and four protection scenarios within the Charleston case study area, we have only listed the overall changes in Tables 6 and 7 (complete protection and no protection). Results by subarea for all four protection scenarios, given in Appendix C, illustrate the variability of land, water, and wetland acreage from one subarea to another. For example, the peninsula currently has a much lower percentage of low marsh than all other areas. Tidal flat distribution was also variable, ranging from 3.2 percent of the Mt. Pleasant zone to 8.6 percent of the Sullivans Island zone. The summary percentages given in Table 6 are appropriately weighted for the five subareas within the study area.

Table 6 lists the number of acres for each elevation zone in 1980 (existing) and for the baseline, low, and high scenarios with and without structural protection by the year 2075. The percentage of the total study area that a habitat covers is given in parentheses in Table 6 and graphically presented in Figure 11. Table 6 indicates losses under all scenarios with no protection for the four upper habitats and gains in area for tidal flats and water areas. For example, without protection, highland would decrease from 46.6 percent of the total area in 1980 to 41.7 percent in 2075 under the

TABLE 6

ACREAGE OF PRINCIPAL HABITAT IN 1980 AND 2075

Habitat	Existing 1980 Acres (%)	Baseline 2075 Acres (%)	Low Scenario - 2075 No Protection Acres (%)	Low Scenario - 2075 Protection Acres (%)	High Scenario - 2075 No Protection Acres (%)	High Scenario - 2075 Protection Acres (%)
Highland	21,200 (46.6)	21,700 (47.7)	20,445 (44.9)	21,195 (46.6)	18,990 (41.7)	21,195 (46.6)
Transition	1,500 (3.3)	2,820 (6.2)	1,355 (3.0)	605 (1.3)	1,420 (3.1)	0 (0)
High Marsh	2,300 (5.1)	3,320 (7.3)	690 (1.5)	690 (1.5)	675 (1.5)	0 (0)
Low Marsh	5,400 (11.9)	3,910 (8.6)	3,235 (7.1)	3,235 (7.1)	860 (1.9)	750 (1.7)
Tidal Flat	2,600 (5.7)	2,600 (5.7)	5,020 (11.0)	5,020 (11.0)	1,425 (3.1)	1,425 (3.1)
Water	12,500 (27.4)	11,150 (24.5)	14,755 (32.5)	14,755 (32.4)	22,130 (48.7)	22,130 (48.6)
TOTALS	45,500 (100.0)	45,500 (100.0)	45,500 (100.0)	45,500 (100.0)	45,500 (100.0)	45,500 (100.0)

TABLE 7

NET CHANGE IN ACRES FOR PRINCIPAL WETLAND HABITATS: 1980-2075

Habitat	Baseline Acres (%)	Low Scenario - 2075 Without Protection Acres (%)	Low Scenario - 2075 With Protection Acres (%)	High Scenario - 2075 Without Protection Acres (%)	High Scenario - 2075 With Protection Acres (%)
Highland	500 (+2.4)	-744 (4)	0 (0)	-2,210 (10)	0 (0)
Transition	1,320 (+88)	-144 (10)	-895 (60)	-80 (5)	-1,500 (100)
High Marsh	1,020 (+44)	-1,610 (70)	-1,610 (70)	-1,625 (71)	-2,300 (100)
Low Marsh	-1,490 (-28)	-2,165 (40)	-2,165 (40)	-4,540 (84)	-4,650 (86)
Tidal Flats	0 (0)	+2,420 (+93)	+2,420 (+93)	-1,175 (45)	-1,175 (45)
Water	-1,350 (-10.8)	+2,255 (+18)	+2,255 (+18)	+9,630 (+77)	+9,630 (+77)

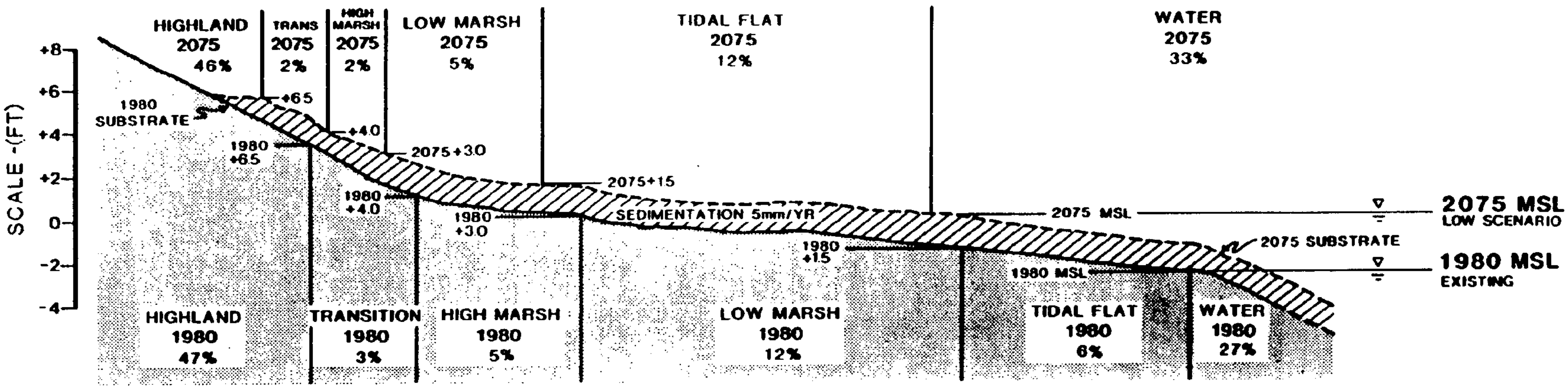


Figure 11. Conceptual model of the shift in wetlands zonation along a shoreline profile if sea level rise exceeds sedimentation rates. In general, the response will be a landward shift and altered areal distribution of each habitat because of variable slopes at each elevation interval.

high scenario. This represents a loss of over 2,200 acres or 10 percent of the present highland area. Land that is now terrestrial would be transformed into transition-zone or high-marsh habitats a century from now. Under the 2075 high scenario with no protection, high and low marsh, combined, would decrease from 7,700 acres to 1,535 acres--a reduction of almost 80 percent. While highland and marsh areas would decrease under the no-protection scenarios, water areas would increase dramatically--from 27.4 percent to as much as 48.7 percent--under the high scenario of 2075.

With structural protection implemented at different times for each community (see Table 5), highland areas would be maintained at a constant acreage, but transition and high-marsh habitats would be completely eliminated by 2075 under the high scenario (because of the lack of area to accommodate a landward shift). Total marsh acreage would decrease from 7,700 acres to 3,925 acres (2075 low scenario), or 750 acres (2075 high scenario), under the assumed mitigation in Table 5.

The net change in areas under the various scenarios listed in Table 7 indicates that all habitats would undergo significant alteration. Even under the baseline scenario, which assumes historical rates of sea level rise, 20-35 percent losses of representative marsh areas are expected by 2075. Protection under the low scenario (as outlined by Gibbs 1984) would have virtually no effect on high or low marsh coverage; but it would cause a substantially increased loss of transition wetlands. Under the high scenario with protection, highland would be saved at the expense of all transition and high marsh areas and almost 90 percent of the low marsh. Even under the low scenario, sea level rise would become the dominant cause of wetland loss in the Charleston area. Although a substantial amount of marsh was filled as the city was built, destruction of coastal wetlands came to a virtual halt with the creation of the South Carolina Coastal Council. Since 1977, the entire state has only lost 35 of its 500,000 acres of wetlands to dry lands (South Carolina Coastal Council 1985). Approximately 100 acres have been flooded by artificial impoundments (U.S. Fish and Wildlife Services, Charleston Office; personal communication). Thus, without the impact of sea level rise, one would expect the Charleston area to lose less than 0.5 percent of its wetlands in the next century.

RECOMMENDATIONS FOR FURTHER STUDY

This study is a first attempt at determining the potential impact of accelerated sea level rise on wetlands. The experience gained in the Charleston area should be built upon with case studies in other estuaries. Louisiana provides a present-day analog for the effect of rapid sea level rise on wetlands because of high subsidence rates along the Mississippi Delta (see Gagliano 1984). Additional studies in that part of the coast should attempt to document the temporal rate of transformation from marsh to submerged wetlands.

Accurate wetland transects with controlled elevations are required to determine the preferred substrate elevations for predominant wetland species. With better criteria for elevation and vegetation, we can use remote-sensing techniques and aerial photography to delineate wetland contours on the basis of vegetation. Scenario modeling can then proceed using computer-enhanced images of wetlands and surrounding areas, for more accurate delineation of marsh habitats. Using historical aerial photos, it may also be possible to infer sedimentation rates by changes in plant coverage or species type, which could be related to elevation using some of the criteria provided in this report.

Another problem that remains with this type of study is the frame of reference for mean sea level. For practical reasons, mean sea level for a standard period (20 years generally) cannot be computed until after the period ends. Therefore, earlier mean sea levels, such as the NGVD of 1929, are used. But sea level has risen about 15 cm since then. If everyone uses the same reference plane for present and future conditions, the problem may be minor. But it does not allow us to determine modal elevations with respect to today's sea level. The transects surveyed for the present study suggest that S. alterniflora (low marsh) grows optimally at an elevation of 2.45 ft above mean sea level, close to mean high water (U.S. Department of Commerce 1981). Compared with today's mean sea level in Charleston, S. alterniflora probably prefers to grow as much as 0.5 ft below actual mean high water, which may confuse the reader who forgets that the report uses 1929 sea level.

The basic criteria for delineating elevations of various wetland habitats in this study can be easily tested in other areas. By applying normalized flood probabilities (similar to those depicted in Figure 12), it will be possible to measure marsh transects in other tide-range areas and relate them to the results for Charleston.

Normalized Elevations

The absolute modal elevation for each species is site-specific for Charleston. Presuming that the zonation is controlled primarily by tidal inundation, it is possible to normalize the data for other tide ranges based on frequency curves for each water level. Figure 12 contains two such "tide

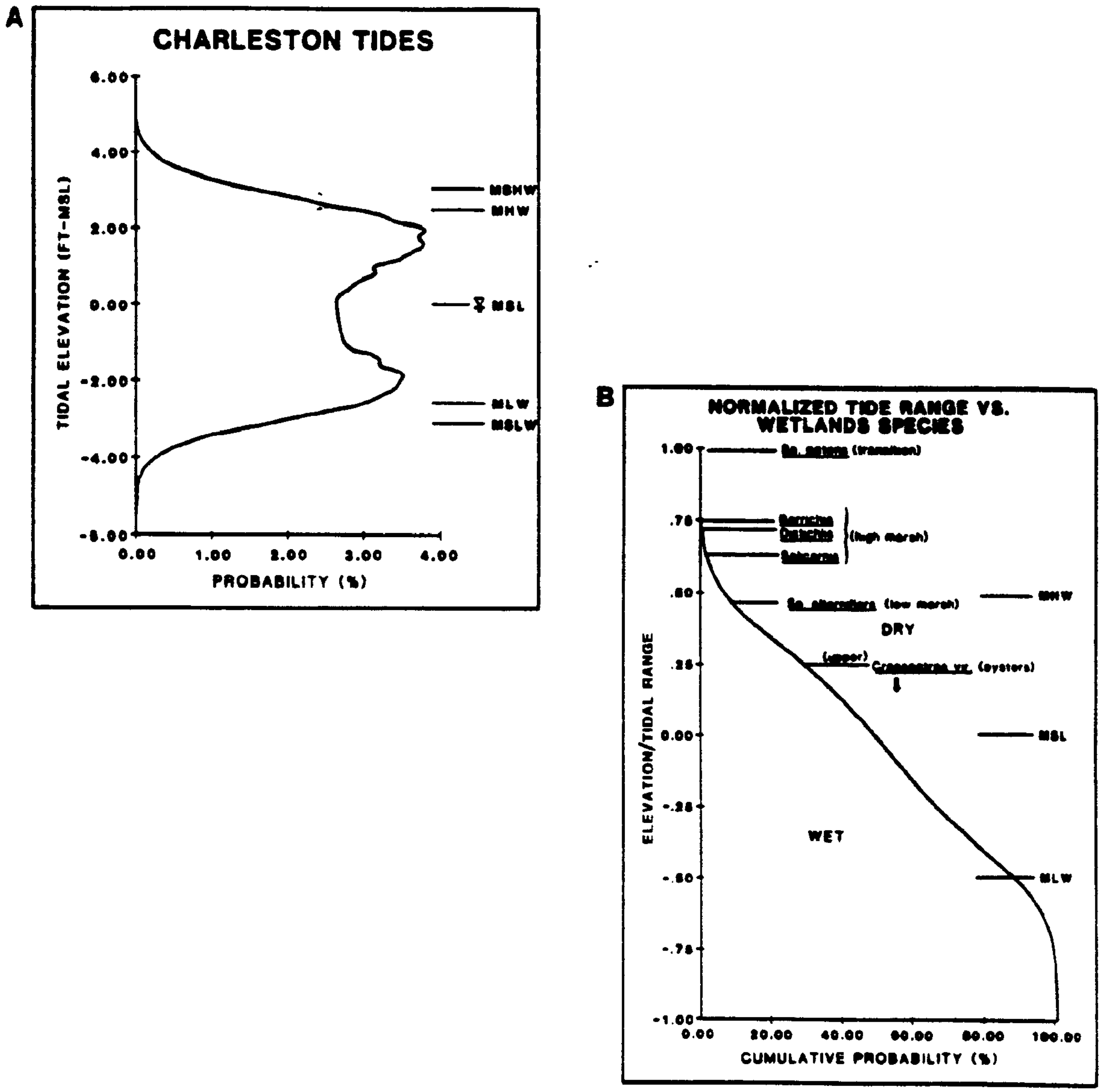


Figure 12. Tide-probability curves based on statistics for Charleston given in Ebersole (1982).

(A) Probability distribution for the range of astronomic tides.

(B) "Normalized" cumulative probability distribution, indicating the preferential elevation for various wetland species.

Abbreviations: MSHW (mean spring high water); MHW (mean high water); MSL (mean sea level); MLW (mean low water); MSLW (mean spring low water).

probability" curves, based on detailed statistics of Atlantic Coast water levels given in Ebersole (1982) and summarized in Appendix B. The graph of Figure 12A gives the probability of various water levels for Charleston. In Figure 12B, the data have been normalized for the mean tide range of 5.2 ft in Charleston and given as a cumulative probability distribution. These graphs are applicable to much of the southeastern U.S. coast by substituting different tide ranges. Each graph provides a measure of the duration of time over the year that various wetland elevations are under water.

In the case of Salicornia virginica (+3.16 ft MSL for Charleston), the cumulative frequency of flooding is approximately 4 percent (Figure 12B and Appendix B). If one wanted to apply these results for an area with a different tide range but similar species occurrence, such as Sapelo Island (Georgia), the flooding frequency for S. virginica could be used to estimate its modal elevation at the locality. With a mean tide range of 8.5 ft at Sapelo, S. virginica is likely to occur around +5.3 ft MSL (based on substitution of the tide range in Figure 12B). This procedure can be applied for other southeastern U.S. marshes as a preliminary estimate of local modal elevations.

We do not consider elevation results for the transects to be definitive because of the relatively small sample size. However, the results are sufficiently indicative of actual trends to allow scenario modeling. With the tide-probability curves presented, it should be possible to check these results against other areas with similar climatic patterns, but different tide ranges.

Conclusion

Wetlands in the Charleston area have been able to keep pace with the recent historical rise in sea level of one foot per century. However, a three- to five-foot rise in the next century resulting from the greenhouse effect would almost certainly upset these ecosystems in a fashion similar to that occurring in Louisiana, which every year loses over one hundred square kilometers (fifty square miles) to the sea.

The success with which coastal wetlands adjust to rising sea in the future will depend upon whether human activities prevent new marsh from forming as inland areas are flooded. If human activities do not interfere, a three-foot rise in sea level would result in a net loss of about 50 percent of the marsh in the Charleston area. A five-foot rise would result in an 80 percent loss.

To the extent that levees, seawalls, and bulkheads are built to prevent areas from being flooded as the sea rises, the formation of new marsh will be prevented. We estimate that 90 percent of the marsh in Charleston--including all of the high marsh--would be destroyed if sea level rises five feet and walls are built to protect existing development.

This study represents only a first investigation into an area that requires substantial additional research. The methods developed here can be applied to estimate marsh loss in similar areas with different tidal ranges without major additional field work. Nevertheless, more field surveys and analysis will be necessary to estimate probable impacts of future sea level rise on other types of wetlands.

In spite of the preliminary nature of this investigation, it appears reasonable to conclude that a three- to five-foot rise in sea level could seriously threaten coastal wetlands in the United States, if human activities prevent natural adaptation to that rise. Because of the long-range nature of the issue, it may be possible to avoid adverse environmental impacts through low-cost nonregulatory measures and market incentives. Future studies should not only focus on the loss of wetlands caused by sea level rise, but on possible measures to avoid those losses.

The assumptions used to predict future sea level rise and the resulting impacts on wetland loss must be refined considerably so that we can have more confidence in any policy responses that are based on these predictions. The substantial environmental and economic resources that can be saved if better predictions become available soon will easily justify the cost (though substantial) of developing them (Titus et al. 1984). However, deferring policy planning until all remaining uncertainties are resolved is unwise.

The knowledge that has accumulated in the last twenty-five years has provided a solid foundation for expecting sea level to rise in the future. Nevertheless, most environmental policies assume that wetland ecosystems are static. Incorporating into our environmental research the notion that ecosystems are dynamic need not wait until the day when we can accurately predict the magnitude of the future changes.

REFERENCES

Barth, M.C., and J.G. Titus (Eds.), 1984. Greenhouse Effect and Sea Level Rise. Van Nostrand Reinhold Co., New York, N.Y., 325 pp.

Boesch, D.F., D. Levin, D. Nummedal, and K. Bowles, 1983. Subsidence in Coastal Louisiana: Cases, Rates and Effects on Wetlands. U.S. Fish and Wildlife Serv., Washington, D.C., FWS/OBS-83/26, 30 pp.

DeLaune, R.D., C.J. Smith, and W.H. Patrick, Jr., 1983. "Relationship of marsh elevation, redox potential, and sulfide to Spartina alterniflora productivity." Soil Science Amer. Jour., Vol. 47, pp. 930-935.

Duc, A.W., 1981. "Back barrier stratigraphy of Kiawah Island, South Carolina." Ph.D. Dissertation, Geol. Dept., University of South Carolina, Columbia, 253 pp.

Ebersole, B.A., 1982. Atlantic Coast Water-level Climate. WES Rept. 7, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Miss., 498 pp.

Gagliano, S.M., 1984. Independent reviews (comments of Sherwood Gagliano). In M.C. Barth and J.G. Titus (Eds.), Greenhouse Effect and Sea Level Rise. Van Nostrand Reinhold Co., New York, N.Y., Chap. 10, pp. 296-300.

Gagliano, S.M., K.J. Meyer Arendt, and K.M. Wicker, 1981. "Land loss in the Mississippi deltaic plain." In Trans. 31st Ann. Mtg., Gulf Coast Assoc. Geol. Soc. (GCAGS), Corpus Christi, Texas, pp. 293-300.

Gallagher, J.L., R.J. Reimold, and D.E. Thompson, 1972. "Remote sensing and salt marsh productivity." In Proc. 38th Ann. Mtg. Amer. Soc. Photogrammetry. Washington, D.C., pp. 477-488.

Gibbs, M.J., 1984. "Economic analysis of sea level rise: methods and results." In M.C. Barth and J.G. Titus (Eds.), Greenhouse Effect and Sea Level Rise. Van Nostrand Reinhold Co., New York, N.Y., Chap. 7, pp. 215-251.

Hatton, R.S., R.D. DeLaune, and W.H. Patrick, 1983. "Sedimentation, accretion and subsidence in marshes of Barataria Basin, Louisiana." Limnol. and Oceanogr., Vol. 28, pp. 494-502.

Hayes, M.O., and T.W. Kana (Eds.), 1976. Terrigenous Clastic Depositional Environments, Tech. Rept. NO. 11-CRD. Coastal Research Division, Dept. Geol., Univ. South Carolina, 306 pp.

Hicks, S.D., H.A. DeBaugh, and L.E. Hickman, 1983. Sea Level Variations for the United States 1855-1980. National Ocean Service, U.S. Department of Commerce, Rockville, Maryland.

Hoffman, J.S., D. Keyes, and J.G. Titus, 1983. Projecting Future Sea Level Rise: Methodology, Estimates To The Year 2100, and Research Needs. U.S. EPA, Washington, D.C., 121 pp.

Kana, T.W., J. Michel, M.O. Hayes, and J.R. Jensen, 1984. "The physical impact of sea level rise in the area of Charleston, South Carolina. In M.C. Barth and J.G. Titus (Eds.), Greenhouse Effect and Sea Level Rise. Van Nostrand Reinhold Co., New York, N.Y., Chap. 4, pp. 105-150.

Keeling, C.D., R. Bacastow, and T.G. Whorf, 1982. "Measurements of the concentrations of carbon dioxide at Mauna Loa Observatory, Hawaii." In Clarke (Ed.), Carbon Dioxide Review: 1982. Clarendon Press, Boulder, CO.

Lacis, A., J.E. Hansen, P. Lee, T. Mitchell and S. Lebedeff, 1981. "Greenhouse effect of trace gases, 1970-80." Geophys. Res. Lett., Vol. 8, p. 1035-1038.

Meier, M.F., et al., 1985. Glaciers, Ice Sheets, and Sea Level. Washington, D.C.: National Academy Press.

Nixon, S.W., 1982. The Ecology of New England High Salt Marshes: A Community Profile. U.S. Fish and Wildlife Serv., Washington, D.C., FWS/OBS-81/55, 70 pp.

Nummedal, D., 1982. "Future sea level changes along the Louisiana coast." In D.F. Boesch (Ed.), Proc. Conf. Coastal Erosion and Wetland Modfification in Louisiana: Causes, Consequences and Options. U.S. Fish and Wildlife Serv., Washington, D.C., FWS/OBS-82/59, pp. 164-176.

Odum, E.P., and M.E. Fanning, 1973. "Comparisons of the productivity of Spartina alterniflora and Spartina cynosuroides in Georgia coastal marshes." Bull. Georgia Acad. Sci., Vol. 31, pp. 1-12.

Pendleton, E.C., 1984. Personal communication. U.S. Fish and Wildlife Serv., National Coastal Ecosystems Team, Slidell, LA.

Ramanathan, V., H.B. Singh, R.J. Cicerone, and J.T. Kiehl, 1985. "Trace Gas Trends and their Potential Role in Climate Change," Journal of Geophysical Research (August).

Redfield, A.C., 1972. "Development of a New England salt marsh." Ecol. Monogr., Vol. 42, pp. 201-237.

Revelle, R., 1983. "Probable future changes in sea level resulting from increased atmospheric carbon dioxide." In Changing Climate. National Academy Press, Washington, D.C.

Schubel, J.R., 1972. "The physical and chemical conditions of the Chesapeake Bay." Jour. Wash. Acad. Sci., Vol. 62(2), pp. 56-87.

Scott, G.I., L.C. Thebeau, and T.W. Kana, 1981. "Ashley River marsh survey - Phase I." Prepared for Olde Charleston Partners; RPI, Columbia, S.C., 43 pp.

South Carolina Coastal Council, 1985. Performance Report of the South Carolina Coastal Management Program. South Carolina Coastal Council, Columbia, South Carolina.

Teal, J.M., 1958. "Energy flow in the salt marsh ecosystem." In Proc. Salt Marsh Conf., Mar. Inst., Univ. Georgia, pp. 101-107.

Titus, J.G., T.R. Henderson, and J.M. Teal, 1984. "Sea level rise and wetlands loss in the United States. National Wetlands Newsletter, Environmental Law Inst., Washington, D.C., Vol. 6(5).

Titus, J.G., "Sea Level Rise and Wetlands Loss." In O.T. Magoon (ed.) Coastal Zone '85. American Society of Civil Engineers, New York, New York, pp. 1979-1990.

Titus, J.G., M.C. Barth, M.J. Gibbs, J.S. Hoffman, and M. Kenney, 1984. "An overview of the causes and effects of sea level rise." In M.C. Barth and J.G. Titus (Eds.), Greenhouse Effect and Sea Level Rise. Van Nostrand Reinhold Co., New York, N.Y., Chap. 1, pp. 1-56.

Turner, R.E., 1976. "Geographic variations in salt marsh macrophyle production: a review." Contributions in Marine Science, Vol. 10, pp. 47-48.

U.S. Department of Commerce, 1979. State of South Carolina Coastal Zone Management Program and Final Environmental Impact Statement. Office of Coastal Zone Management, National Oceanic and Atmospheric Administration, Washington, D.C.

U.S. Department of Commerce, 1981. "Tide tables, east coast of North and South America." NOAA, National Ocean Survey, Rockville, MD., 288 pp.

Valiela, I., J.M. Teal, and W.G. Deuser, 1978. "The nature of growth forms in the salt marsh grass Spartina alterniflora." American Naturalist, Vol. 112(985), pp. 461-470.

Ward, L.G., and D.D. Domeracki, 1978. "The stratigraphic significance of back-barrier tidal channel migration." Geol. Soc. Amer., Abs. with Programs, Vol. 10(4), p. 201.

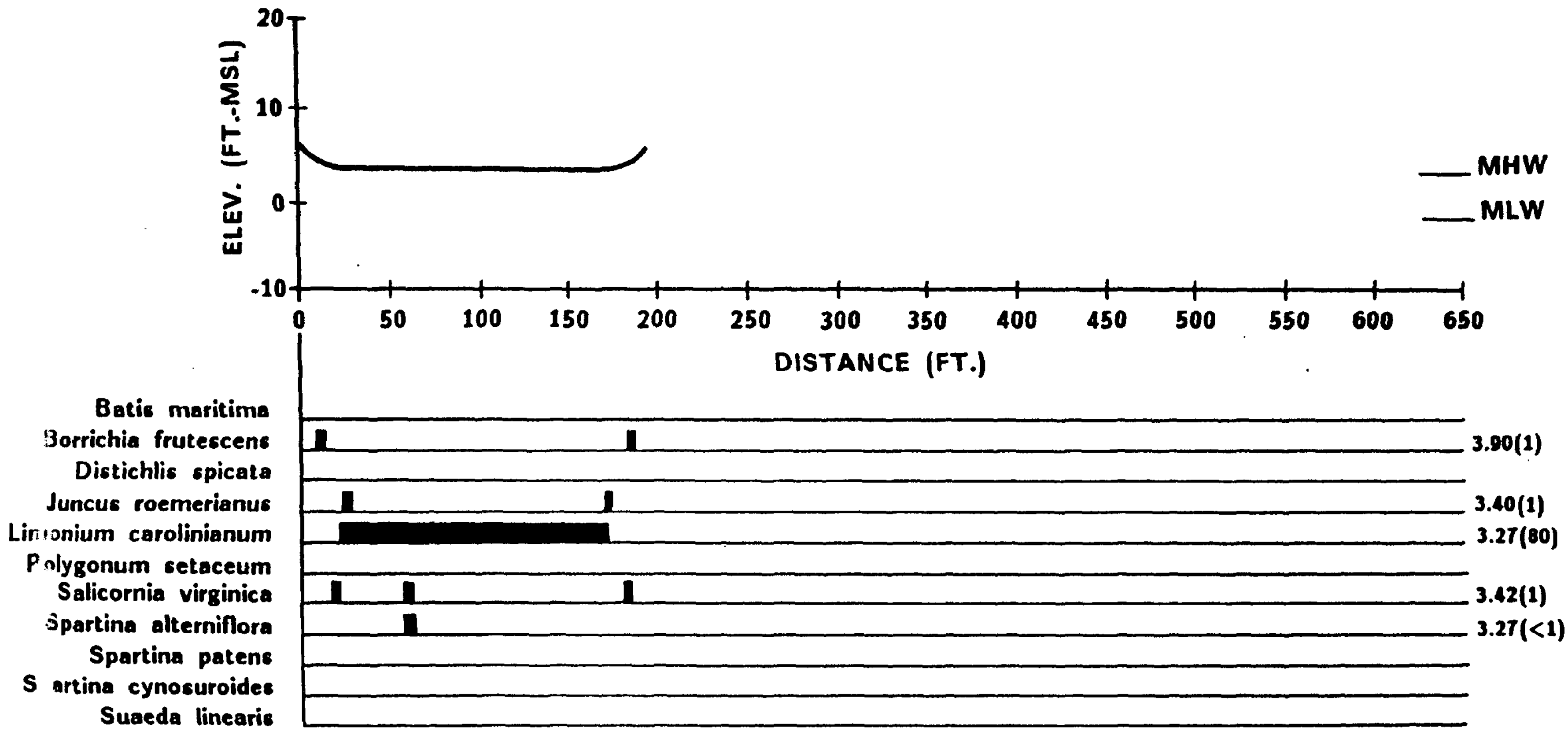
Wilson, K.A., 1962. North Carolina Wetlands: Their Distribution and Management. North Carolina Wildlife Resources Commission, Raleigh, N.C.

APPENDIX A

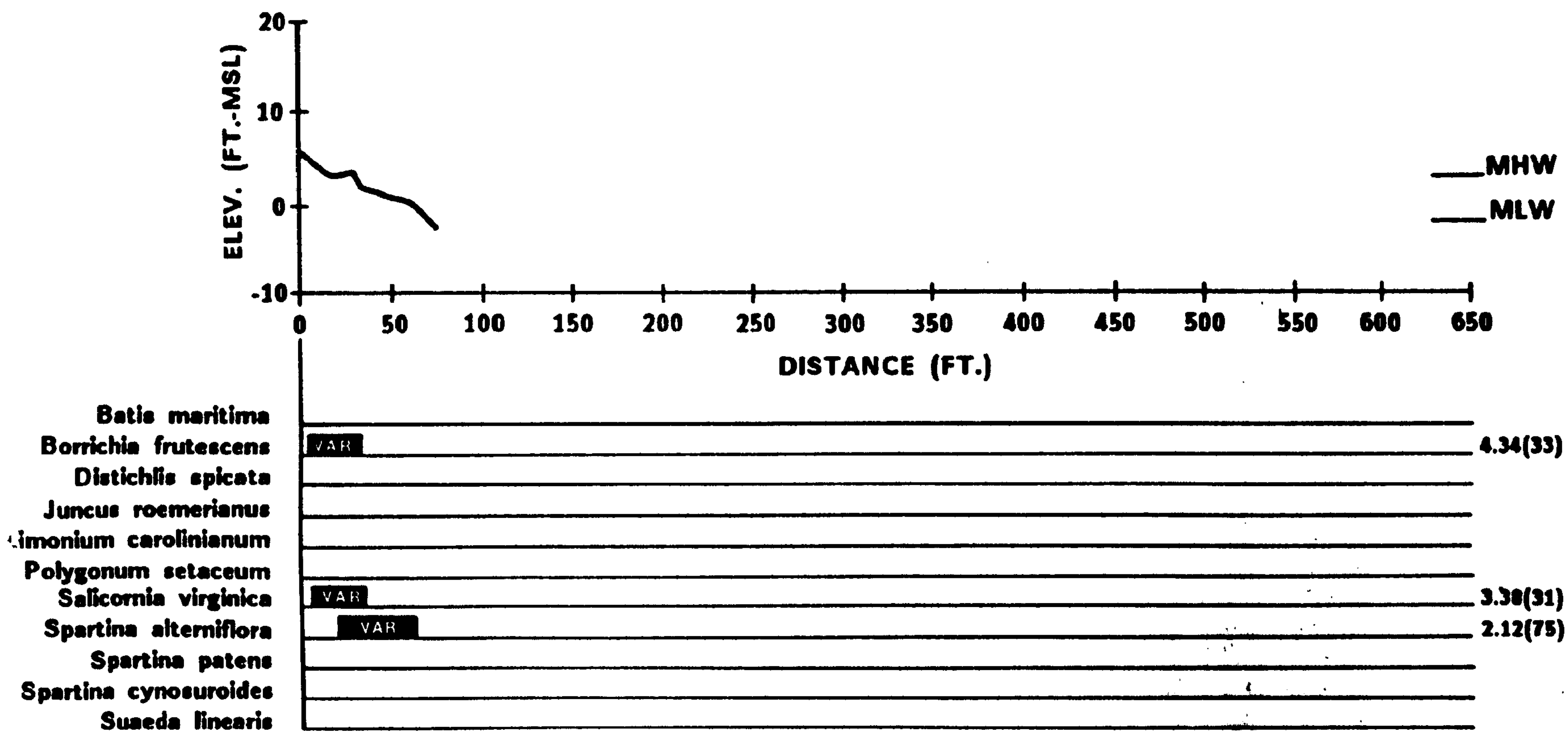
WETLANDS TRANSECTS AND DISTRIBUTION OF SPECIES

Surveyed wetlands transects and distribution of species for 12 profiles in the general vicinity of Charleston, South Carolina (field notes are available at RPI Coastal Science & Engineering).

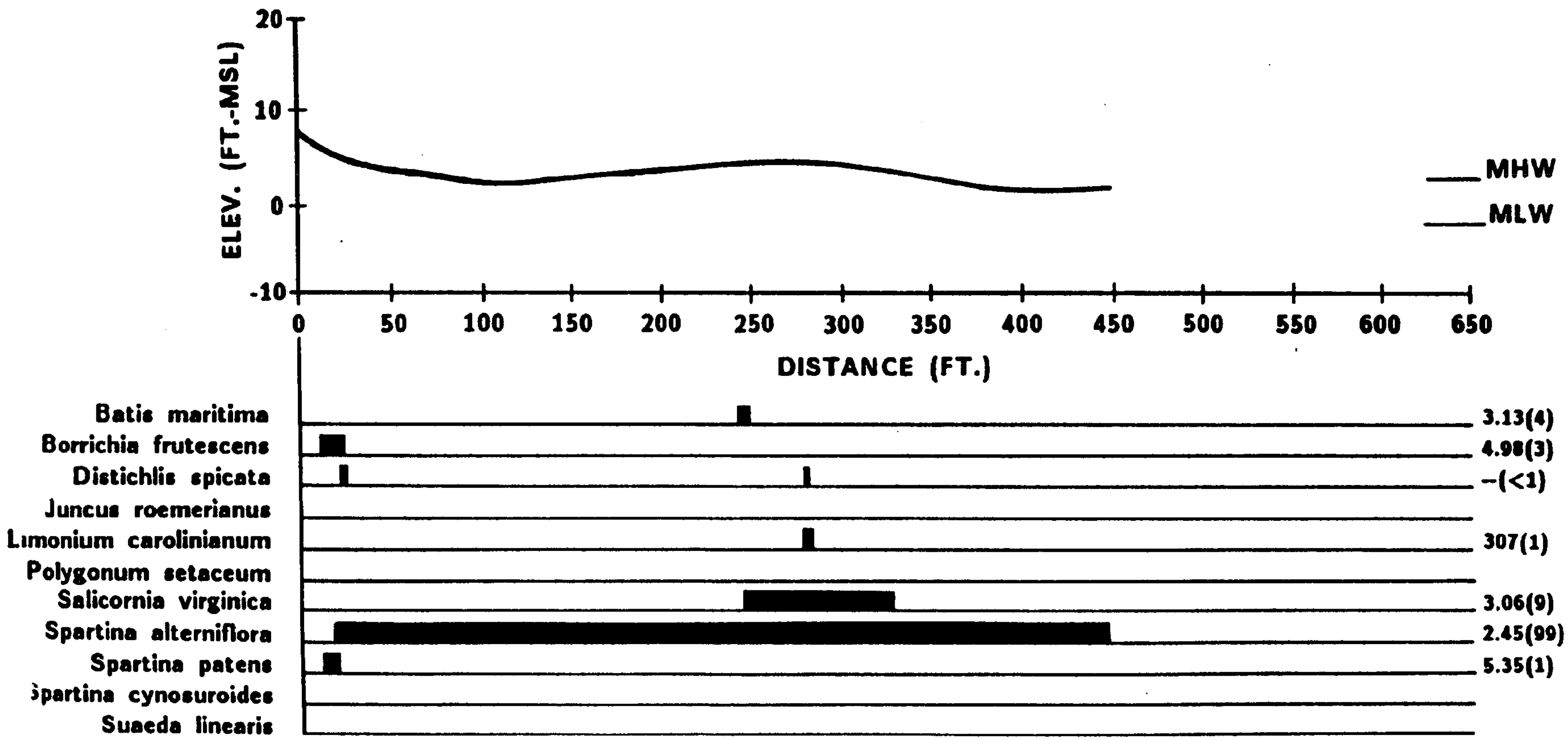
RANGE # EPA-1 EAST SIDE OF MARSH ISLAND PARK BOARDWALK
KEY: 16 MAY 1984



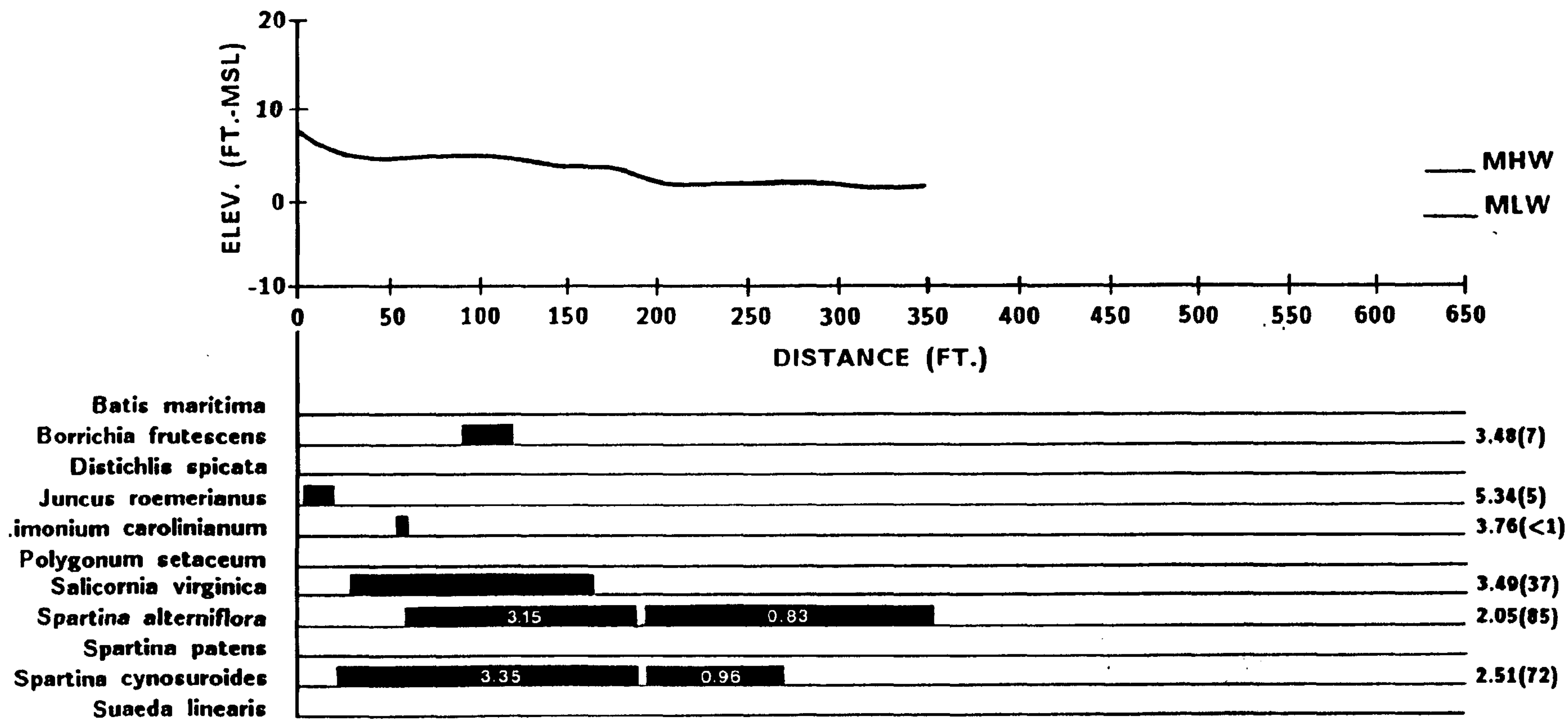
RANGE # EPA-2 BOAT RAMP RD., WEST OF MARSH ISLAND PARK
KEY: 16 MAY 1984



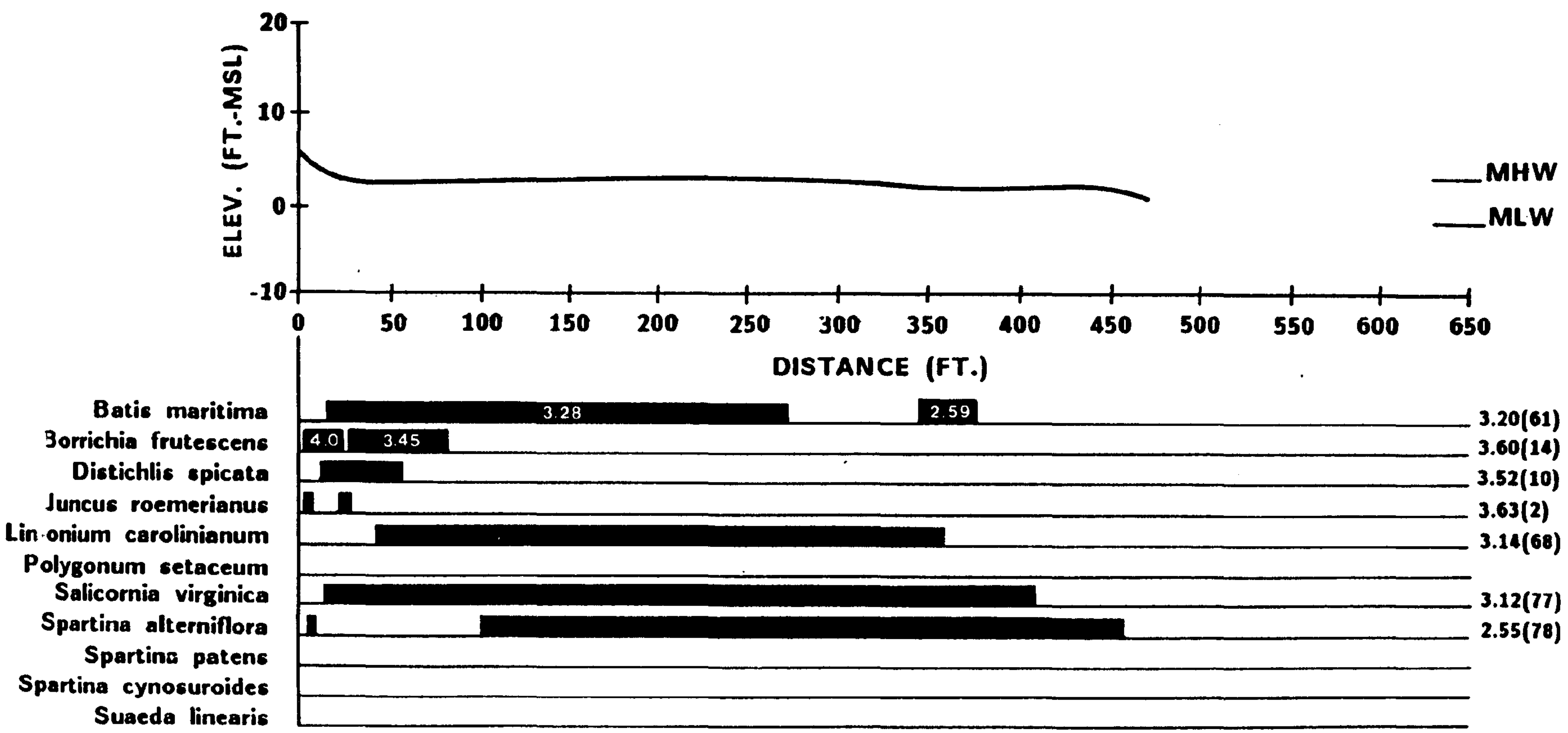
RANGE # EPA-3 LOT 246, END OF SALTGRASS CT.
KEY: 15 JUNE 1984



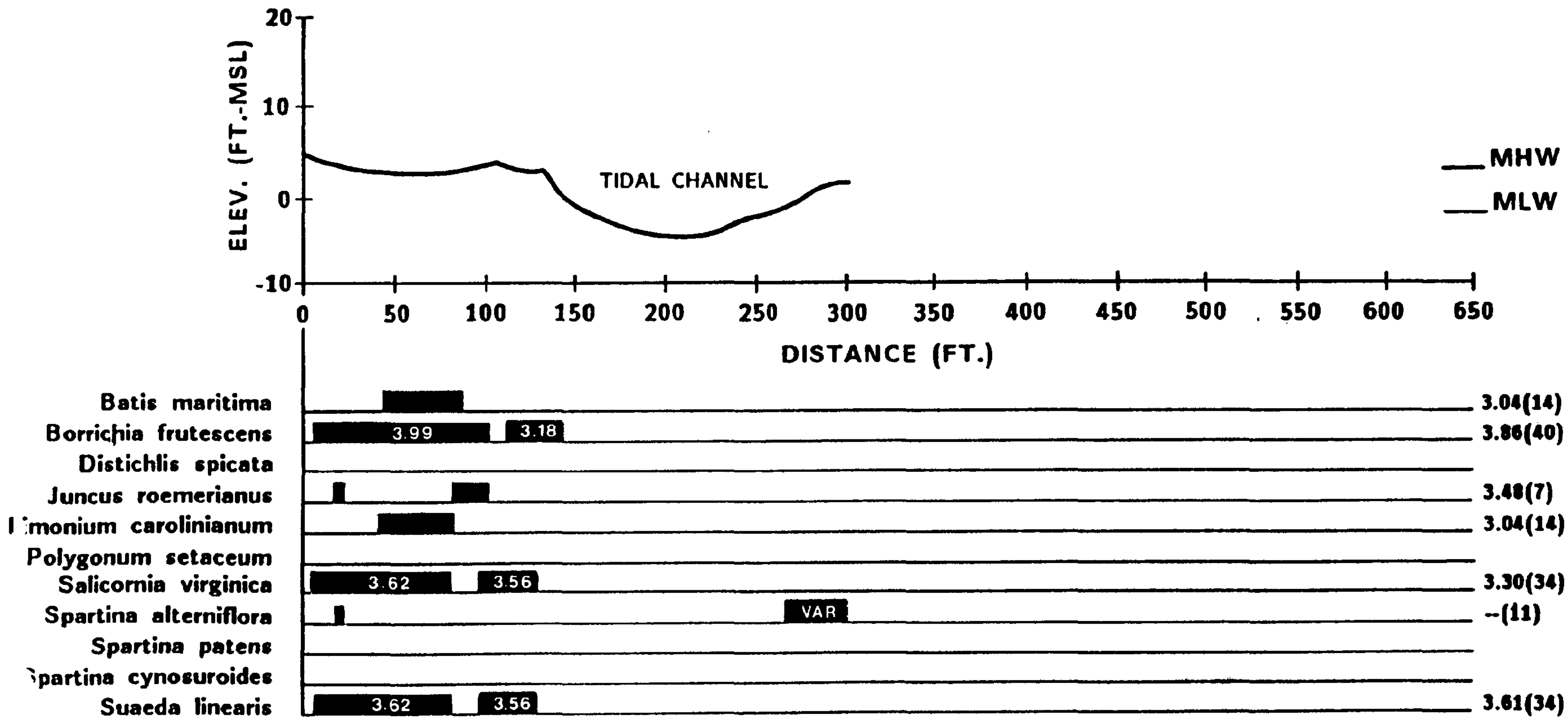
RANGE # EPA-4 LOT 177, MARSH HAWK LANE
KEY: 16 MAY 1984



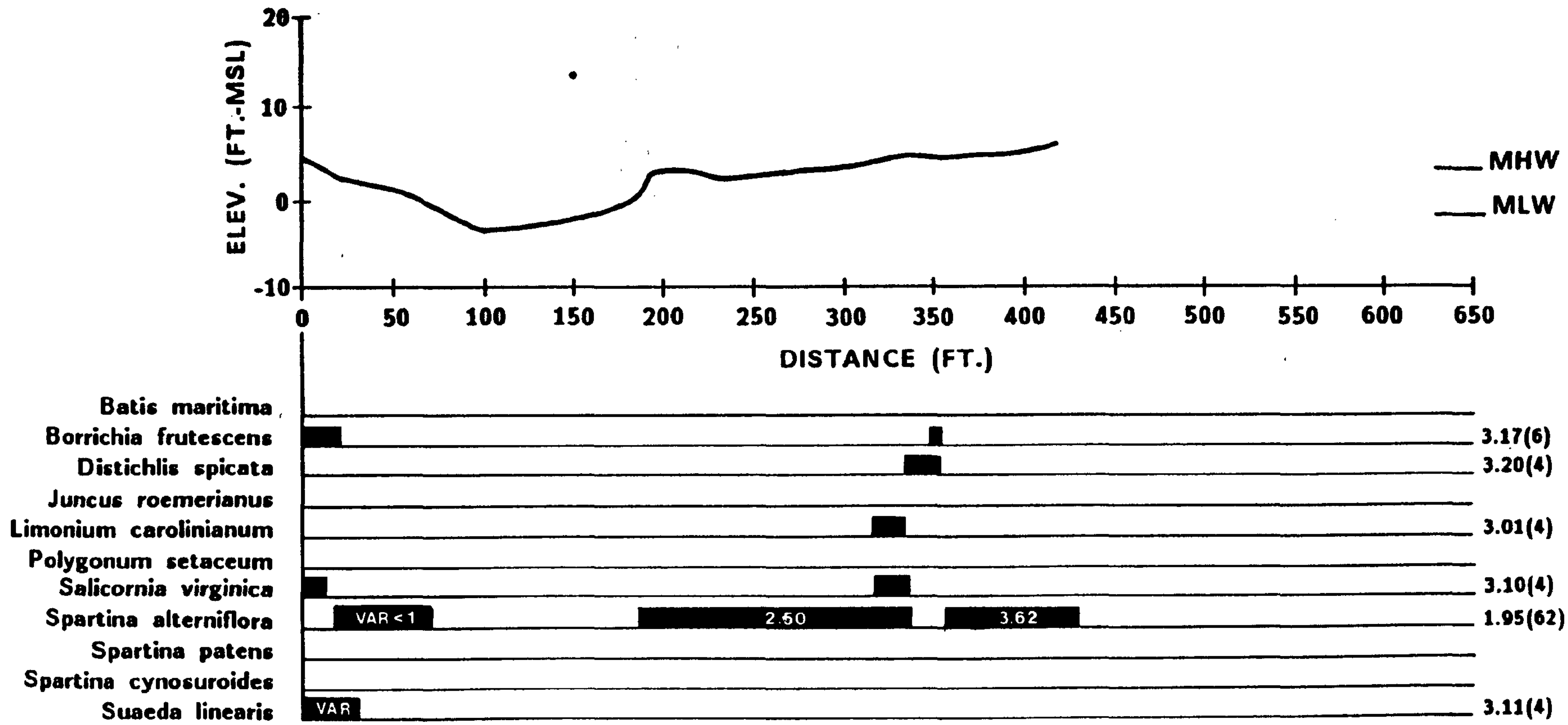
RANGE # EPA-5 BETWEEN B&RC TRACT "D" BLOCK "P" AND TRACT "D" BLOCK "Q"
KEY: 15 JUN 1984



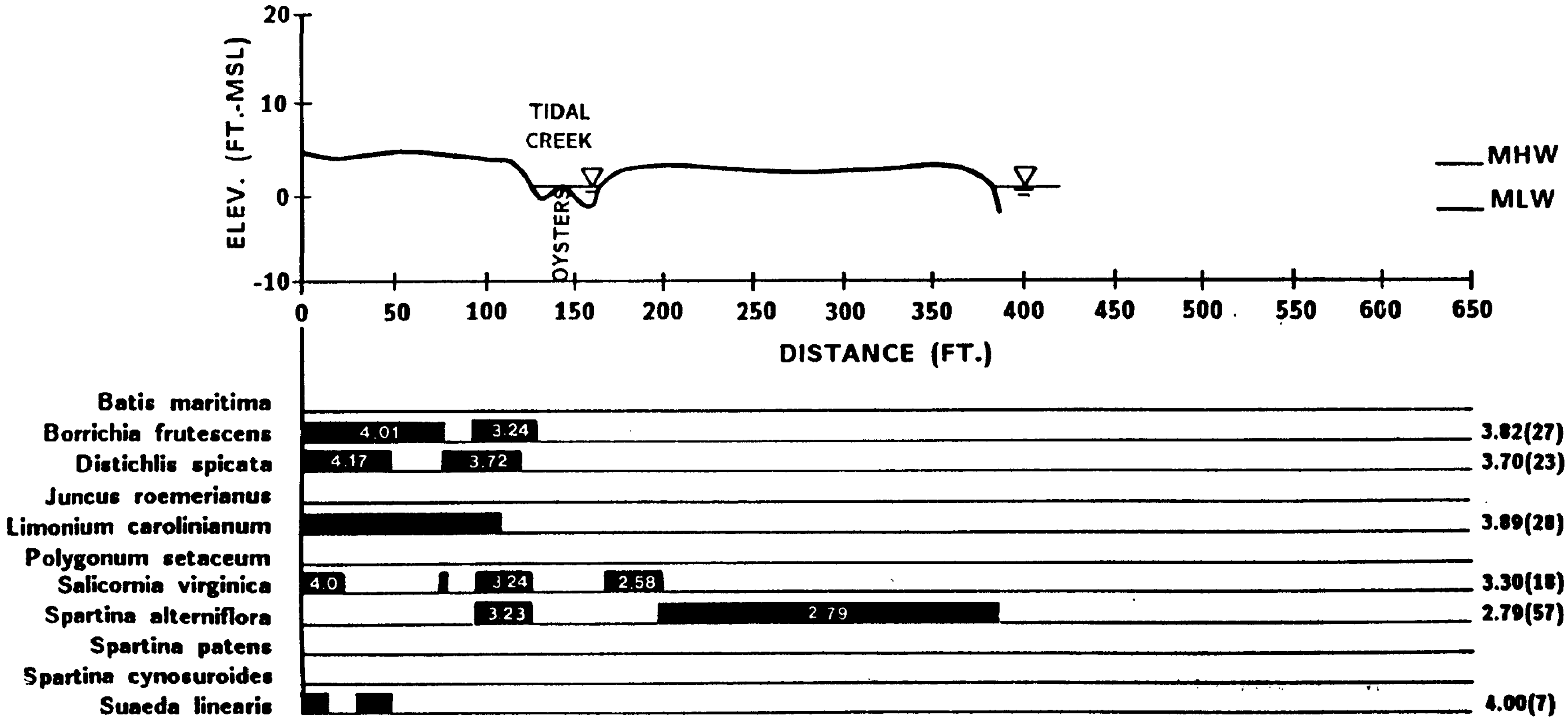
RANGE # EPA-6 LOT 54, WATERWAY ISLAND DRIVE
KEY: 15 JUNE 1984



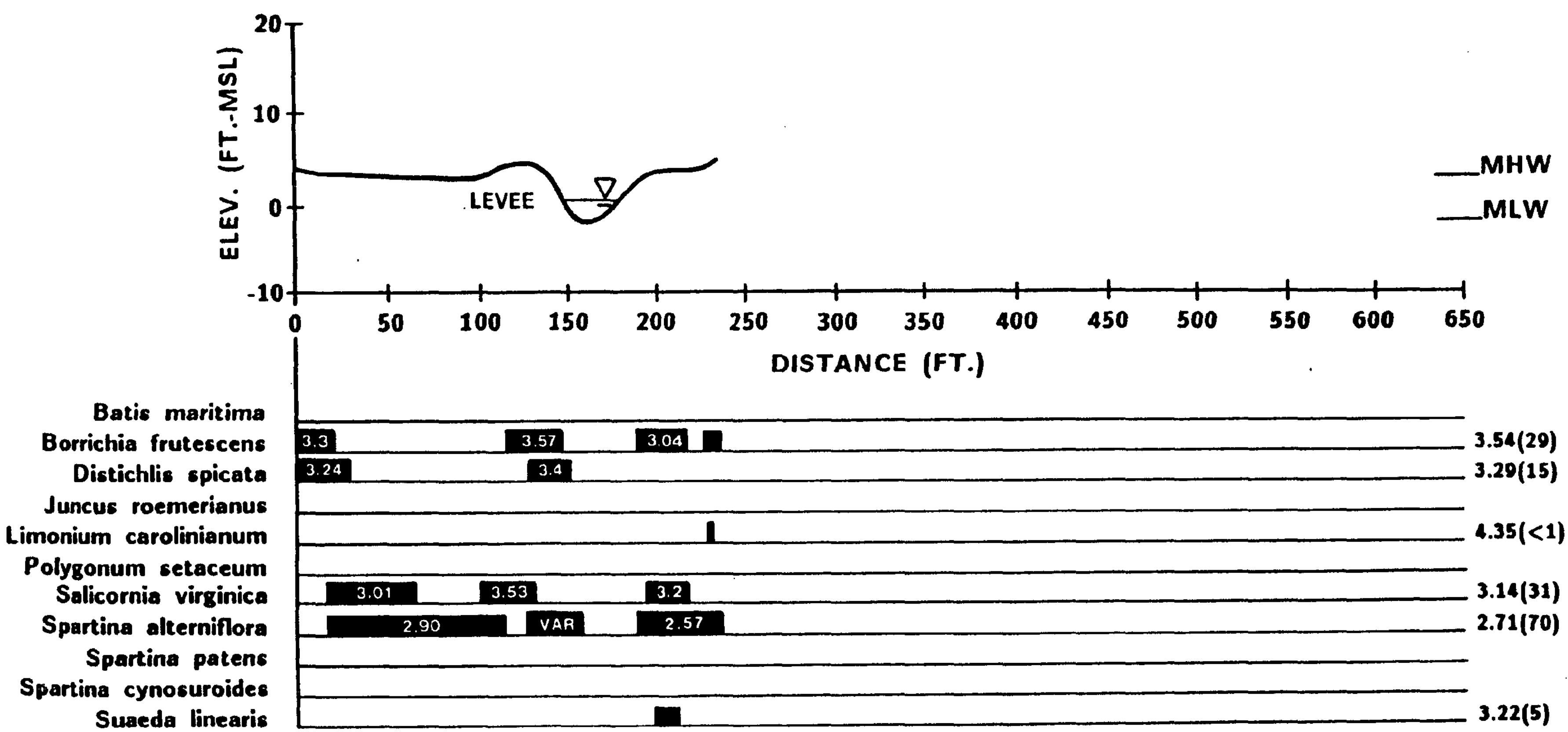
RANGE # EPA-7 LOT 57, WATERWAY ISLAND DRIVE
KEY: 15 JUNE 1984



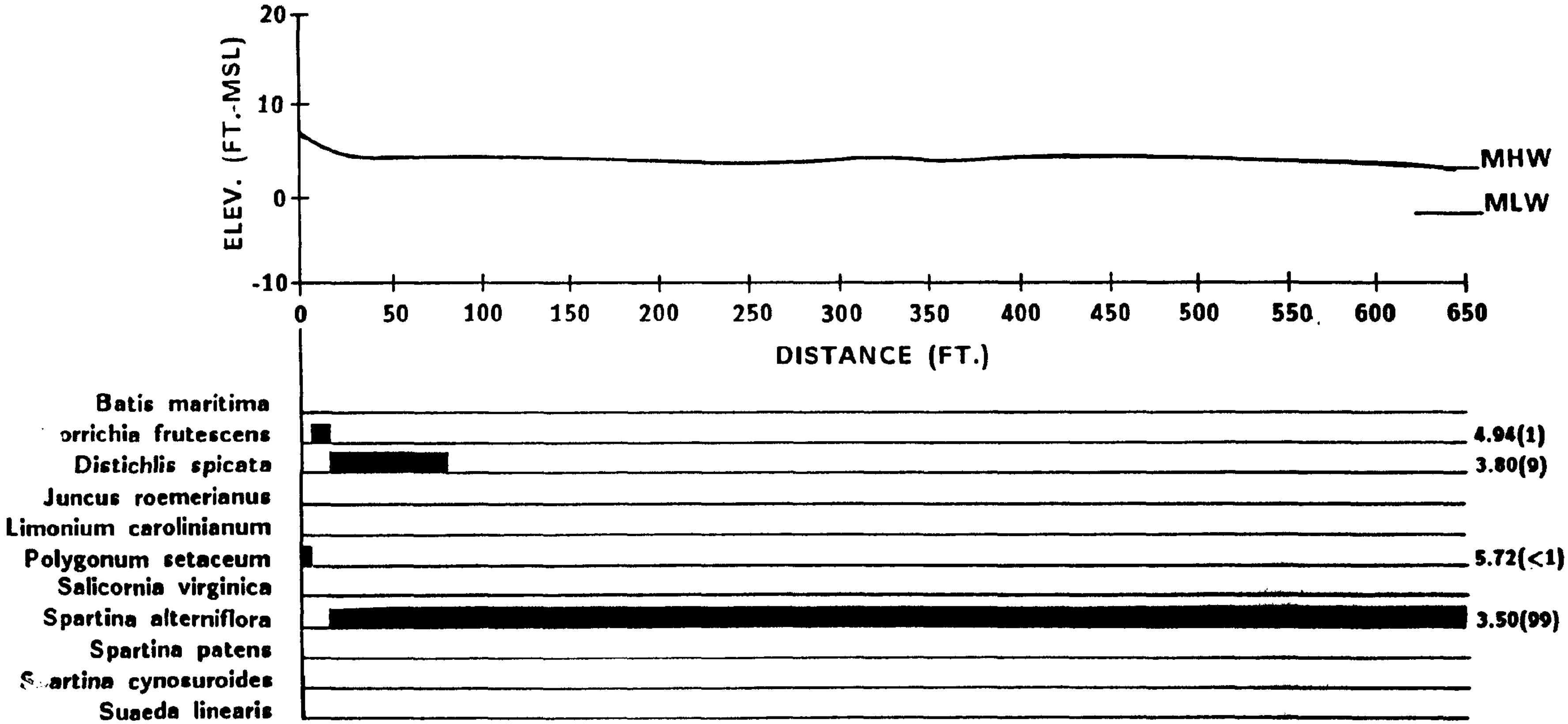
RANGE # EPA-8 DEWEES INLET, NEAR RPI MON. STATION 13, RUNNING WEST
KEY: 16 JUNE 1984



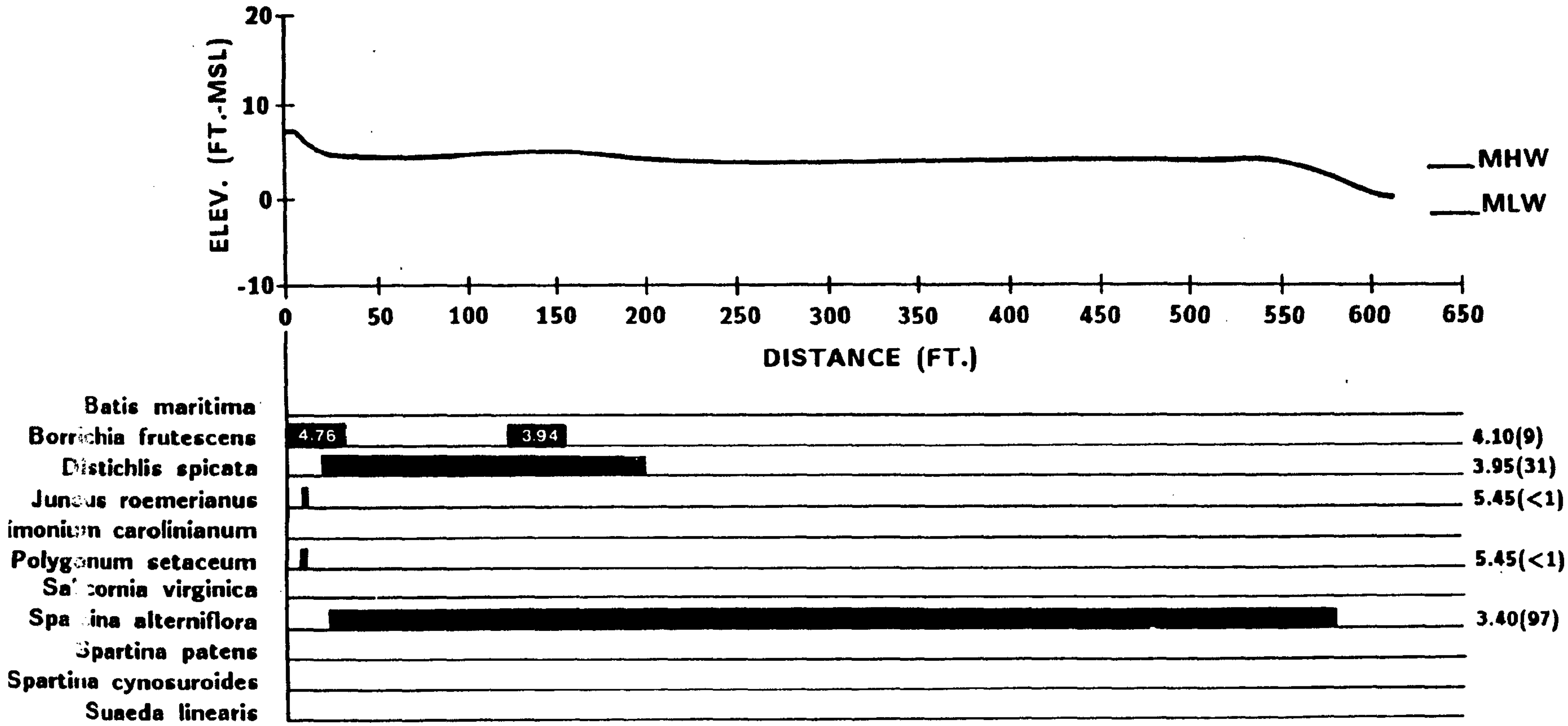
RANGE # EPA-9 DEWEES INLET, NEAR RPI MON. STATION 13, RUNNING NORTH
KEY: 16 JUNE 1984



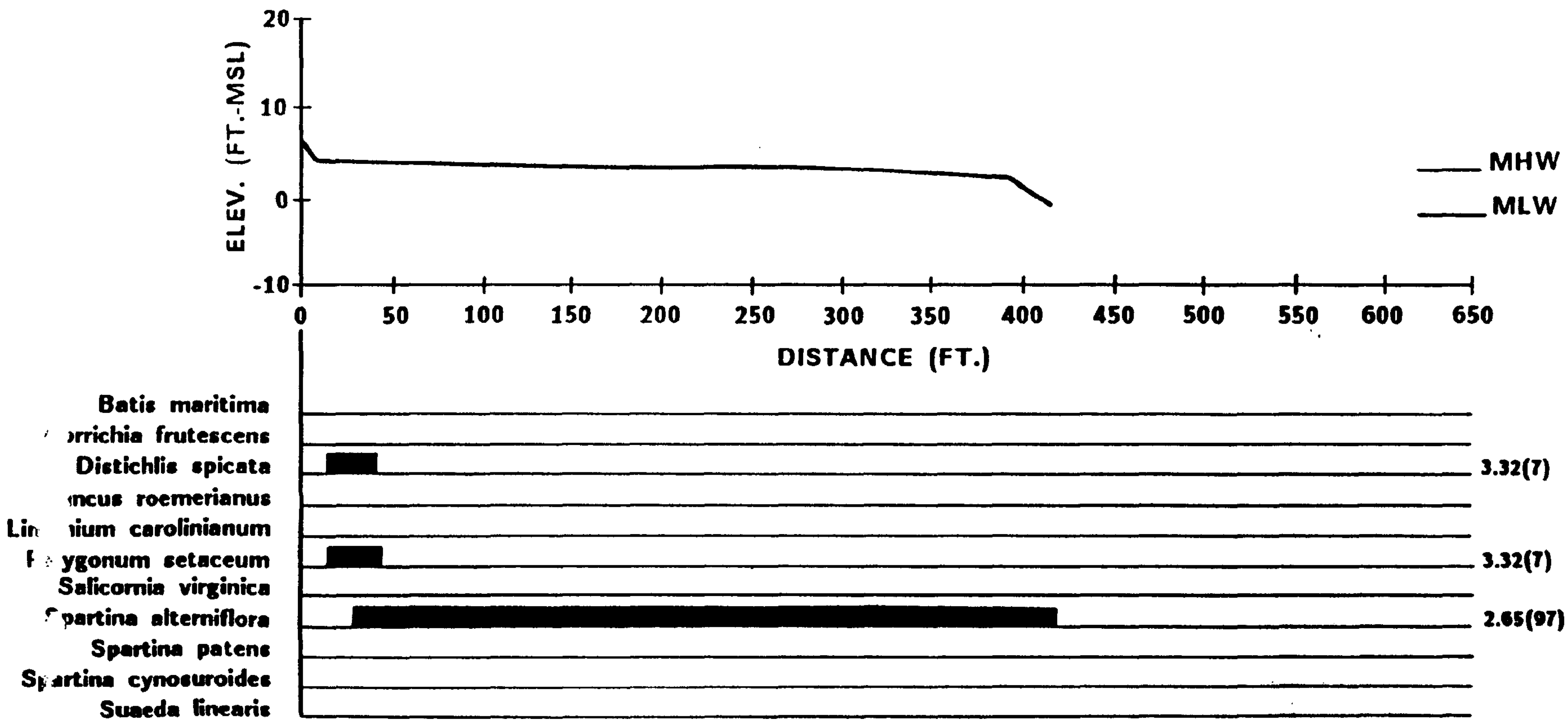
RANGE # EPA-10 790 WOODWARD RD., RUNNING WEST
KEY: 16 JUNE 1984



RANGE # EPA-11 790 WOODWARD ST., RUNNING SOUTH
KEY: 16 JUNE 1984



RANGE # EPA-12 END OF OAKDALE ST.
KEY: 16 JUNE 1984



APPENDIX B

TIDE ELEVATION PROBABILITY DISTRIBUTION FOR CHARLESTON, SOUTH CAROLINA

APPENDIX B. Tide elevation probability distribution for Charleston (based on data given in Ebersole, 1982).

*Common Reference**	*Elevation (ft)*	*Normalized Elev. (Elevation/ Tidal Range)*	*Probability (%)*	*Cumulative Probability (%)*
	5.2	1.000	0.00	0.00
	5.0	0.962	0.01	0.01
	4.8	0.923	0.02	0.03
	4.6	0.885	0.03	0.06
	4.4	0.846	0.08	0.14
	4.2	0.808	0.13	0.27
	4.0	0.769	0.26	0.53
	3.8	0.731	0.44	0.97
	3.6	0.692	0.72	1.69
	3.4	0.654	1.01	2.70
MSHW	3.2	0.615	1.54	4.24
	3.0	0.577	2.02	6.26
	2.8	0.538	2.55	8.81
MHW	2.6	0.500	2.97	11.78
	2.4	0.462	3.20	14.98
	2.2	0.423	3.40	18.38
	2.0	0.385	3.47	21.85
	1.8	0.346	3.48	25.33
	1.6	0.308	3.22	28.55
	1.4	0.269	3.18	31.73
	1.2	0.231	2.89	34.62
	1.0	0.192	2.76	37.38
	0.8	0.154	2.71	40.09
	0.6	0.115	2.69	42.78
	0.4	0.077	2.66	45.44
	0.2	0.038	2.65	48.09
	0.0	0.000	2.66	50.75
	-0.2	-0.038	2.67	53.42
	-0.4	-0.077	2.80	56.22
	-0.6	-0.115	2.94	59.16

APPENDIX B. Continued.

Common Reference*	Elevation (ft)	Normalized Elev. (Elevation/ Tidal Range)	Probability (%)	Cumulative Probability (%)
	-0.8	-0.154	3.13	62.29
	-1.0	-0.192	3.17	65.46
	-1.2	-0.231	3.47	68.93
	-1.4	-0.269	3.64	72.57
	-1.6	-0.308	3.78	76.35
	-1.8	-0.346	3.72	80.07
	-2.0	-0.385	3.77	83.84
	-2.2	-0.423	3.39	87.23
	-2.4	-0.462	3.14	90.37
MLW	-2.6	-0.500	2.54	92.91
	-2.8	-0.538	2.13	95.04
	-3.0	-0.577	1.67	96.71
MSLW	-3.2	-0.615	1.16	97.87
	-3.4	-0.654	0.86	98.73
	-3.6	-0.692	0.53	99.26
	-3.8	-0.731	0.35	99.61
	-4.0	-0.769	0.21	99.82
	-4.2	-0.808	0.12	99.94
	-4.4	-0.846	0.03	99.97
	-4.6	-0.885	0.02	99.99
	-4.8	-0.923	0.01	100.00
	-5.0	-0.962	0.00	100.00
	-5.2	-1.00	0.00	100.00

*MHW - mean high water
MLW - mean low water
MSL - mean sea level
MSHW - mean spring high water
MSLW - mean spring low water

APPENDIX C

AREA DISTRIBUTION BY ELEVATION ZONE FOR EACH OF THE FIVE PRINCIPAL LAND DIVISIONS IN THE CHARLESTON STUDY AREA

APPENDIX C. Area distribution (%) by elevation zone for each of the five principal communities or land divisions in the Charleston case study area under various sea level rise and mitigation scenarios.

ZONE	NO PROTECTION				LOW SCENARIO			HIGH SCENARIO		
	Existing (1980)	Baseline (2075)	Low Scenario (2075)	High Scenario (2075)	Protection @ 1980	With Anticipation Protection @2030	Without Anticipation Protection @2050	Protection @1980	With Anticipation Protection @2010	Without Anticipation Protection @2020
CHARLESTON PENINSULA -- 14,000 ACRES -- % AREA @ 2075										
Highland	53.4	52.3	51.5	47.9	53.4	52.4	51.9	53.4	51.6	51.0
Transition	3.7	3.6	3.1	3.1	1.2	2.2	2.7	0.0	0.0	0.0
High Marsh	1.1	1.4	2.0	2.1	2.0	2.0	2.0	0.0	1.5	2.1
Low Marsh	2.5	2.1	1.9	2.2	1.9	1.9	1.9	1.9	2.2	2.2
Tidal Flat	7.1	4.6	3.2	2.1	3.2	3.2	3.2	2.1	2.1	2.1
Water	32.0	36.0	38.3	42.6	38.3	38.3	38.3	42.6	42.6	42.6
TOTALS	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
WEST ASHLEY -- 9,500 ACRES -- % AREA @ 2075										
Highland	29.5	29.0	28.6	26.4	29.5	28.55	28.60	29.5	27.15	28.2
Transition	2.1	1.9	1.8	2.1	0.9	1.85	1.80	0.0	1.35	0.3
High Marsh	7.4	2.2	0.9	0.9	0.9	0.9	0.9	0.0	0.9	0.9
Low Marsh	16.8	14.3	9.9	0.9	9.9	9.9	9.9	0.8	0.9	0.9
Tidal Flat	7.4	12.2	15.6	3.5	15.6	15.6	15.6	3.5	3.5	3.5
Water	36.8	40.4	43.2	66.2	43.2	43.2	43.2	66.2	66.2	66.2
TOTALS	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
MT. PLEASANT: TOTAL ACRES = 15,750 -- % AREA @ 2075										
Highland	53.3	52.1	51.3	47.7	53.3	53.1	51.3	53.3	52.7	49.2
Transition	3.8	3.8	3.7	3.8	1.7	1.9	3.7	0.0	0.0	2.3
High Marsh	7.1	2.6	1.6	1.5	1.6	1.6	1.6	0.0	0.3	1.5
Low Marsh	16.7	13.5	9.8	2.3	9.8	9.8	9.8	2.0	2.3	2.3
Tidal Flat	3.2	10.4	14.9	3.9	14.9	14.9	14.9	3.9	3.9	3.9
Water	15.9	17.6	18.7	40.8	18.7	18.7	18.7	40.8	40.8	40.8
TOTALS	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

APPENDIX C. Continued.

ZONE	NO PROTECTION Existing (1980)	NO PROTECTION Baseline (2075)	NO PROTECTION Low Scenario (2075)	NO PROTECTION High Scenario (2075)	LOW SCENARIO Protection @ 1980	LOW SCENARIO With Anticipation Protection @2030	LOW SCENARIO Without Anticipation Protection @2050	HIGH SCENARIO Protection @1980	HIGH SCENARIO With Anticipation Protection @2010	HIGH SCENARIO Without Anticipation Protection @2020
SULLIVANS ISLAND: TOTAL ACRES = 1,750										
Highland	37.1	36.2	35.6	32.8	37.1	NA	NA	37.1	NA	NA
Transition	2.9	2.9	2.8	3.4	1.3	-	-	0.0	-	-
High Marsh	7.1	2.3	1.2	0.7	1.2	-	-	0.0	-	-
Low Marsh	15.7	13.0	9.6	1.7	9.6	-	-	1.5	-	-
Tidal Flat	8.6	12.4	14.7	3.5	14.7	-	-	3.5	-	-
Water	28.6	33.2	36.1	57.9	36.1	-	-	57.9	-	-
TOTALS	100.0	100.0	100.0	100.0	100.0	-	-	100.0	-	-
DANIEL ISLAND: TOTAL ACRES = 4,500										
Highland	41.6	40.7	40.2	37.5	41.6	NA	NA	41.6	NA	NA
Transition	2.8	2.8	2.6	2.8	1.2	-	-	0.0	-	-
High Marsh	5.0	1.9	1.2	1.1	1.2	-	-	0.0	-	-
Low Marsh	11.7	9.5	7.0	1.7	7.0	-	-	1.5	-	-
Tidal Flat	5.7	8.9	10.9	2.8	10.9	-	-	2.8	-	-
Water	33.2	36.2	38.1	54.1	38.1	-	-	54.1	-	-
TOTALS	100.0	100.0	100.0	100.0	100.0	-	-	100.0	-	-

☆U.S. GOVERNMENT PRINTING OFFICE: 1986—621—734—00190