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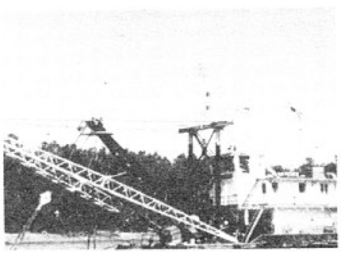

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GUIDELINES FOR VEGETATIVE EROSION CONTROL ON WAVE-IMPACTED COASTAL DREDGED MATERIAL SITES

by

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This report provides guidelines that permit the evaluation of vegetative stabilization alternatives for dredged material disposal areas using salt marsh wetland plants. The guidelines provide a methodology for classifying dredged material shorelines with respect to wave energy (low-, moderate-, or high-energy sites) and specify a vegetative stabilization strategy (standard planting techniques, root-anchored techniques, or wave protection structures) for each energy regime. Such guidelines provide dredged material planners and operations personnel the means to use dredged material for combined beneficial uses of wetlands creation, habitat development, and erosion control. The report also presents two case studies of salt marsh creation on dredged material sites located in North Carolina along the Atlantic Intracoastal Waterway and in Texas along the Gulf Intracoastal Waterway near Galveston. These studies provide guidelines for creating salt marsh on moderate- to high-energy sites exposed to both ship- and wind-generated waves.

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PREFACE

This study was conducted under the auspices of the Dredging Operations Technical Support (DOTS) Program, Beneficial Uses of Dredged Material Work Unit, which is sponsored by the Headquarters, US Army Corps of Engineers (HQUSACE). The DOTS is managed by the Environmental Laboratory (EL) of the US Army Engineer Waterways Experiment Station (WES) as part of the Environmental Effects of Dredging Programs (EEDP). Dr. Robert M. Engler was Program Manager for the EEDP; Mr. Thomas R. Patin was the DOTS Program Manager. Technical Monitor was Mr. Joseph Wilson, HQUSACE.

Parts I through IX of the report were prepared by Messrs. Paul L. Knutson and Hollis H. Allen, Coastal Ecologist and Botanist, respectively, Wetlands and Terrestrial Habitat Group (WTHG), Environmental Resources Division (ERD), EL. Appendix A of the report was prepared by Mr. Knutson; Dr. Steve Broome, Professor of Soil Science at North Carolina State University at Raleigh; and Mr. Frank E. Yelverton, Biologist, US Army Engineer District, Wilmington. Appendix B was prepared by Dr. James W. Webb, Professor of Ecology at Texas A&M University at Galveston, and Mr. Allen. Dr. Webb was employed by the WES under the terms of an Intergovernmental Personnel Act agreement.

Technical reviews were provided by Dr. Charles V. Klimas and Mr. Robert L. Lazor of the WTHG and by Mr. Donald D. Davidson of the Wave Research Branch, Coastal Engineering Research Center, WES. The report was edited by Ms. Jessica S. Ruff of the WES Information Technology Laboratory.

The work was conducted under the direct supervision of Dr. Hanley K. Smith and Mr. E. Carl Brown, respective Chiefs of the WTHG, and under the general supervision of Dr. Conrad J. Kirby, Chief, ERD, and Dr. John Harrison, Chief, EL.

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GUIDELINES FOR VEGETATIVE EROSION CONTROL ON WAVE-IMPACTED COASTAL DREDGED MATERIAL SITES

PART I: INTRODUCTION

Background

1. The US Army Corps of Engineers' dredging program involves maintenance work and the improvement of some 40,000 km of navigation channels that serve over 400 ports. This effort entails the disposal of about 230 million cubic meters of dredged material.

2. Dredging within the bays, sounds, and estuaries of the coastal United States consists of the excavation, transport, and disposal of material at an environmentally acceptable location within a reasonable distance from the navigation channel. Commonly, the margins of these disposal areas are subject to erosion from wind-generated waves or the wakes of passing boats or ships. Erosional losses may contribute to the infilling of navigation channels, increasing dredging requirements. A wide variety of engineering structures have been employed to abate erosional losses from these areas. However, because of the high cost of structural shore protection measures, it is often more cost effective to simply compensate for erosional losses with increased dredging.

3. Over the past decade, the US Army Engineer Waterways Experiment Station has assisted various Corps of Engineer Districts in stabilizing dredged material and developing coastal marshes. Early work focused on developing salt marshes on dredged material for habitat development in low-wave energy environments (Environmental Laboratory 1978) (Figures 1 and 2). More recently, the use of marshes to provide erosion control on wave-impacted dredged material shorelines has been evaluated (Allen, Webb, and Shirley 1984). Salt marsh plants have proven to be a cost-effective erosion control measure on dredged material shorelines while providing the combined benefit of wildlife and fisheries habitat.

4. These guidelines include a discussion of (a) vegetative stabilization theory, (b) site selection criteria, (c) advanced marsh-planting techniques, (d) cost evaluation procedures, and (e) salt marsh development demonstrations in North Carolina and Texas. Most of the research and

practical experience on this subject comes from projects on the Atlantic and gulf coasts of the United States. Practices such as the building of dredged material islands are more common in these coastal regions. The theory and principles presented in these guidelines will be generally applicable to the Pacific coast, but specific information may not apply. Few opportunities for shore protection with salt marsh vegetation will be encountered in the Pacific region due to a general avoidance of intertidal disposal alternatives.

5. Vegetative stabilization will continue to play a limited role in the Great Lakes. Hall and Ludwig (1975) evaluated the potential use of marsh plants for erosion control in the Great Lakes. They concluded that there were few areas suitable for this method of shore protection because of high wave energy, winter icing, and fluctuating lake levels. In Alaska, a relatively short growing season, broad tidal ranges, high-energy conditions, and icing prevent the use of salt marsh vegetation for erosion control. This alternative has not been used in the limited bays and estuaries of Hawaii.

Role of Marshes in Shore Stability

Wave damping

6. The aerial stems of marsh plants form a flexible mass that dissipates wave energy. A series of field experiments were conducted to measure wave dissipation in smooth cordgrass (*Spartina alterniflora*) marshes in Chesapeake Bay (Knutson, Seelig, and Inskeep 1982) (Figure 3). Table 1 summarizes the average wave height loss and associated wave energy loss for the Chesapeake study as a function of the distance across the marsh the wave

Table 1

Wave Height and Wave Energy Loss

Distance m	Wave Height* m	Wave Height Loss, percent	Wave Energy Loss, percent
2.5	0.15	40	64
5.0	0.15	57	72
10.0	0.17	65	88
20.0	0.16	87	98
30.0	0.18	94	100

* Wave height represents initial wave height when wave reached the edge of the marsh stand.

has traveled. Of importance is that more than 50 percent of the energy associated with these waves dissipated within the first 2.5 m of the marsh and that virtually no wave energy persisted at the 30-m distance for the conditions evaluated.

Sediment capture

7. As wave energy impacting a shoreline is reduced, there is increased potential for sediment deposition and decreased potential for erosion (sediment mobilization, suspension, and transport). Sediment deposition resulting from marsh planting has been observed in both laboratory and field studies. In laboratory studies, Gleason et al. (1979) observed increased sediment deposition coincident with increased stem density. Accretion was more than 5 cm after only 60 waves passed over a 3-percent slope containing plants at a density of about 100 stems per square meter. This phenomenon has also been documented in long-term field experiments. Woodhouse, Seneca, and Broome (1974) reported vertical accretion of 15 to 30 cm of sediment along planted shore profiles over about a 2-year period.

8. Under conditions of abundant sediment supply, marshes can prograde (advance) seaward. A recent study of historic shoreline trends in Charleston, SC, between 1939 and 1981 found net erosion on only 5 of 32 marsh shorelines (Kana et al. 1984). Some marshes were prograding at a rate of more than 10 m per year. The accretionary environment of Charleston Harbor has been attributed to the 1942 diversion of the Santee River into a tributary that discharges into the harbor. Studies have shown that the diversion may be responsible for 85 percent of harbor sedimentation.

Sediment reinforcement

9. Many marsh plants form dense root-rhizome mats that add stability to shore sediments. This protective mat is of particular importance during severe winter storms when the aerial stems provide only limited resistance to the impact of waves. Though it is empirically evident that root systems of coastal plants improve soil stability, there is little experimental evidence on the subject. Field measurements of shear strength of tidal flat and tidal marsh (Pacific cordgrass, *Spartina foliosa*; pickleweed, *Salicornia* spp.) sediments were measured in two California bays (Pestrong 1969) (Figure 4). The marsh sediments were found to have 2 to 3 times more shear strength than comparable tidal flat environments. The rate at which blocks of marsh are eroded from a marsh shore will be directly related to the shear strength of these marsh sediments.

Impact of Marshes on Shore Erosion

10. Chesapeake Bay, one of the world's largest estuaries, has one of the highest rates of tidewater erosion in the United States (Slaughter 1964). Rosen (1980) conducted an extensive evaluation of the erosion susceptibility of various types of shorelines in the Virginia portion of Chesapeake Bay. He calculated shore erosion and classified shore environments along 80 percent of the Virginia portion of Chesapeake Bay. He classified shorelines as (a) impermeable beaches--sand veneer overlying impermeable sediments, (b) permeable beaches--sand, (c) marsh barrier beaches--sand veneer overlying marsh peat, and (d) marsh margins. Table 2 summarizes erosion rates associated with these four shoreline types.

Table 2

Erosion of Shore Environments, Chesapeake Bay

Shore Type	Mean Erosion m/year
Impermeable	1.13
Permeable beach	0.85
Marsh barrier beach	0.66
Marsh margin	0.54

11. Rosen (1980) also observed fringe marshes (narrow marsh seaward of the beach) in association with all of the above beach environments. When present, fringe marshes reduced the mean rate of erosion on impermeable beaches by 38 percent, on permeable beaches by 20 percent, and on marsh barrier beaches by 50 percent. Rosen concluded that the presence of salt marsh in the structure of the shore, as a layer beneath the beach (marsh barrier), seaward of the beach (fringe marsh), or alone (marsh margin), results in increased shore stability.

12. The increased stability of marsh shorelines was also measured in a recent evaluation of historic shoreline change in Galveston Bay. Leatherman (1984) measured mean erosion rates of 1.3 m per year on sandy or silt-clay shores and only 0.6 m on marshy shores (rate calculated from the period 1850 to 1960).

PART II: SHORELINE REVEGETATION OBJECTIVES

Reduction of Channel Infilling

13. When dredged material is placed adjacent to an existing shoreline or in the form of an island, a new shoreline (beach) is created. Dredged material beaches typically experience short-term erosion and commonly are subject to continual, long-term losses. The beach, the intersection of the land and the sea, is where wave forces encounter the land. The beach responds to this attack by a variety of "give-and-take" measures that effectively dissipate the sea's energy.

14. The first defense against the sea's energy is in the form of the sloping nearshore bottom. When a wave reaches a water depth equal to about 1.3 times its wave height, the wave collapses or breaks (Munk 1949). Thus, a wave 0.3 m high will break in a depth of about 0.4 m. If there is an increase in the incoming wave energy, the beach adjusts its profile to facilitate the dissipation of the additional energy. This is most frequently done by the seaward transport of beach material to an area where the bottom water velocities are sufficiently reduced to cause sediment deposition. Eventually, enough material is deposited to form an offshore bar, which causes the waves to break farther seaward, widening the surf zone over which the remaining energy must be dissipated (Coastal Engineering Research Center 1984) (Figure 5).

15. All beaches go through continual change as sediments are temporarily removed from and later redeposited on the beach in response to wave conditions. In general, high, steep waves move material offshore, and low waves of long period (low steepness) move material onshore. However, when disposal areas are close to navigation channels, movement of sediment may be primarily offshore. During storms, steep waves may move sediment offshore into adjacent channels where it may be lost to the beach system; this material might have to be redredged to maintain safe navigation. This net loss of material from the beach system makes the beach increasingly vulnerable to erosion during subsequent storms and increases the potential for continued channel deposition.

16. Salt marsh vegetation can be established on the intertidal portion of some dredged material sites to reduce sediment loss. Woodhouse, Seneca, and Broome (1974) report on a series of salt marsh plantings on sandy dredged

material in Snow's Cut, North Carolina. Elevational profiles over a 2.5-year period indicate a continued accumulation of 4 to 10 cu m of sand per linear meter of shoreline per year. The stabilization or capture of material of this magnitude can substantially reduce dredging requirements in adjacent channels.

Shore Protection

17. The second major objective of vegetative establishment on dredged material is shore protection. Dredged material is frequently confined within containment dikes. Containment dikes allow more material to be placed in a smaller area and alleviate many water quality considerations. Continued use of containment areas depends upon the maintenance of the integrity of the dike structure. These structures are typically earthen in construction and may be in direct contact with the water. Where dikes are constructed, shoreline erosion is a common problem. To avoid direct wave attack, berms are often established seaward of the dike. Salt marsh plantings have proven to be an effective method of stabilizing the intertidal portion of the berm area, reducing erosion, and decreasing maintenance on the diked structure.

Environmental Enhancement

18. Establishing marsh plants to abate shore erosion generally will be considered as an "environmental enhancement." Positive biological and aesthetic benefits are typically associated with vegetative stabilization projects. Salt marshes are valued as sources of primary production (energy), as nursery grounds for sport and commercial fishery species, and as a system for storing and recycling nutrients. Once established, planted salt marshes function as natural salt marshes and gradually develop comparable animal populations (Cammen 1976; Cammen, Seneca, and Copeland 1976; Landin 1986; Landin, Webb, and Knutson 1989).

19. The primary pathway of energy flow from salt marshes is believed to be through the detrital food chain. Dead grass is broken down by bacteria in the surrounding waters and on the surface of the marsh. This process greatly decreases the total energy content but increases the concentration of protein, thereby increasing the food value. Some detrital particles and microalgae are eaten by a variety of deposit- and filter-feeders, such as fiddler crabs, snails, and mussels; these organisms are, in turn, eaten by predators such as

mud crabs, fish, and rails. The remaining detritus is washed from the marsh by tidal action. This exported detritus, with material from submersed aquatic plants and plankton, feeds the myriad of larvae and juvenile fish and shellfish that use estuaries, bays, and adjoining shallow waters. Marsh grasses may account for most of the primary production of the system in waters where high turbidity reduces light penetration, limiting phytoplankton and submersed aquatic vegetation.

20. Salt marshes are also a habitat for many coastal species. They are used by birds such as herons, rails, shorebirds, migratory waterfowl, and songbirds. A much larger population of animals lives in or on the mud surface. The more conspicuous inhabitants are crabs, mussels, clams, and periwinkles. Less obvious but more numerous are annelid and oligochaete worms and insect larvae. In addition, larvae, juveniles, and adults of many shellfish and fish are commonly found in the marsh creeks.

21. Marshes are a visual transition between land and water, and a natural feature of the landscape. They add form, color, and texture to the shoreline. Unlike other forms of shore protection, marsh plants, once established, provide no visible evidence that there has been a human effort to reduce erosion, as illustrated in Figure 6.

PART III: DETERMINING SITE SUITABILITY

Salinity

22. Salinity is a common factor affecting all salt marsh plants. These plants must have some salt tolerance, a prime requirement in this habitat. Some of the more tolerant species have the capacity to excrete salt through special structures (salt glands) in their leaves. A number of them possess another mechanism in their roots for screening toxic ions and slowing their inward penetration (Waisel 1972). Plants of the regularly flooded low marsh, such as smooth cordgrass, are well equipped to live and grow in salinities up to 35 ppt (sea strength). However, even smooth cordgrass establishes more quickly and grows more rapidly in salinities below sea strength. Seeds and young seedlings are usually more sensitive to salt concentration than are established plants.

23. Soil salinity is not easy to investigate because of the high variability, in time and space, of salt concentrations. The concentration of salt required to eliminate a particular species from a site need not occur often or persist for more than a few hours or days. Consequently, these events may elude fairly intensive sampling. Toxic concentrations usually do not develop in sandy marsh soils within the regularly flooded zone. The salinity in such soils tends to remain close to that of the surrounding water. However, this may not always be true of fine-textured soils in which salt may accumulate through ion exclusion by roots (Barko and Smart 1977). Also, depositing dredged material over hypersaline soils may create toxic, subsurface lenses.

24. Irregularly flooded high marshes are subject to occasional salt buildup through evaporation and ion exclusion regardless of soil texture. However, this is usually limited to poorly drained areas. In humid climates, precipitation, plus freshwater seepage from higher ground, tends to keep salinities in most high marshes well below sea strength. Under more arid conditions, salt concentrations often exclude marsh species altogether. In general, suitable plants that can be established in salinities up to about sea strength may be found in all coastal areas. Stabilizing dredged material with intertidal vegetation in bays and estuaries, where salinities seasonally exceed sea strength, is not likely to succeed. If salinity is a suspected problem, the presence, abundance, and vitality of native intertidal plants in

sheltered areas near the proposed project will be the most reliable indicator of probable success.

Soils

25. The distribution of most salt marsh plants is not limited by soil type or texture. They may be found growing on mineral soils ranging from coarse sands to heavy clays and on peats and mucks of widely varying nutrient content and degree of decomposition. This does not mean that soils are unimportant to marsh establishment and growth. Soil characteristics affect marsh planting in at least three respects--substrate stability, nutrient supply, and ease of planting.

26. Even under the most favorable conditions, transplants require several weeks to anchor themselves and still more time to develop an appreciable protective effect. Substrate is important to this process. In loose sands, even when net erosion may be minimal, substrate movement resulting from wave action may dislodge the transplants before they can become fully anchored. The threat of substrate movement is less critical in cohesive soils, which tend to be more stable.

27. Nutrient deficiencies are seldom encountered on dredged sediments because of their alluvial origins. However, the objective of erosion control on dredged material is to establish rapid plant cover. For this reason, nutrient supplements (fertilizer) are routinely applied, particularly on sandy materials. Black (1968), Epstein (1972), Gauch (1972), Tisdale and Nelson (1975), and Russell (1977) adequately cover the subject of soil fertility and plant growth.

28. The nature and origin of the soils in a region will often provide general guidance as to the probability of fertilizer needs. For example, young soils formed from moderately weathered materials, such as occur in the Mississippi Delta, are much less likely to be deficient in nutrients than the much older, highly weathered sediments that predominate along much of the Atlantic coast.

29. Soil characteristics can greatly influence the planting process. It is essential that the soil be taken into account early, as it will often dictate the planting method and thus have a major effect on costs. Loose, sandy soils are usually easy to plant; planting holes are readily opened by hand with shovels, spades, or dibbles and are easily closed and firmed after

transplanting. Tractor-drawn planters work well on these soils (Figure 7). On fine-grained dredged material deposits, mobility may be greatly reduced, which complicates hand planting and often precludes mechanical planting.

Elevation

30. The target area in vegetative stabilization projects is the portion of the shore in direct contact with the waves--the intertidal zone. The portion of the intertidal zone suitable for plant establishment is dependent upon (a) the plant species selected, (b) the local tidal range, and (c) regional trends. Though there is some variation in the elevation (tidal) zones in which marsh plants can be established, the following is a general guide. On the Atlantic and gulf coasts, marsh plants can be found throughout much of the intertidal zone where the tidal amplitude is less than about 1.0 m. Where the tidal amplitude exceeds 1.0 m, the lower elevational limit of invasion is more restricted. In areas of the north Atlantic, where the tidal amplitude may reach or exceed 3.0 m, plants are restricted to the upper one half or less of the tidal zone. On the southern Pacific coast, marsh plants seldom extend below the elevation of mean tide, irrespective of tidal amplitude. In the northern Pacific coast, most of the intertidal zone lacks marsh vegetation because of the influence of large tidal ranges and the absence of suitable adapted species. Marshes are rarely found below the elevation of mean lower high water in this region. Local variability can often be accounted for by measuring the elevational range of existing natural marshes in the project area.

PART IV: EVALUATING WAVE CLIMATE SEVERITY

Wave Energy Indicators

31. It is a complex task to describe wave environments in which marsh plantings are likely to survive and thrive. Many physical and biological variables must be acknowledged when attempting to describe the impact of waves on marsh stability. First, the frequency and magnitude of severe wave conditions will be largely influenced by local climatological patterns, the expanse of open water (fetch), and water depth. Second, the impact these waves have on the shore will depend on the tidal stage or water level coincident with these waves, as well as such factors as offshore contours, foreshore slope, and shore configuration. Third, the ability of the marsh to withstand wave stress will depend on its growth stage, density, vigor, and overall width.

Wind-generated waves

32. Knutson et al. (1981) developed a method for classifying shorelines with respect to wave energy based upon a limited number of shore characteristics. Ten shore characteristics were identified as potential indicators of wave severity. Eighty-six marsh-planting sites in 12 coastal states were evaluated with respect to these indicators as part of the National Marsh Survey (NMS) and Erosion Control Project. Four parameters proved to be useful indicators: average fetch and longest fetch (defined below), shore geometry, and sediment grain size. The relationships between these parameters and planting success were condensed into a vegetative stabilization site evaluation form, which provides an estimate of planting success.

33. Because the NMS evaluated only natural shorelines, difficulty is often encountered in applying this information to dredged material disposal areas. Marsh development on dredged material typically requires an appraisal of site suitability prior to the disposal of the material and the creation of a new intertidal shoreline. The sediment grain size parameter, in particular, cannot be validly applied to potential disposal sites. Sediment grain size will be influenced by the type of material that is deposited and will not be a valid indicator of wave severity at the site.

34. Similar site evaluation studies were initiated by the Virginia Institute of Marine Sciences (VIMS) in 1981 (Hardaway et al. 1984). Twenty-four sites were selected in the tidelands of Virginia on Chesapeake Bay. Each

of the selected sites was then planted by VIMS and evaluated over a 2-year period. The VIMS program found excellent agreement between the single parameter of average fetch and the multiple parameters identified in the NMS. Knutson and Steele (1988) discuss the use of the single parameter "average fetch" for evaluating wave climate and potential planting success on dredged material.

35. Fetch is the distance over open water the wind blows to generate waves. Average fetch is simply the average of three measured fetch lengths--one measurement perpendicular to the shore and two measurements at 45-deg angles (0.8 rad) to perpendicular. For coastal engineers, fetch is an important parameter in estimating wave height. The height of a wave formed by a constant wind blowing over water of a constant depth is directly related to fetch length (Coastal Engineering Research Center 1984). This relationship is not linear. For example, a constant wind blowing 50 km/hr over a constant water depth of 6 m will generate a 15-cm wave over a fetch of about 150 m, a 30-cm wave over 750 m, a 45-cm wave over 2 km, and a 60-cm wave over 4 km. As fetch length increases, it has incrementally less influence on wave height; however, in general, the greater the fetch, the greater the potential for extreme wave conditions. For this reason, fetch is a useful indicator of potential planting success (the presence of vegetation and the absence of measurable erosion landward of the vegetation).

36. Figure 8 compares average fetch and planting success for all sites evaluated in the NMS (86 sites) and in the VIMS study (24 sites). The number of sites with fetches over 9.0 km was limited (only 16); however, the value of this parameter is clearly illustrated.

37. A second useful parameter in evaluating wave climate severity is shore geometry (the shape of the shoreline). Common sense would dictate that sites located in narrow coves may be effectively sheltered from waves approaching at oblique angles and will be subjected to large waves only when winds blow directly onshore. Conversely, sites located on headlands are exposed to waves from many directions. A more complex, though equally important, concept involves the bending of waves as they approach the shore (wave refraction). Under the influence of nearshore contours, wave crests bend toward alignment with the shore (Figure 9). This produces a divergence of energy in coves and a convergence of energy on headland features. Consequently, similar wave events may focus more erosive force on a headland than

in a cove. Figure 10 summarizes planting success with respect to shore geometry in the 110 sites evaluated in the NMS and the VIMS study.

38. Webb, Allen, and Shirley (1984) found shore configuration useful in describing within-site variability at a large planting in Mobile Bay. They evaluated a 1.6-km-long marsh planting along one leg of a triangular-shaped dredged material island. Though the entire leg was exposed to comparable wind-generated waves, plant cover was variable. They found that the degree of shore exposure (shore configuration) had a measurable impact on plant density. Sixty-three percent of the samples on indented shorelines (less than 120 deg (2.1 rad) of exposure) had medium to dense cover, versus 34 percent on more exposed shores (more than 120 deg of exposure). Sixty-five percent of samples on exposed shores were sparsely vegetated, versus 37 percent on indented shores.

Boat-generated waves

39. Even on shores relatively sheltered from wind waves, concern is often expressed over the potential impact of ship- or boat-generated waves. Shore areas close to ship traffic will be subject to vessel-generated waves. The height of waves produced by a given vessel depends primarily on the speed of the ship relative to water depth and, to a lesser extent, on the hull form and draft. The wave climate produced by vessels at a particular shore site will depend on the magnitude of the boat traffic and the distance between the shore and the passing vessels.

40. Developing accurate estimates of the severity of boat-generated waves at a particular site requires direct observation of the boat traffic and the associated waves. Recent studies (described in Appendix A) have helped contrast the relative importance of wind-generated versus boat-generated waves. A wind-sheltered dredged material island in Swansboro, NC, was planted with salt marsh vegetation for stabilization in 1987 (Appendix A). The island is exposed to a fetch of only 0.5 km, but is located on the Atlantic Intracoastal Waterway where it is exposed to waves produced by the passing of approximately 25,000 boats per year at a distance of 100 to 200 m. The magnitude and frequency of wind and boat waves were studied at this site over a 2-year period. The study found that boats could produce waves equal to those produced by extreme wind conditions. However, in every category of waves (Table 3), wind-generated waves were 10 times more frequent than were boat-generated waves. Boat waves are probably responsible for less than 5 percent of the wave energy impacting this site. Considering the

limited fetch and the heavy vessel traffic of this example, it would appear that vessel traffic alone will seldom be the limiting factor in establishing coastal marshes for erosion control.

Table 3

Wind Waves Versus Boat Waves

Swansboro, NC

Wave Height cm	Cumulative Duration and Frequency 1,000 min/year	1,000 waves/year
	Wind Waves	
0-15	326	9,780
15-24	40	1,200
24-30	4	120
>30	1	63
	Boat Waves	
0-15	6.6	197
15-24	1.3	38
24-30	0.3	8
>30	0.2	5

Wave Energy Evaluation Form

41. In the previous section, the importance of average fetch and shore geometry as indicators of average climate severity was discussed. In this section, these parameters are combined into a single Wave Climate Evaluation Form (Figure 11). This form permits the user to classify shorelines within three categories: (a) low wave energy, (b) moderate wave energy, or (c) high wave energy. After the shoreline has been appropriately classified with respect to wave energy, the form specifies the minimum acceptable option for vegetative stabilization on this shoreline. Shorelines classified as low-wave energy sites can be stabilized with the Standard Planting Techniques discussed in Part V of this report. Shorelines classified as moderate wave energy should employ either the Specialized Planting Techniques discussed in Part VI or the Wave Protection Structures discussed in Part VII. Usually, shorelines classified as high-wave energy sites should have wave protection structures employed at a minimum. At some sites, however, erosion control mats have shown promising results without wave protection structures (Appendix B).

PART V: STANDARD PLANTING TECHNIQUES (LOW-WAVE ENERGY SITES)

Site Preparation

42. An important first step in the process of stabilizing dredged material shorelines is the creation of a broad, gradual sloping beach. Broad beaches dissipate wave energy, protecting plants during the establishment period, and are the foundation of a broad marsh that will ultimately provide long-term shore protection. When practicable, a design slope of about 1 vertical to 15 horizontal (1V:15H) or more gradual should be maintained.

43. Planting width (the width of the beach at an elevation suitable for plant establishment) will also influence the relative effectiveness of the planting. Waves are dampened as they pass through stands of marsh vegetation. The amount of dampening that occurs is directly related to the width of the marsh. From a survey of erosion control plantings, Knutson et al. (1981) concluded that erosion control plantings should maintain a width of at least 6.0 m. In this report, a more conservative minimum width of 10.0 m is recommended. The potential width (landward to seaward) of a particular planting depends on the tidal amplitude and shore slope. Broader marshes can be established coincident with greater tidal ranges and more gradual sloping shorelines.

44. In most cases, compliance with the recommended preplanting beach slope of 1V:15H will provide a potential planting area equal to or greater than 10.0 m. Where potential planting width exceeds the recommended minimum, the entire width should be planted to maximize opportunity for success. When the planting area is not sufficiently wide, the beach must be graded further to accommodate the 10.0-m minimum width. Creating beach slopes more gradual than 1V:15H will only be necessary in microtidal environments where tidal amplitude is less than about 0.5 m. Creating a minimum planting width in these environments is often critical to success because wave energy is focused upon such as a narrow elevational range. For example, Rosen (1980) observed that erosion in Chesapeake Bay was inversely related to tidal amplitude (higher rates of erosion associated with narrow tidal ranges).

Selecting Plant Species

Principal species

45. The regularly flooded portion of the intertidal zone is the focus of vegetative stabilization efforts. This is the region in which erosion normally begins; continuing erosion of the lower slopes in this region will undermine and weaken well-stabilized upper slopes. Consequently, the primary emphasis will be on the planting and management of the few specially adapted species found useful for this purpose. Often, the establishment and maintenance of a healthy band of intertidal salt or brackish marsh along a shore will eventually result in the natural growth of vegetation on the slope behind it.

46. Four species of pioneer plants have demonstrated potential in stabilizing the part of the intertidal zone which is in direct contact with waves. Smooth cordgrass (*Spartina alterniflora*) (Figure 12) is an effective erosion control plant along the gulf and Atlantic coasts; Pacific cordgrass (*Spartina foliosa*) (Figure 13) is effective on the southern Pacific coast from Humboldt Bay, south to Mexico; and Lyngbye's sedge (*Carex lyngbyei*) (Figure 14) and tufted hairgrass (*Deschampsia caespitosa*) (Figure 15) are effective for stabilization in the northern Pacific coast from Humboldt Bay to Puget Sound. Detailed planting specifications for these species can be found in Environmental Laboratory (1978) and Knutson and Woodhouse (1983).

Other useful species

47. In some cases, the planting of the upper portion of the intertidal zone (mean high water to the highest estimated tide) is advisable to control erosion caused by storm surges, surface runoff, and wind, or is desirable for wildlife/fisheries habitat development, aesthetic, or other reasons. Several potentially useful species that have been used to supplement intertidal plantings are black needle rush (*Juncus roemerianus*), common reed (*Phragmites australis*), big cordgrass (*Spartina cynosuroides*), gulf cordgrass (*S. spartinae*), saltmeadow cordgrass (*S. patens*), saltgrass (*Distichlis spicata*), seaside arrowgrass (*Triglochin maritima*), and seashore paspalum (*Paspalum vaginatum*). The need to plant these species should be evaluated for each individual site. Planting specifications and guidelines for the use of these species are given in Environmental Laboratory (1978) and Knutson and Woodhouse (1983).

Planting Procedures

Materials

48. Choosing the type of planting materials and determining a source of suitable planting stock should be done early in the planning process. The cost of planting stock usually represents a substantial part of the total expense, and this cost can vary over a wide range. Locating a suitable source of plants may be the most difficult problem to be solved. The practice of salt marsh planting is still relatively new in this country. Both the development and the demonstration of planting techniques have taken place over the past 15 years. Although a substantial number of successful field-scale plantings have been made, this has not yet become a standard practice. Therefore, the demand for planting stock is still small, erratic, and unpredictable. Consequently, such materials are not generally commercially stocked; however, a number of nurseries produce plant materials on order. In general, state offices of the Soil Conservation Service maintain lists of potential commercial growers.

49. Marsh plants are propagated either by seeds or some type of vegetative transplant. Since direct seeding is effective only under fairly sheltered conditions, the planting of dredged material areas subject to erosion will usually be confined to the following vegetative transplants: (a) sprigs, which are bare root plants dug from the wild or from field nurseries, (b) pot-grown seedlings; or (c) plugs, which are root-soil masses containing several intact plants dug from the wild. There is no one best type of planting stock. The quality of the material is often the key to success. High-quality material in any form can be very successful. High quality in this context means young, vigorous, actively growing vegetation that is large enough to carry appreciable stored food reserves. Early initiation of new growth is essential if transplants are to establish under the rigorous conditions existing on most eroding shorelines. This new growth cannot be expected of old or stunted plants, regardless of transplant form.

50. The three types of planting stock vary in availability, cost, and ease of planting:

- a. Sprigs are the least expensive of the three types and easier to handle, transport, and plant. They must be obtained from field nurseries (planted a year or more in advance), from young developing natural stands, or along the edges of stable or expanding marshes. Sprigs are best dug from sandy substrates (Figure 16).

_b_. Pot-grown seedlings are more expensive to grow and plant, more awkward to handle and transport, but relatively easy to produce. Seedlings of most species can be grown to transplanting size in 3 to 5 months, and this can be done almost anywhere with very simple, inexpensive facilities and equipment. However, their cost is usually at least 2 to 5 times that of sprigs. Seedlings become increasingly expensive to carry over when transplanting is delayed. Repotting in larger containers soon becomes essential. The coordination of plant production and site preparation is a frequent stumbling block in the use of seedlings. However, potted material is often used when wild sources are not readily available or when local regulations discourage wild harvest. Potted materials are also superior for use in late-season plantings (Figure 17).

_c_. Plugs are the most expensive planting type: the cost is usually about twice the cost of pot-grown seedlings. Plugs are heavy, laborious to dig, difficult to transport, and more difficult to plant. Satisfactory plugs can be dug only from marshes growing on cohesive substrates. Plugs from old crowded stands are likely to be too slow in initiating new growth. However, plugs are occasionally the only planting stock available on short notice.

Methods

51. The essentials in successfully transplanting salt marsh plants include opening a hole or furrow deep enough to accommodate the plant to the required depth, closing the opening, and firming the soil around the plant. This operation should be done during low water, as it is virtually impossible to do a satisfactory job of transplanting while the surface is flooded. Openings can close too rapidly, and plants tend to float out. A number of tools and procedures are effective in substrate that is not flooded.

52. Hand planting can be very satisfactory if adequate attention is given to details, particularly planting depth and soil firming after planting; this is usually the most practical method for small-scale plantings. Opening of planting holes is readily done with dibbles, spades, and shovels in loose, sandy soils. Portable power-driven augers work well in the more difficult cohesive or compact soils. Normally, planting crews work in pairs, one worker opening holes and the other inserting the plant and closing the hole. A third worker is used if fertilizer is added in the planting hole; this worker drops in a measured amount of material just after the hole is opened and before the plant is inserted.

53. Machine planting can do a much more uniform job and is far more economical than hand planting in large-scale plantings. Tractor-drawn

planters designed to transplant crop plants such as cabbage, tomatoes, and tobacco are available in most regions. Although some may require an alteration of the row opener for certain soils, they can often be used without alteration. The principal barriers to machine planting are usually inadequate traction on compact and slippery substrates, insufficient bearing capacity on soft sites, or the presence of tree roots or stones that interfere with the functioning of the row opener.

54. Most species will develop satisfactorily when planted 2 to 5 cm deeper than their depth when originally dug or removed from pots. However, in planting exposed shores, it is often highly desirable to anticipate erosion or accretion trends that are likely to prevail during the first month or two after planting. Where erosion is expected, plants should be set even deeper than the 2- to 5-cm depth. Where deposition is likely, they should be set very close to their original depth when dug or removed from pots.

Replanting

55. Achieving stability on dredged material shores with vegetation often requires both perseverance and patience. First, severe storms during establishment may cause temporary setbacks, even on highly promising sites, but these setbacks should not discourage the planter. More formidable and expensive coastal engineering structures are often damaged by the untimely occurrence of severe storms. Low-wave energy sites as defined in this report are sites that are exposed to less than a 9.0-km average fetch, or exposed to fetches of 9.0 to 18.0 km but located in a sheltered cove (see Wave Climate Evaluation Form, Figure 11).

56. Use of the Standard Planting Techniques, as described in this section, is recommended for vegetative stabilization on these sites. However, the success of an initial planting is far from guaranteed. Knutson et al. (1981) observed that one of three initial plantings fails on sites exposed to fetches of less than 9.0 km, and one of two initial plantings fails in the fetch range of 9.0 to 18.0 km.

PART VI: SPECIALIZED PLANTING TECHNIQUES (MODERATE-WAVE ENERGY SITES)

Recent Research

57. Planting failure is frequently encountered when Standard Planting Techniques are employed in moderate-wave energy environments. Moderate-wave environments are straight shorelines that are exposed to an average fetch of 9.0 to 18.0 km or have the prescribed combination of average fetch and shoreline geometry summarized in the Wave Climate Evaluation Form (Figure 11). In moderate environments, plants are often dislodged by waves before they can become established.

58. The WES has been assisting the US Army Engineer District, Mobile, since 1981 with the vegetative stabilization of a dredged material island. During 1981 and 1982, portions of Gaillard Island, a dredged material island in Mobile Bay, Alabama, were planted with marsh grass sprigs, the most often used Standard Planting Technique. The purpose of the planting was to stabilize an unvegetated shoreline on the northwest side of the island (1.5 km long) that is subject to low and moderate wave energies (average fetch = 6.0 km; shoreline geometry = variable cove to headland). The northwest side of the island is actually a dike, one of three dikes that enclose the disposal area (Figure 18). In some places, washout occurred even after three planting attempts. Washout of transplants was a problem in areas with long, straight beaches and steep shorelines. Coves and broad, shallow flats vegetated rapidly and experienced relatively little washout (Allen, Webb, and Shirley 1984).

59. In 1983, experiments were initiated on a series of new transplant techniques aimed at holding the plants in place until they could become established (plant-stem stabilization). A total of 10 new techniques were tested at Gaillard Island in areas that had been previously planted and had washed out two or three times. Two plant-stem stabilization techniques demonstrated potential at Gaillard: plant rolls and erosion control mats. These techniques were subsequently tested in Galveston Bay, Texas (see Appendix B); the Southwest Pass of the lower Mississippi River; and on Coffee Island in Mississippi Sound.

Site Preparation

60. Creating a broad, gradual sloping beach to dissipate wave energy is even more critical in moderate wave climates (see Site Preparation, Part V). As noted in the previous description of Gaillard Island, repeated failures were encountered on steeply sloping shores. In moderate-wave energy environments, the criteria for a maximum slope of 1V:15H and the minimum planting width of 10 m should be strictly observed.

Selecting Plant Species

61. In Part V, several species of pioneer plants are listed that have demonstrated potential for stabilizing low-energy environments. However, because this is a very new technology, only one salt marsh plant species has been tested using plant-stem anchoring techniques--smooth cordgrass (Figure 12). Smooth cordgrass can be used throughout the Atlantic and gulf coasts. However, smooth cordgrass is not native to the Pacific coast and should be avoided. Planting of Pacific coast natives such as Pacific cordgrass (Figure 13) in moderate-wave environments must be considered experimental in nature. None of the common intertidal species on the west coast establish and spread as rapidly as smooth cordgrass.

Planting Procedures

62. Two planting methods have demonstrated the potential for increasing plant survival by anchoring the plant stem during establishment: plant rolls and erosion control mats.

Plant roll

63. A plant roll is constructed by placing soil and six transplant clumps (several stems from one intact root mass) at 0.5-m intervals on a strip of 4-m-long by 0.9-m-wide burlap. The sides and ends of the burlap are brought together around the plants and fastened with metal rings. This creates a 3-m-long roll of plants and soil (Figure 19). The plant rolls are placed end-to-end and parallel to the shoreline and buried to such a depth that only the plant stems are exposed. Typically, individual plant rolls are installed about 1 m apart.

64. Plant rolls have also been used to add stability to standard single-stemmed transplant areas. This technique was used at Coffee Island in Mississippi Sound south of Bayou La Batre, Alabama (Figure 18). The site was formed from dredged material consisting largely of clay that was deposited in 1981 adjacent to the east side of Coffee Island, a natural island. The dredged material formed an eroding face due to wave action. The site was subject to low wave energy along straight portions of the shore and moderate energy on protruding headland features (Wave Climate Evaluation Form - average fetch = 6.0 km; shoreline geometry = straight to headland). Plant rolls (one row) were placed end-to-end seaward of single-stemmed transplants over a linear distance of about 0.5 km to cover an area 5 to 10 m in width (landward to seaward).

65. Periodic inspection revealed that the plant rolls placed end-to-end and seaward of single-stemmed transplants satisfactorily stabilized the eroding dredged material face. This is evident from a comparison of the photo presented as Figure 20a, taken 3 months after planting, and Figure 20b, taken 1.5 years after planting. Upon inspection of the site at the time of the latter, the marsh fringe showed signs of accreting sediment and protecting the island from further erosion (Allen, Shirley, and Webb 1986).

Erosion control mats

66. As noted earlier, marshes abate erosion by damping wave energy and binding the sediment. Erosion control mats attempt not only to anchor the plant but also to bind the surrounding sediment. The mats act as an instant root mat, providing the sediment with a fibrous, erosion-resistant surface. A type of mat found to be effective is a biodegradable fabric mat that consists of 0.1 kg/sq m of natural fibers (coconut and horsehair). The mat is laid like a carpet on the shore, and single-stemmed transplants are inserted into slits cut through the material. The edges of the mat are buried in the sediment.

67. Erosion control mats are about three times as costly to install as plant rolls, and experimental evidence is lacking to justify their extensive use. In fact, in the Mobile Bay experiments (Allen, Webb, and Shirley 1984), plant rolls were somewhat superior in performance. The Gaillard Island shoreline was exposed to low and moderate wave energy, and sediments were a mixture of fine sand and cohesive material. However, in the Galveston Bay studies (Allen, Shirley, and Webb 1986), erosion control mats showed an impressive performance under extreme wave conditions (see Appendix B).

68. The Bolivar site in Galveston Bay is a sandy, high-wave energy shoreline (Wave Climate Evaluation Form - average fetch = 20 km; shoreline geometry = straight). As discussed, the planting of such sites is not recommended without wave protection. Plant rolls were washed out at the Bolivar site, although portions of three of four mat plots remained intact long enough to promote colonization and growth of plants, which have remained to the present. Researchers speculate that erosion control mats may be superior on eroding sandy shorelines where sand particles can be captured in the interstices of the material. Conversely, they suspect that plant rolls will be more cost effective on sediments that have a cohesive component.

Wave Protection

69. In moderate-wave climates, wave protection devices can be used to reduce wave impact on the shore. Once protected from wave impact, it is often possible to employ Standard Planting Techniques (Part V) on a shore that would not otherwise be suitable for these low-energy planting techniques. In these situations, wave protection is used in lieu of plant-stem anchoring. The types of low-cost, temporary devices that are used for this purpose are discussed in detail in Part VII.

PART VII: WAVE PROTECTION ENGINEERING (HIGH-WAVE ENERGY SITES)

70. In moderate wave climates, wave protection is an alternative to the use of plant-stem anchoring techniques. In high-energy environments, wave protection will always be required. However, experience suggests that a breakwater is only necessary for the first 2 to 3 years after planting, until the plants have spread by rhizomes and completely covered the target planting area (Newling and Landin 1985). Therefore, in this discussion, only less expensive and expedient breakwaters, such as sandbag breakwaters, floating tire breakwaters, and fixed tire breakwaters, are considered. It should be noted that when dikes are used to contain dredged material, the area inclosed is sheltered from wave activity. In this respect, containment dikes are breakwaters. When planting the interior of contained dredged material areas, low-energy, standard planting techniques are appropriate (Part V).

71. Breakwaters should be placed far enough offshore to allow maximum marsh development width (landward to seaward). They should be placed in water depths so they continue to float at mean low water. Marsh planting should begin at a distance equal to or exceeding half an average wavelength landward of the breakwater. This is done to prevent the marsh from being scoured and eroded from turbulence and backwash caused by the breakwater.

72. Though marsh can be established on virtually any shoreline if adequate wave protection is provided, there are practical limits to the wise use of this alternative. Temporary breakwaters will provide protection to plantings for a period of 2 to 3 years. Experience indicates that once the breakwater ceases to protect the planting, an eroding scarp may form on the leading edge of the planted area. This scarp or bank will be the focus of continued erosion until the entire planted marsh is gone.

73. Knutson et al. (1981) describe a planting at Cedar Island, North Carolina, that was fully established after 2 years (Figure 21a) but completely eroded after 8 years (Figure 21b). This was a high-energy site (average fetch = 20 km). One should anticipate that after a breakwater ceases to function, erosion will begin to degrade the seaward edge of the marsh. The greater the wave energy at the site, the shorter will be the effective life (design life) of the vegetative stabilization effort. For shallow water (about 3.0 m deep), a practical average fetch-length limit for vegetative stabilization projects (even when temporary wave protection is provided) might

be about 36 km. Under these wave climate extremes, the effective life of the planting will approach the design life of the breakwater structure. In addition, extreme wave conditions also increase the chance that the temporary breakwater will fail prior to its expected functional life.

Sandbag Breakwater

74. Any container filled with sand, sand-cement, or concrete that is used as building block material for a breakwater will be considered a sandbag breakwater for purposes of this discussion. In construction projects, nylon fabric bags are typically used because of their durability. Sandbag breakwater life expectancy is 2 to 5 years, depending upon site accessibility to humans and subsequent vandalism, exposure to sunlight (ultraviolet rays degrade fabric), and energy forces exerted against the dike. Bags can be filled onsite with hydraulic pumps (sand/water slurry) until inflated and then sealed. Bag breakwaters must be underlain with filter cloth to prevent scour and resultant subsidence of the structure. While intact, sandbag breakwaters provide nearly total protection from wave attack. One consequence of this protection is that sediment deposition may initially be quite high in the protected area. To avoid burial of the new plantings, the planting operation should be delayed several weeks until a measure of stability has been achieved.

75. A sandbag was successfully used in 1975 to develop salt marsh on a dredged material site on the Bolivar Peninsula adjacent to Galveston Bay, Texas (Figure 22) (Allen et al. 1978). This site is a high-wave energy shore (Wave Climate Evaluation Form - average fetch = 20 km; shore geometry = straight). A breakwater 300 m long and 1.5 m high was constructed from 0.5- by 1.4- by 2.9-m nylon bags (Figure 23). Sprigs of smooth cordgrass were planted immediately landward of the breakwater.

76. Before this project, no natural marsh existed on this side of Galveston Bay because of the high-energy conditions. The sandbag breakwater provided enough initial protection of the transplants to permit marsh establishment (Newling and Landin 1985, Landin 1986). Despite the eventual degradation of the breakwater structure, the marsh has continued.

Floating Tire Breakwater

77. Floating tire breakwaters (FTBs) and shoreward salt marsh plantings have been successfully used to stabilize shores of unconfined dredged material deposits at two sites on the gulf coast. In 1981, a two-tier FTB (Figure 24) and smooth cordgrass sprigs stabilized part of the dredged material dike on Gaillard Island in Mobile Bay (Figure 18). A two-tiered breakwater was tested in 1984 at the Bolivar Peninsula, Texas, 1 km west of the 1975 high-energy site described in paragraph 75 (see also Appendix B). The configuration was selected for field testing after wave tank studies demonstrated that it could reduce wave energies by as much as 80 percent (Markle and Cialone 1986). Smooth cordgrass was planted shoreward of the breakwater using conventional single-stem techniques. Plantings unprotected by a breakwater were also planted in an adjacent area. Results to date indicate that the protected area has been completely covered by smooth cordgrass.

Fixed Tire Breakwater

78. A breakwater consisting of tires threaded on 15-cm-diam poles (Figure 25) was also tested at the Bolivar Peninsula site in 1984. Shoreward plantings similar to those used behind the two-tiered breakwater (previous section) were employed. Plant cover after 2 years was similar to that observed behind the FTB (47 percent). In subsequent years, however, the poles holding the tires which formed the breakwater broke, scattering the tires. Then, lack of wave protection led to significant plant washout (see Appendix B).

PART VIII: COSTS

Comparison of Vegetative Stabilization Alternatives

79. Single-stemmed propagules can be harvested and planted for about $0.15 per plant or $6,000/ha (planting costs based upon labor rate of $6.00/hr and an additional $0.10/plant for digging, gathering, and transporting). Because of their low unit cost, they are the primary planting method used in low-wave energy areas and in conjunction with breakwaters in high-energy areas. Potted seedlings and plugs are approximately 3 times more expensive than single-stemmed materials. Plant rolls are the lowest cost of the plant-stem anchoring methods, having a unit cost of about $0.60 or about $24,000/ha. Anchoring plants with erosion control mats increases the per unit cost to about $1.58 or about $63,000/ha.

80. The lowest cost method of providing temporary wave protection is the FTB. The two-tiered breakwater can be installed on the shoreline for about $114/m. Planting a 10-m-wide area with single-stemmed plants behind the breakwater increases the cost per meter to $120. A similar installation using a fixed tire breakwater increases the cost to $148/m of shoreline. Table 4 provides a cost comparison of these vegetative stabilization alternatives.

Cost Comparison with Other Shore Protection Methods

81. Vegetative stabilization is the least costly of all erosion control measures (Figure 26). A 10-m-wide (landward to seaward) planting using Standard Planting Techniques (single-stemmed plants, potted seedlings, and plugs) on low-energy shorelines will range in cost from $6 to $18/m. The plant-stem anchoring planting methods (plant roll and erosion control mat) used in moderate-wave energy areas can be installed for $24 to $63/m. The use of wave protection devices (tire or sandbag breakwaters) in high-energy areas further increases costs to a range of $120 to $259/m. However, traditional erosion control structures usually require a substantially higher investment. For example, the cost of a 10-m-wide rock (riprap) revetment is about $340/m of shoreline protected, and bulkheads may exceed $1,000/m (Eckert, Giles, and Smith 1978).

Table 4

Costs of Alternative Vegetative Stabilization Techniques

Vegetative Stabilization Alternative	Planting Cost/m	Structure Cost/m	Total Cost/m
Single-stemmed plants*	$ 6.00	--	$ 6.00
Potted seedlings and plugs	$18.00	--	$ 18.00
Plant roll (anchoring)	$24.00	--	$ 24.00
Erosion control mat (anchoring)	$63.00	--	$ 63.00
Floating tire breakwater with single-stemmed plants	$ 6.00	$114.00	$120.00
Fixed tire breakwater with single-stemmed plants	$ 6.00	$142.00	$148.00
Sandbag breakwater with single-stemmed plants**	$ 6.00	$253.00	$259.00

* Costs are based on an hourly rate of $6.00 plus $0.10 per plant for digging, gathering, and transporting. Costs of material are included; other direct and indirect costs are not included. Costs per meter also assume that plants are placed on 0.5-m centers and are planted to a width (landward to seaward) of 10 m.

** Costs of the sandbag breakwater construction are based on personal communication with James L. Wells, US Army Engineer District, Wilmington, 12 April 1988. Estimate is for 1.5-m-high breakwater.

PART IX: CONCLUSIONS

82. These guidelines permit the evaluation of vegetative stabilization alternatives for both existing and anticipated dredged material disposal areas. The guidelines provide a methodology for classifying dredged material shorelines with respect to wave energy (low-, moderate-, or high-energy sites) and specify a vegetative stabilization strategy (Standard Planting Techniques, root-anchored techniques, or wave protection structures) for each energy regime. Evaluating the potential use of these strategies will require the consideration of both economic and environmental factors.

83. The economic benefit of any dredged material stabilization effort is usually the reduction of operation and maintenance costs. These costs are associated primarily with the redredging of material due to erosion and channel infilling and the maintenance of containment structures. When the potential benefits of shore protection measures exceed their costs, their use is fully justified. Because vegetative stabilization is the least costly of all erosion control alternatives (Figure 26), its use will often be justified when more costly structural measures are not.

84. The process of vegetative stabilization involves the construction of a new wetland. Because of a general acceptance of the intrinsic value of wetlands as a National environmental resource, wetland construction can be justified upon grounds other than the traditional cost-benefit analysis. Engineer Regulation 1165-2-27, 30 July 1982, outlines the water resource policies and authorities for the establishment of wetland areas in connection with dredging. The following is an excerpt from the regulation:

> Establishment of any wetland area in connection with the dredging required for an authorized water resources development project may be undertaken in any case where the Chief of Engineers in his judgment finds that:
>
> (1) environmental, economic and social benefits of the wetland area justify the increased cost thereof above the cost required for alternative methods of disposing of dredged material for such project; and
>
> (2) the increased cost of such wetland area will not exceed $400,000 and
>
> (3) there is reasonable evidence that the wetland area to be established will not be substantially altered or destroyed by natural or man-made causes.

85. This regulation will not be widely used for vegetative stabilization projects because these projects will typically (a) be economically

justified on their own, (b) entail relatively small wetland acreages, and (c) have a limited design life of perhaps 10 to 20 years. The regulation will be more generally applicable to wetland construction in sheltered areas or those protected by containment dikes. However, the regulation underscores the fact that constructed wetlands have environmental values in addition to the engineering values that are emphasized in these guidelines.

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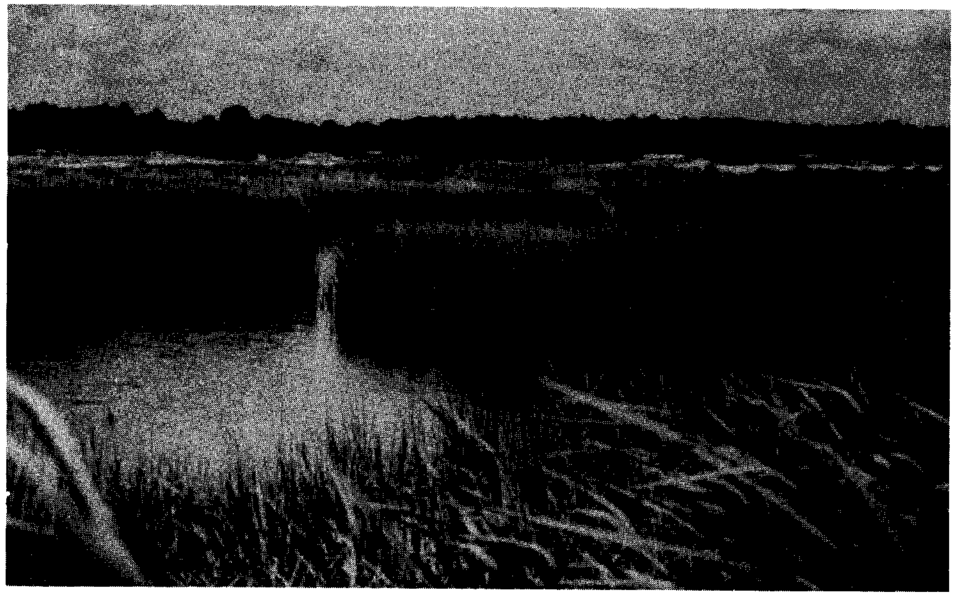


Figure 1. Marsh development site, Apalachicola Bay, Florida (from Environmental Laboratory 1978)

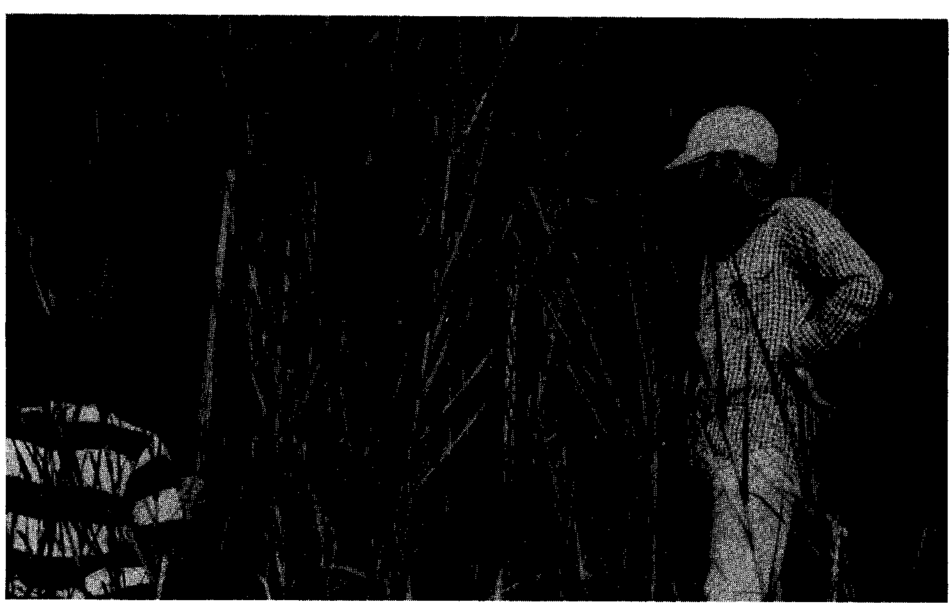


Figure 2. Buttermilk Sound habitat development field site, Altamaha River, Georgia (from Landin, Webb, and Knutson 1989)

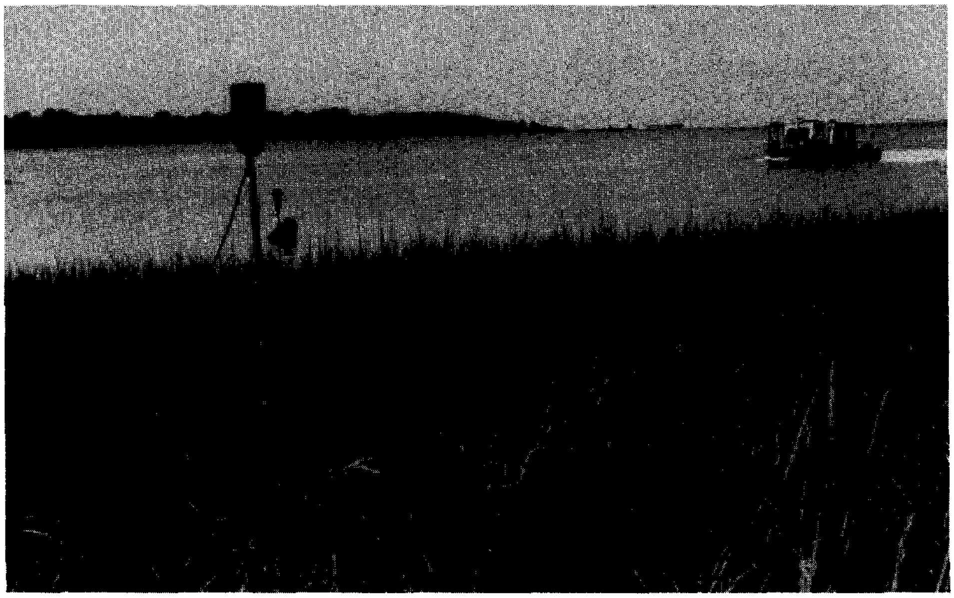


Figure 3. Measuring wave dissipation in smooth cordgrass marsh, Chesapeake Bay, Virginia (from Knutson, Seelig, and Inskeep 1982).

Figure 4. Scarp or bank on seaward edge of coastal marsh, San Francisco Bay, California (from Knutson and Woodhouse 1983)

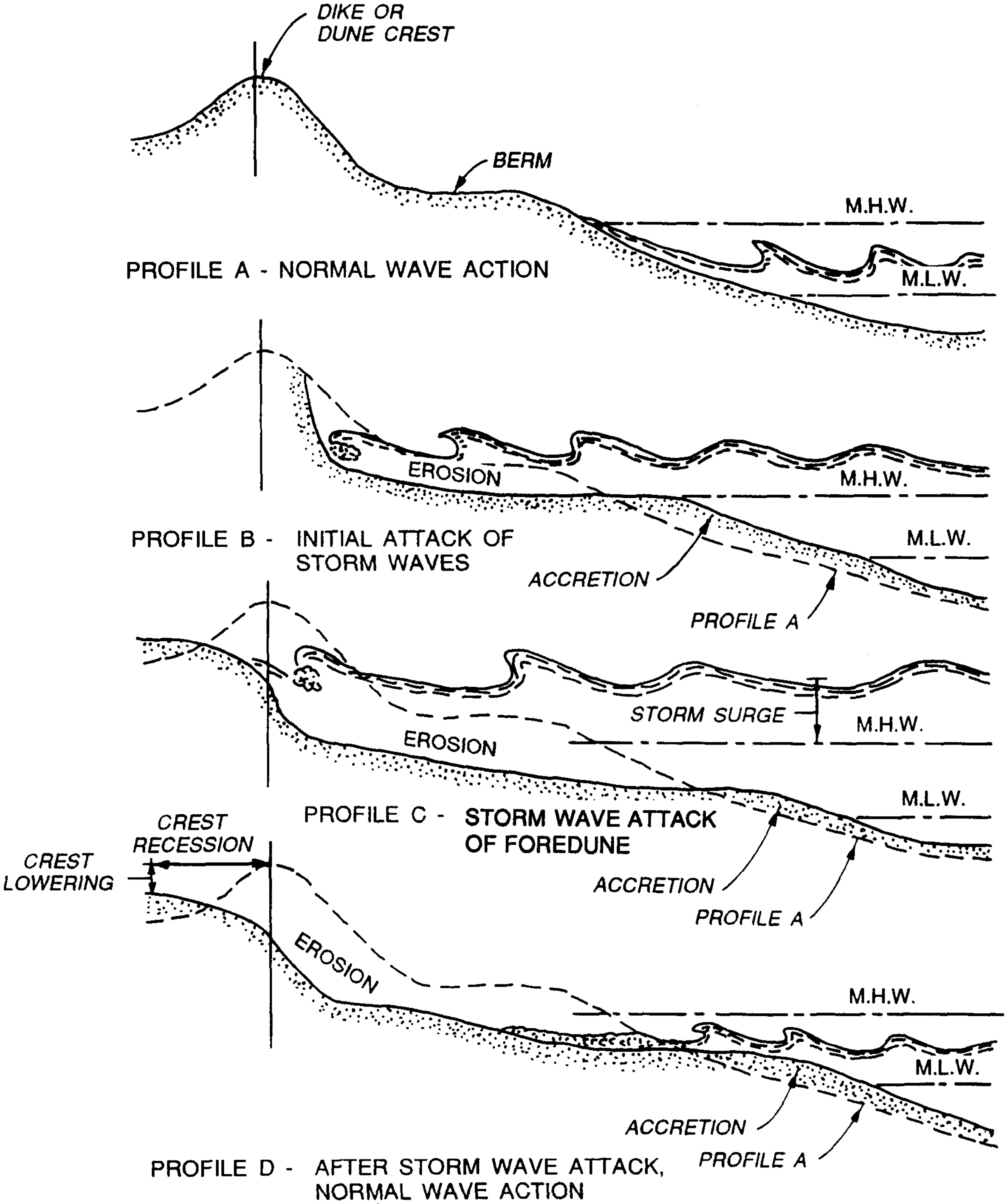


Figure 5. Erosion during storm wave attack on beach (from Coastal Engineering Research Center 1984)

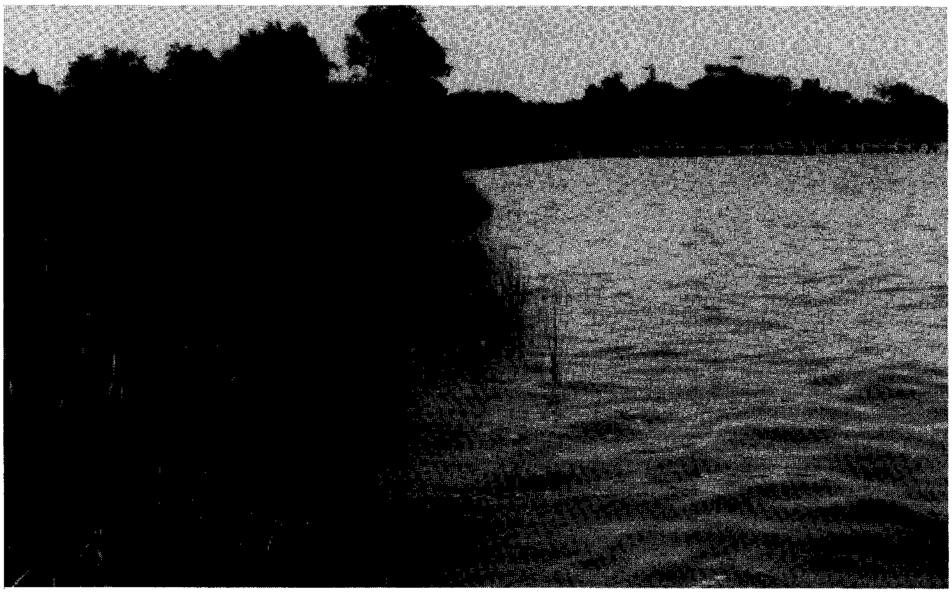


Figure 6. Appearance of natural shoreline, planted in 1934, Cherrystone Inlet, Virginia (from Knutson et al. 1981)

Figure 7. Mechanical planting with disk-type tobacco planter

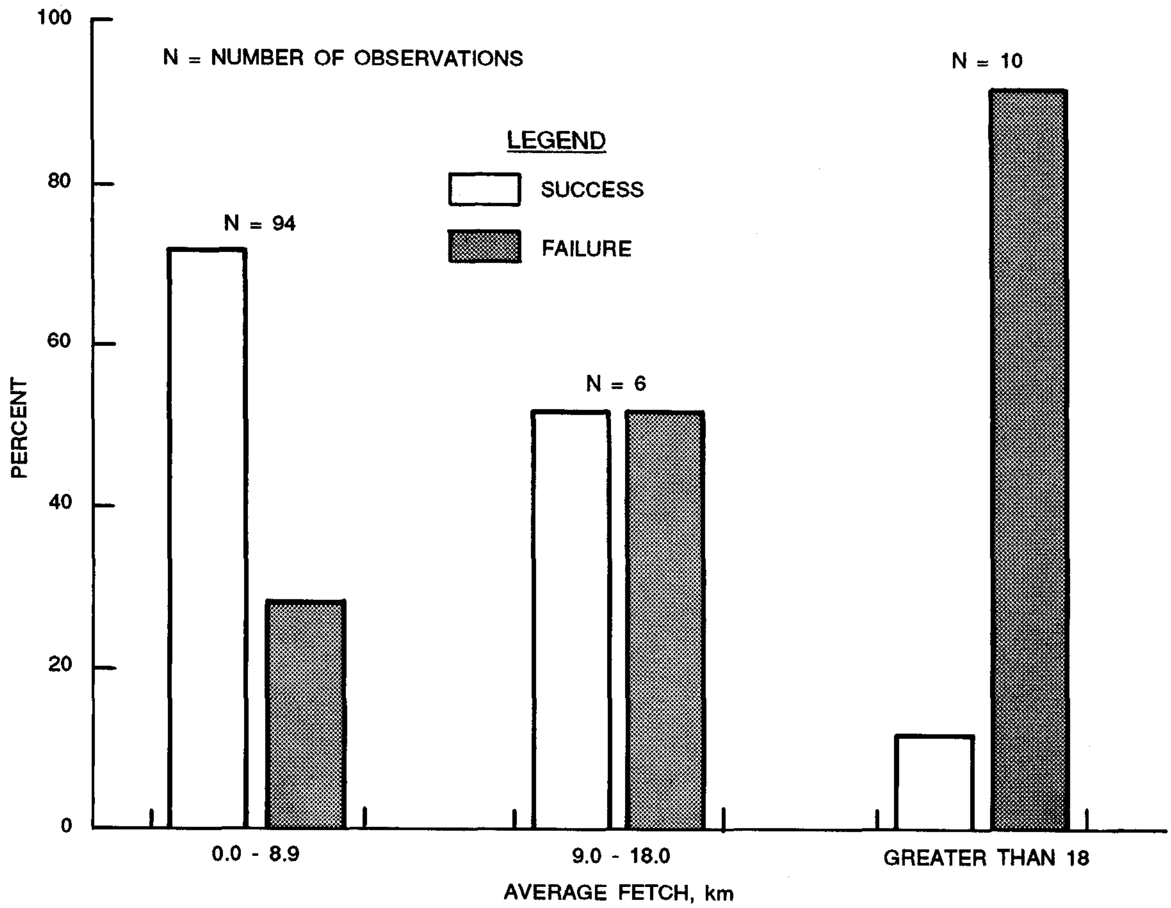


Figure 8. Average fetch versus planting success in National Marsh Survey and Vegetative Erosion Control Project and in the Virginia Institute of Marine Science Study

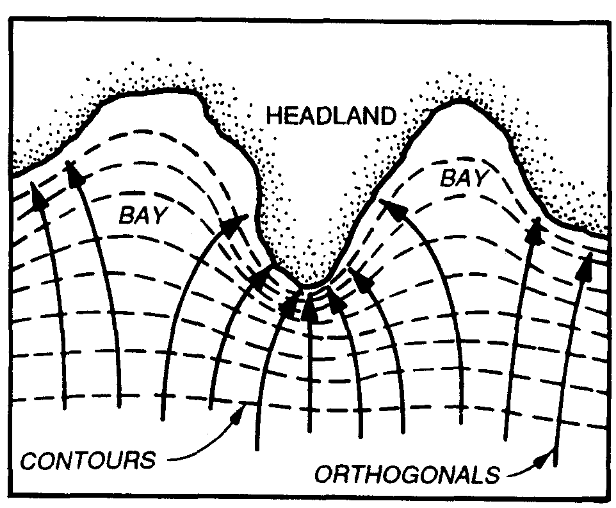


Figure 9. Wave refraction along bays and headlands

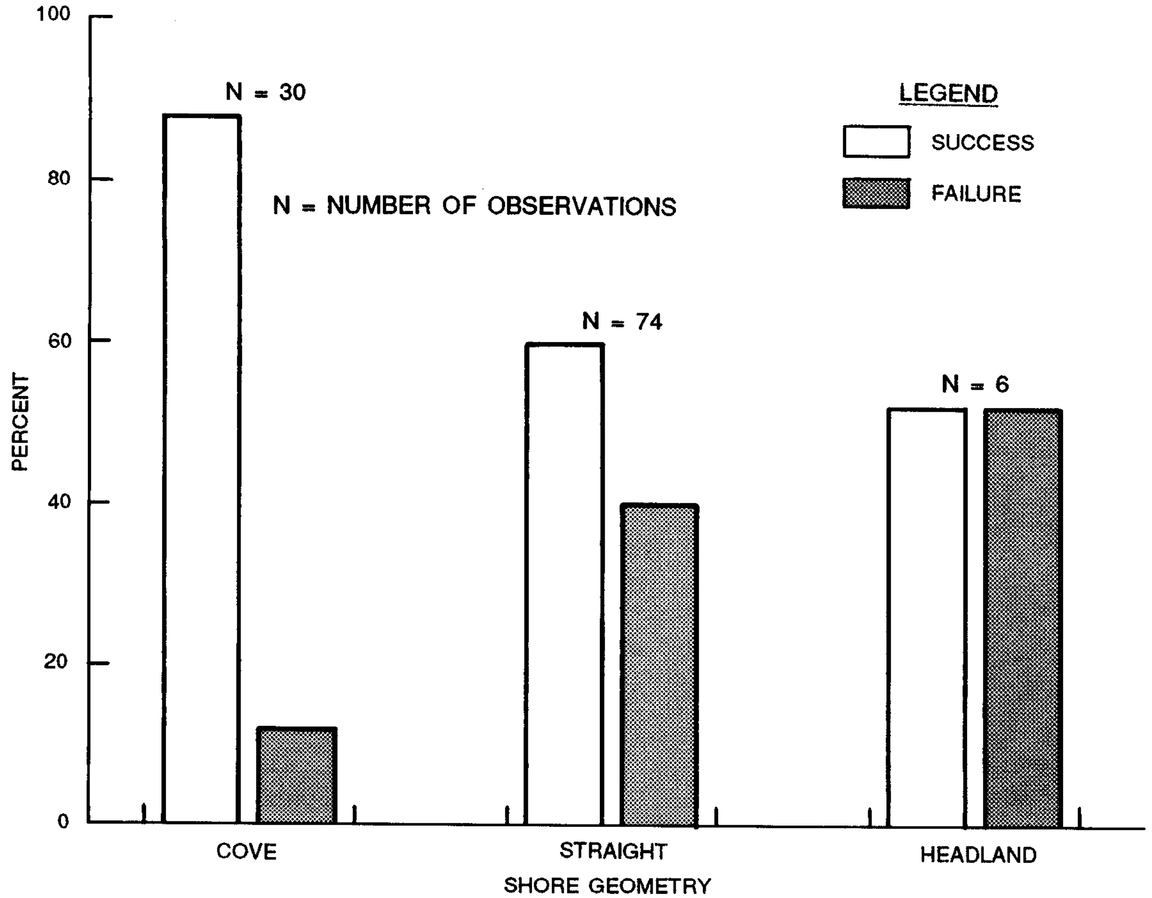


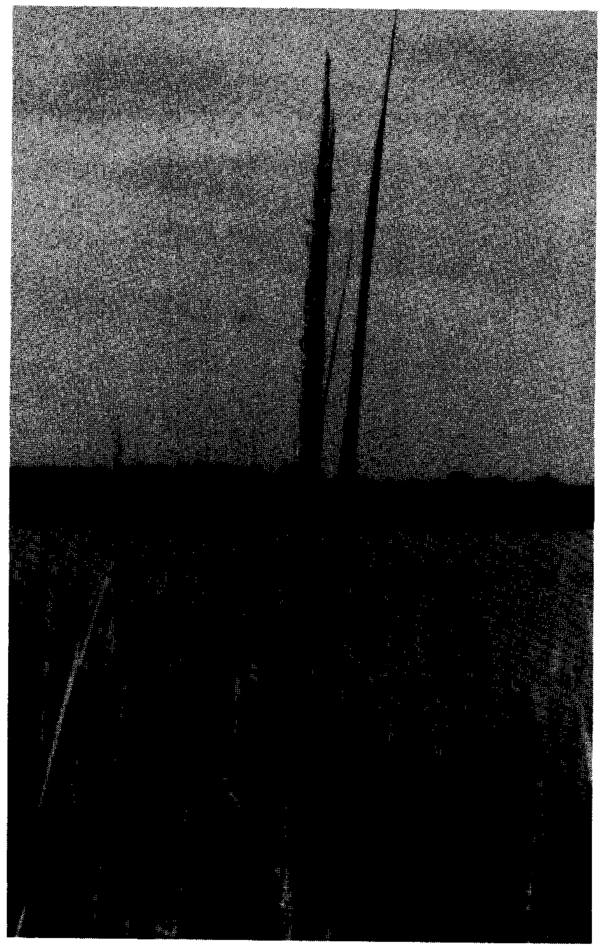
Figure 10. Shore geometry versus planting success in National Marsh Survey and Vegetative Erosion Control Project and in the Virginia Institute of Marine Science Study

DESCRIPTIVE CATEGORIES SELECT APPROPRIATE DESCRIPTIVE CATEGORY FOR EACH SHORE CHARACTERISTIC (A & B) AND NOTE ASSOCIATED SCORE (1 - 3).			
a. AVERAGE FETCH AVERAGE DISTANCE IN KILOMETERS OF OPEN WATER MEASURED PERPENDICULAR TO THE SHORE AND 45 DEG TO EITHER SIDE OF PERPENDICULAR	LESS THAN 9.0 km	9.0 TO 18.0 km	GREATER THAN 18.0 km
	SCORE = 1	SCORE = 2	SCORE = 3
b. SHORELINE GEOMETRY GENERAL SHAPE OF THE SHORELINE AT THE POINT OF INTEREST AND 100 m TO EITHER SIDE OF POINT	COVE OR INDENTED	MEANDER OR STRAIGHT	ISLAND OR HEADLAND
	SCORE = 1	SCORE = 2	SCORE = 3

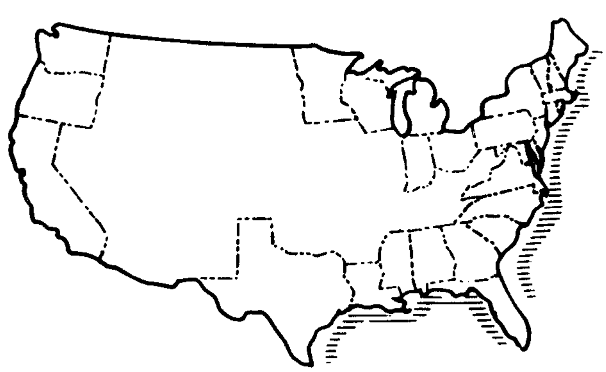
WAVE ENERGY CLASSIFICATION TOTAL SCORES OF SHORE CHARACTERISTICS (A & B).		
LOW WAVE ENERGY TOTAL SCORE 2 - 3	MODERATE ENERGY TOTAL SCORE 4	HIGH WAVE ENERGY TOTAL SCORE 5 - 6

VEGETATIVE STABILIZATION OPTIONS MINIMAL ACCEPTABLE OPTION FOR EACH WAVE ENVIRONMENT.		
LOW WAVE ENERGY STANDARD PLANTING TECHNIQUES	MODERATE ENERGY ROOT-ANCHOR PLANTING TECHNIQUES OR WAVE PROTECTION STRUCTURE	HIGH WAVE ENERGY WAVE PROTECTION STRUCTURE

Figure 11. Wave Climate Evaluation Form for estimating wave climate severity and determining appropriate vegetative stabilization options

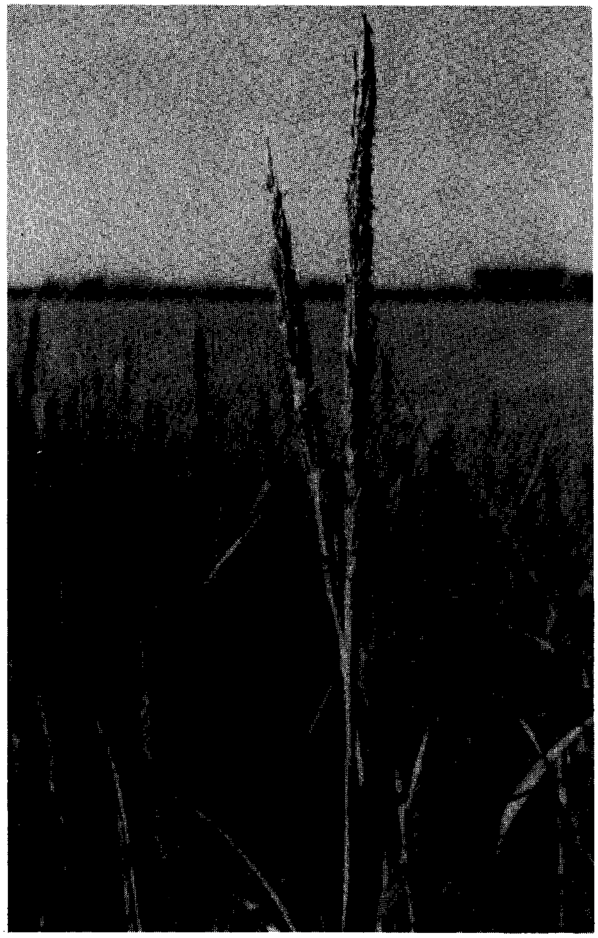


a. Seed head (inflorescence)

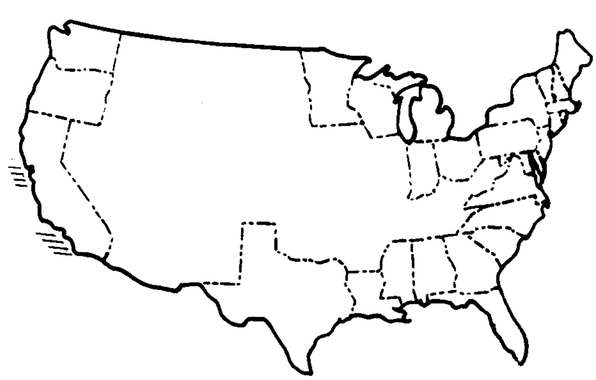


b. Distribution (shaded area)

Figure 12. Smooth cordgrass (*Spartina alterniflora*)



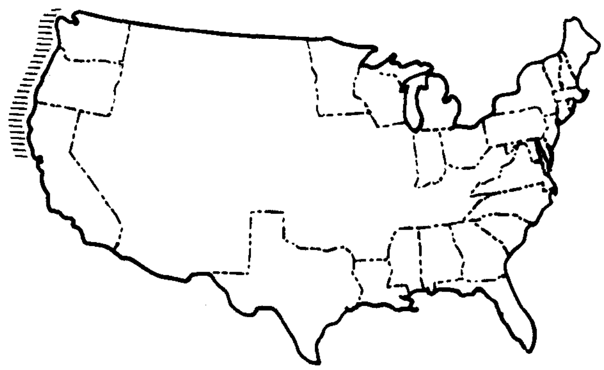
a. Seed head (inflorescence)



b. Distribution (shaded area)

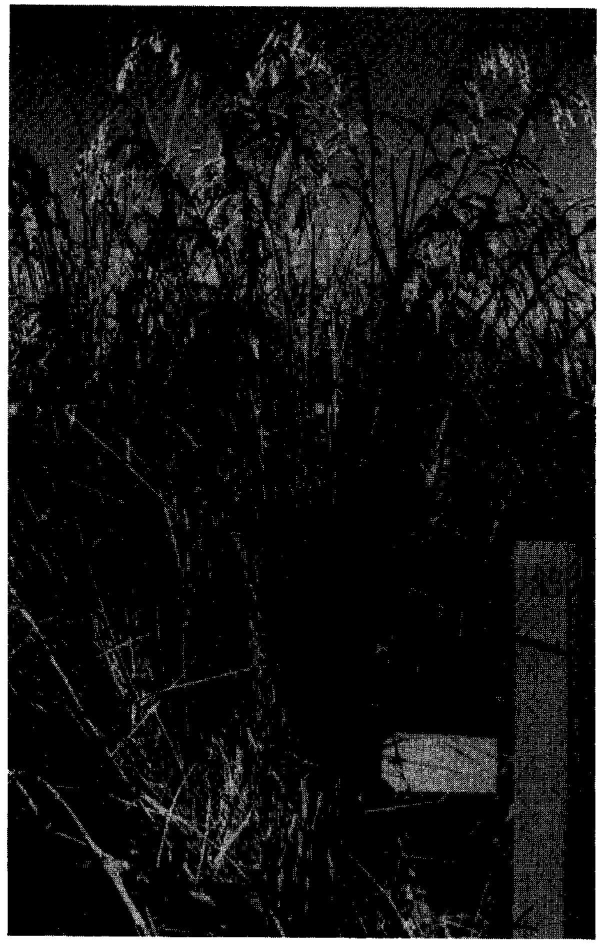
Figure 13. Pacific cordgrass (*Spartina foliosa*)

a. Seed head (inflorescence)

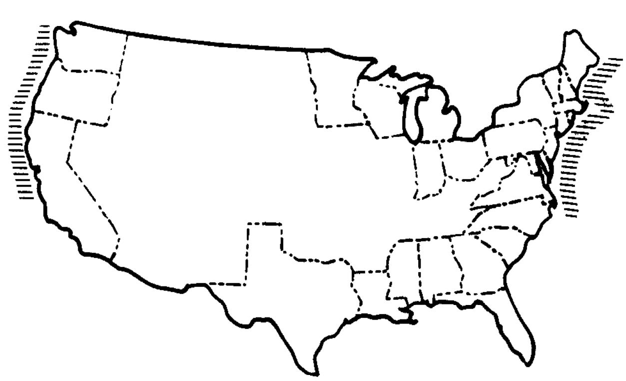


b. Distribution (shaded area)

Figure 14. Lyngbye's sedge (*Carex lyngbyei*)



a. Seed head (inflorescence)



b. Distribution (shaded area)

Figure 15. Tufted hairgrass (*Deschampsia caespitosa*)

Figure 16. Hand-planting sprigs (photo courtesy of W. W. Woodhouse, Jr., E. D. Seneca, and S. W. Broome, North Carolina State University at Raleigh)

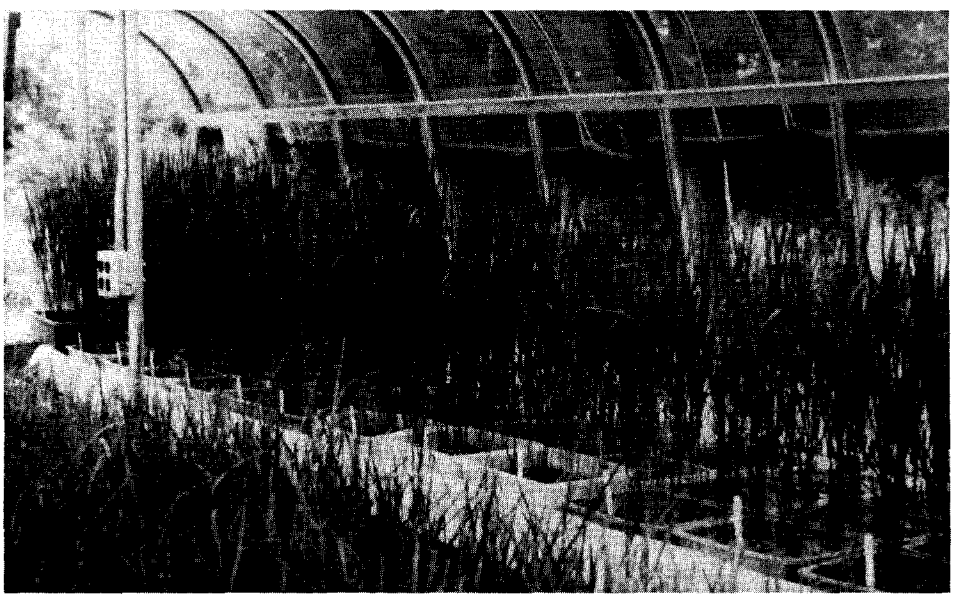


Figure 17. Pot-grown nursery seedlings at Environmental Concern, Inc., nursery in St. Michael's, MD

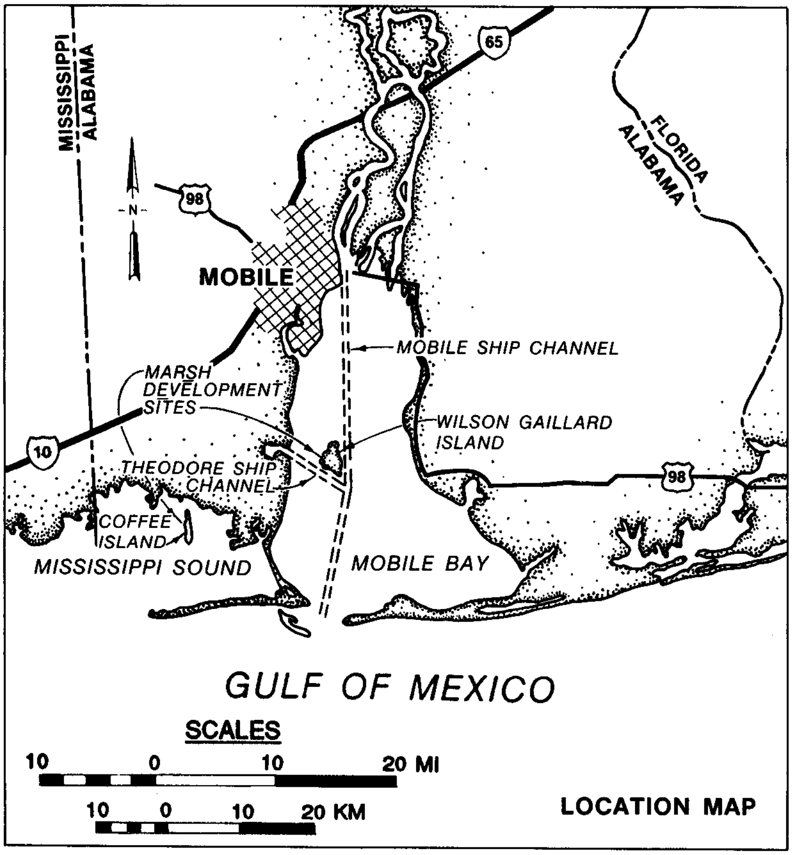
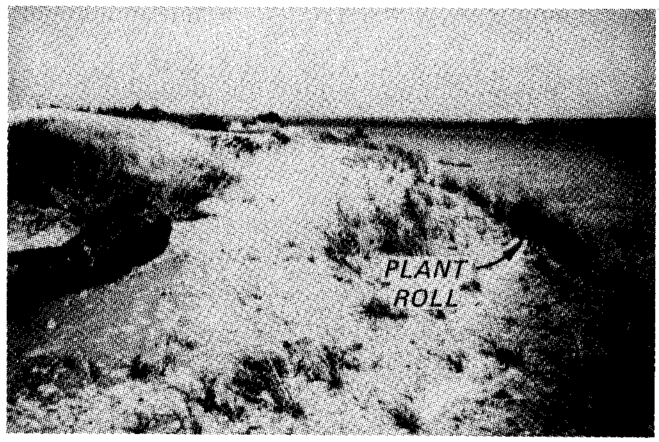


Figure 18. Gaillard Island (Mobile Bay, Alabama) and Coffee Island (Mississippi Sound, Alabama) marsh development sites

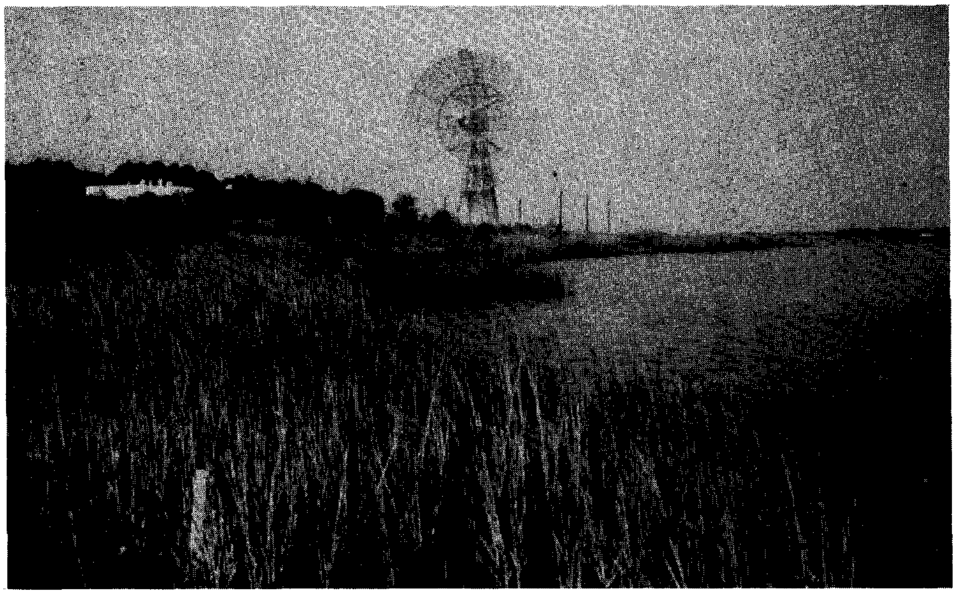
Figure 19. Plant rolls constructed onsite, ready for installation



a. Photo taken 3 months after planting (note plant rolls seaward of single-stemmed plants)

b. Photo taken after 18 months after planting

Figure 20. Coffee Island marsh development site



a. Photo taken 17 months after planting

b. Photo taken 8 years after planting (note absence of planting)

Figure 21. Erosion control planting site at Cedar Island, North Carolina

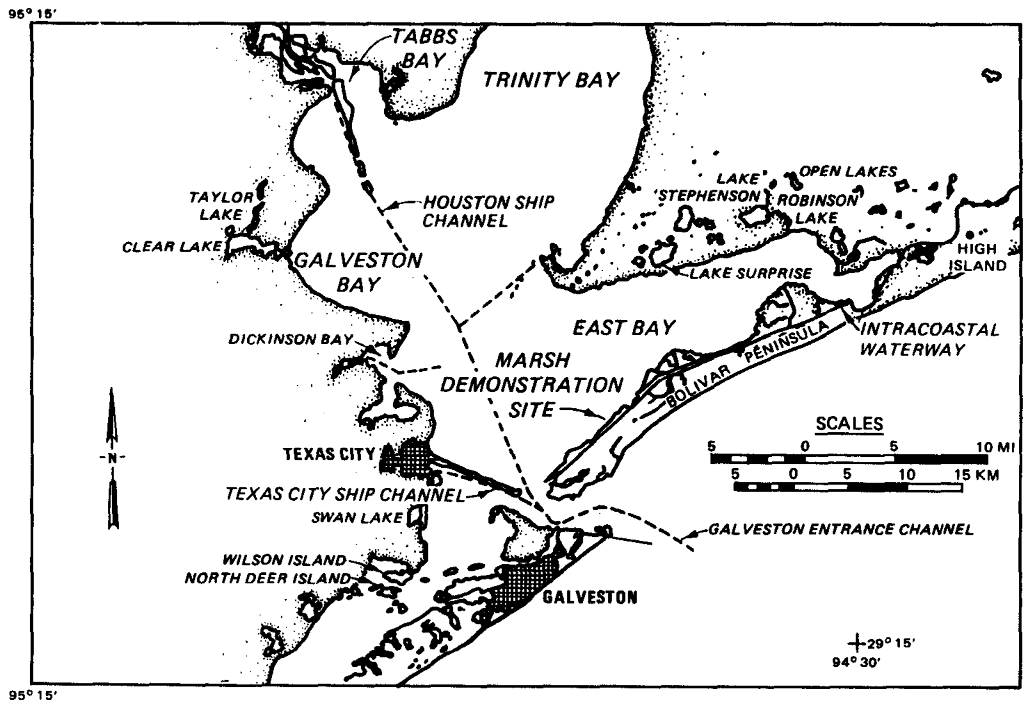
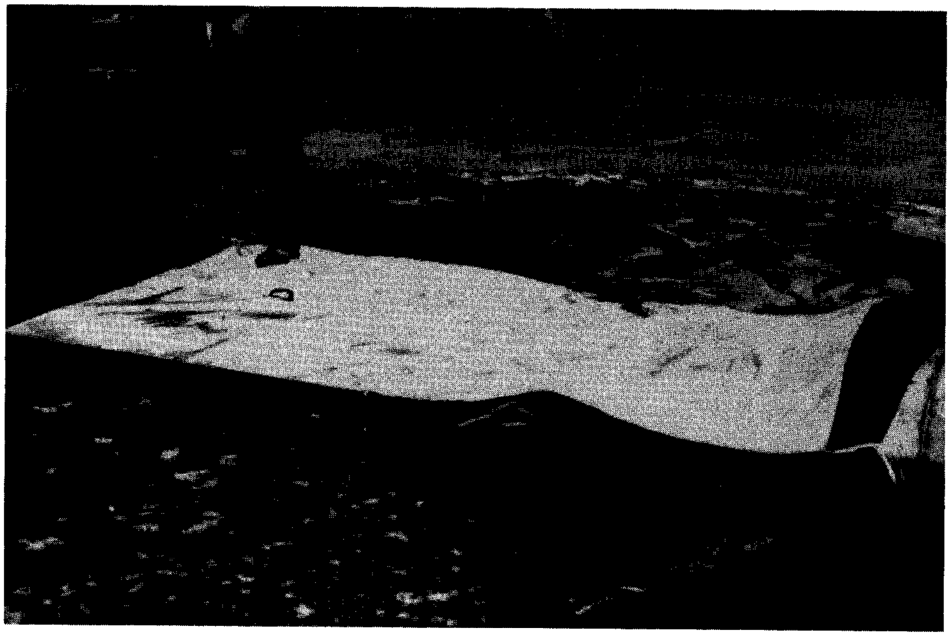
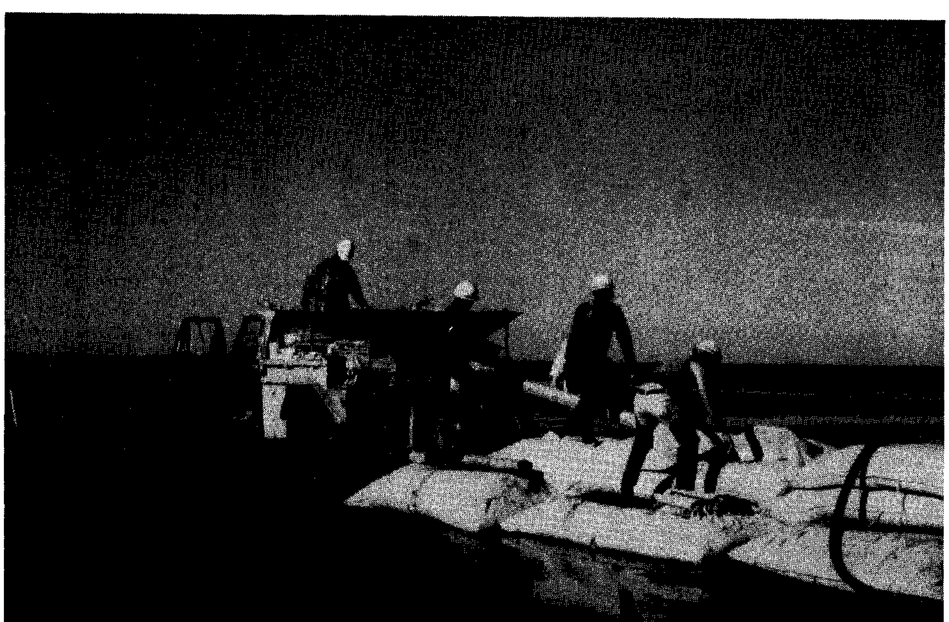


Figure 22. Marsh demonstration site at Bolivar Peninsula, Galveston Bay, Texas



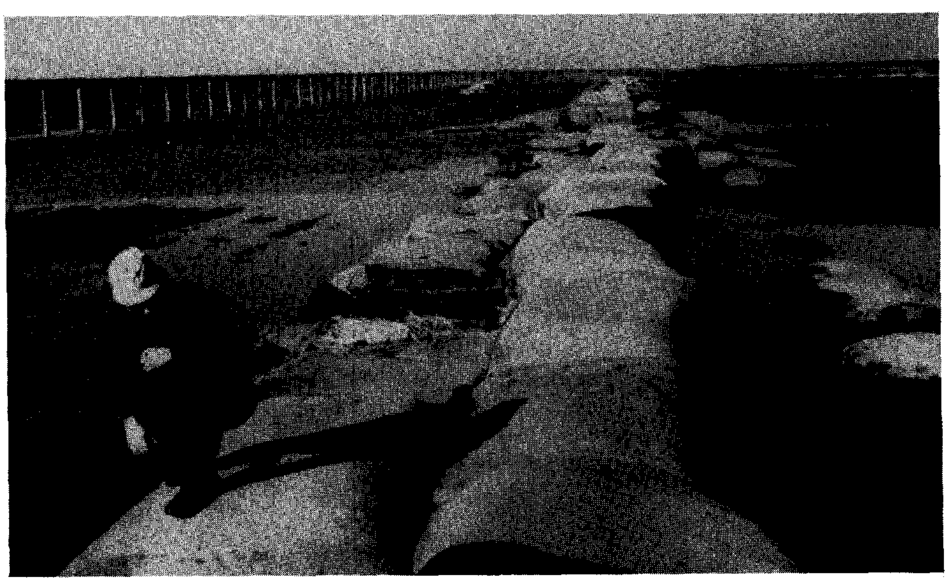
a. Empty cloth bags placed on filter cloth



b. Bags filled with a sand slurry in-place

Figure 23. Construction of sandbag breakwater (Continued)

c. Newly completed dike



d. Dike after exposure to the elements for 2 years

Figure 23. (Concluded)

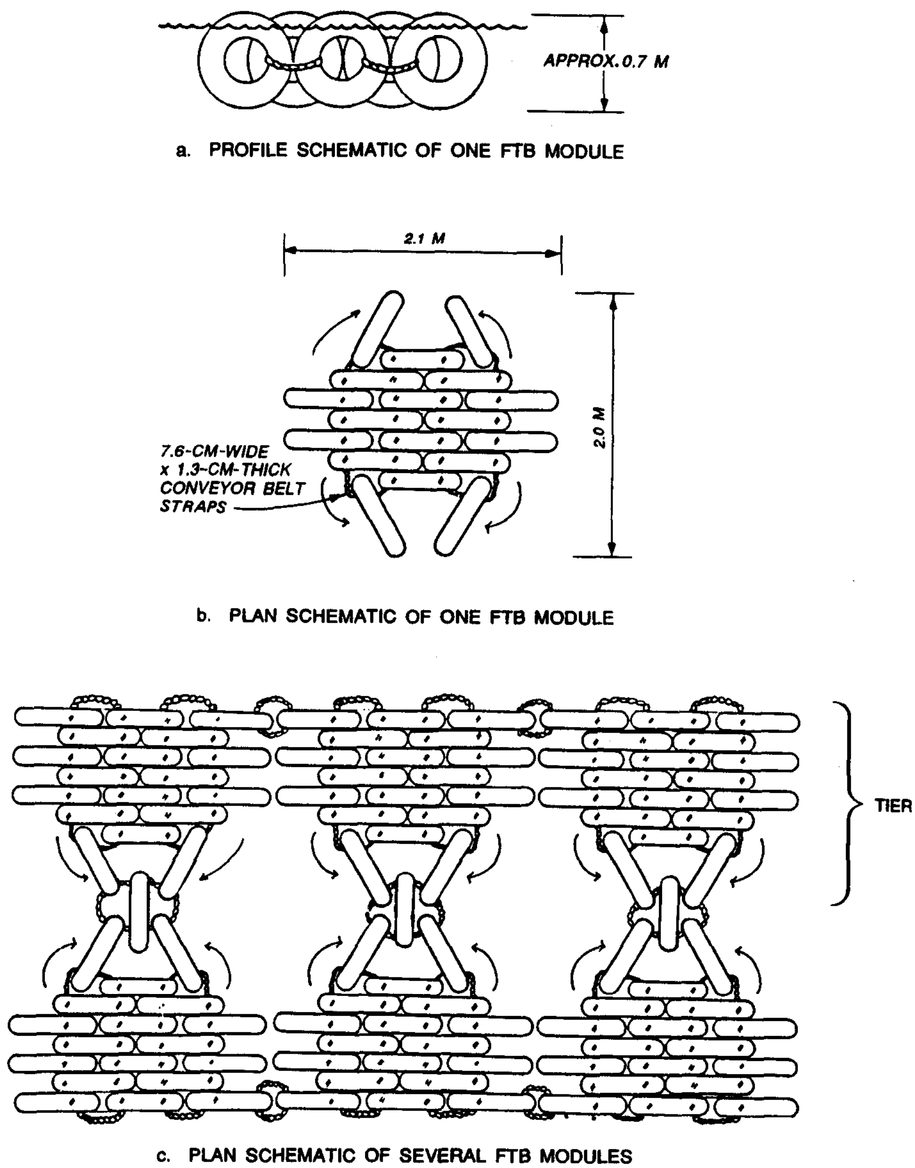


Figure 24. Two-tier floating tire breakwater, constructed by strapping tires and tire modules together

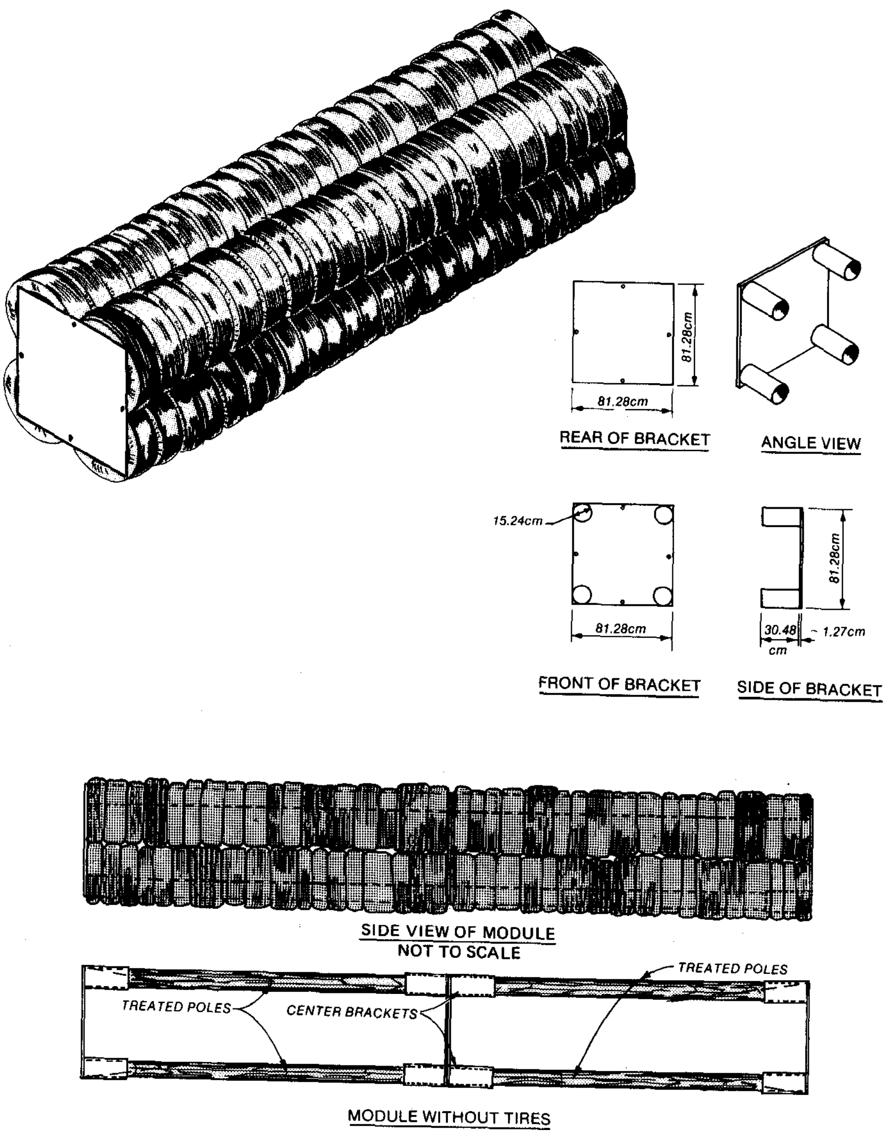


Figure 25. Schematic of fixed tire-pole breakwater

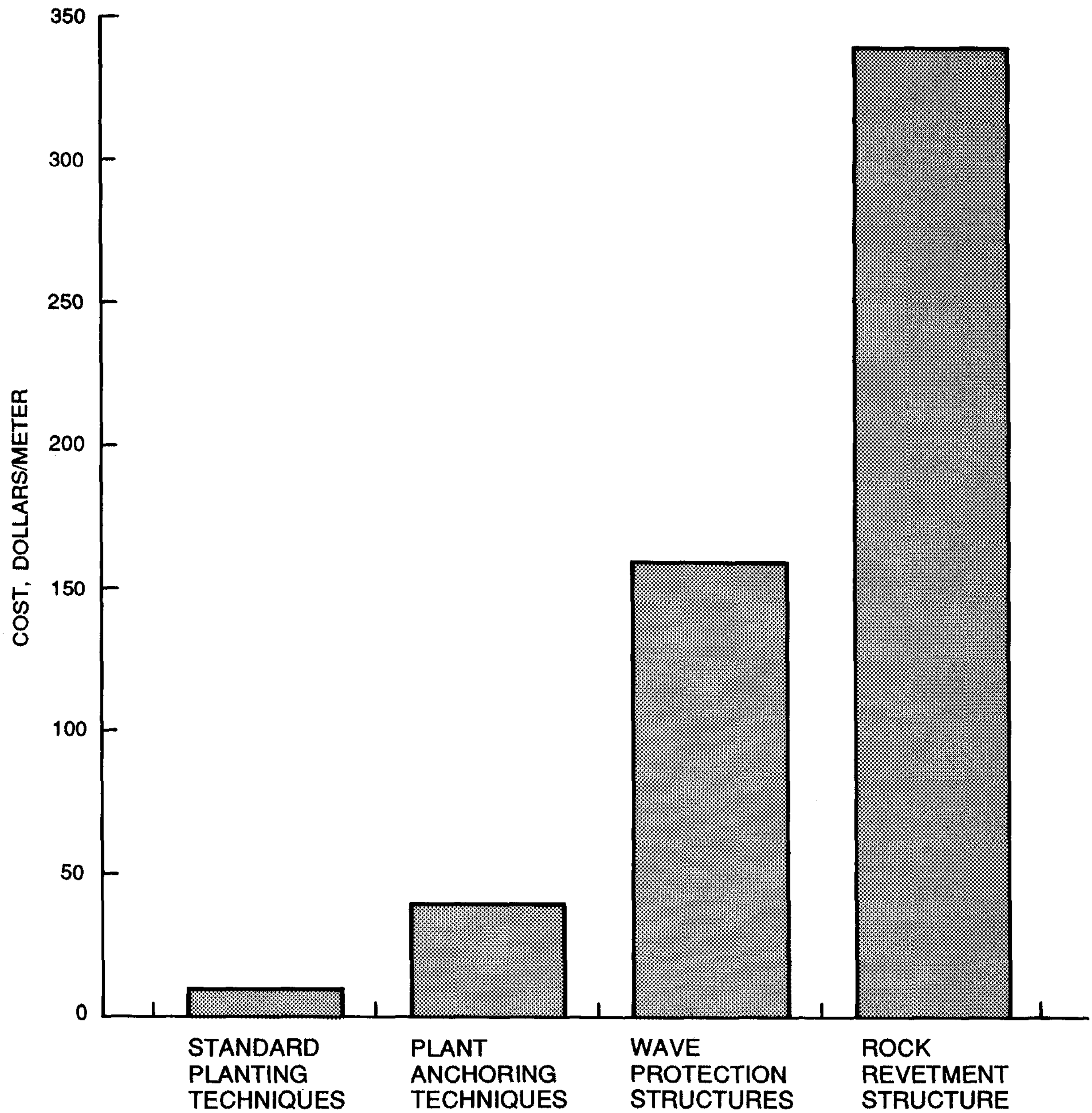


Figure 26. Approximate costs of alternative shore stabilization techniques

APPENDIX A: STABILIZATION OF THREE DREDGED MATERIAL ISLANDS WITH MARSH PLANTINGS ON THE ATLANTIC INTRACOASTAL WATERWAY*

Introduction

1. The Corps of Engineers and the National Marine Fisheries Service entered into a Memorandum of Agreement in October 1985 for determining the practicality of establishing a nationwide fisheries habitat restoration and creation program. As part of the nationwide program, three study sites were selected in North Carolina. The North Carolina studies had two specific goals. One goal was to evaluate various techniques for establishing wetland habitat in order to reduce erosion and channel refilling at dredged material disposal sites. The second goal was to develop primarily fishery habitat and to evaluate the potential of this type of habitat development in future management plans. If these goals are achieved, beneficial uses of dredged material can be realized that will have positive implications for the long-term management of dredged material.

2. This appendix focuses upon information developed to date in these studies concerning erosion abatement using salt marsh plantings. Specific information is presented on wave climate conditions, plant growth, and sediment movement.

Study Sites

3. The three study sites are located on dredged material disposal islands in coastal North Carolina adjacent to the Atlantic Intracoastal Waterway (AIWW). Two sites are diked disposal islands located next to the AIWW channel. One island is at Sneads Ferry near New River Inlet (Figures A1 and A2); the second island is at Swansboro near Bogue Inlet (Figures A1 and A3). These two sites are relatively protected from severe wind wave conditions. Sneads Ferry is exposed to a fetch of about 1.6 km to the north, 1.6 km to the northwest, and 3.7 km to the west. Swansboro is even more sheltered from local winds since the fetch in any direction is less than

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* This appendix was prepared by Paul L. Knutson, Steve Broome, and Frank E. Yelverton.

0.5 km. Because both sites are close to the AIWW, boat traffic passes within 100 to 200 m of their shores. The third site is a sandbag-diked disposal island located in Core Sound at Harkers Island near Beaufort Inlet (Figures A1 and A4). The Harkers site is not subjected to significant boat wakes, but receives more severe wind-wave activity due to exposure to greater fetch, 12 km from the northeast, 2.5 km from the southeast, 3 km from the southwest, and 6.6 km from the northwest.

4. Each test site was constructed to consist of approximately 200 m of shoreline graded to an intertidal slope of 2 to 3 percent. The upper 20 m of the intertidal zone was planted with smooth cordgrass (*Spartina alterniflora*) on 0.5-m centers. A 10-m-wide band immediately landward of the smooth cordgrass planting was planted with saltmeadow cordgrass (*Spartina patens*) on 0.5-m centers. The initial planting was conducted in the spring of 1987. In 1988, damaged areas of each site were replanted. The replanting involved approximately 5,000 plants at Harkers Island to repair an area damaged by waves and movement of sand. Only 300 plants were required at Swansboro and Sneads Ferry to replace small areas that were killed by high salinity. By the end of 1988, complete plant cover was achieved at all three sites.

Results

Boat-generated waves

5. During 1987-1988, boat wake observations were made at Sneads Ferry and Swansboro. Boats were classified according to type (motor- or sail-powered), length (0 to 5 m, 6 to 10 m, or >10 m), speed (0 to 5 m/sec, 6 to 10 m/sec, or >10 m/sec), and distance from shore (0 to 100 m or 100 to 200 m). The highest wave produced by each boat passage was recorded on shore with a staff gage. Table A1 summarizes wave-height observations made during the study.

6. Boat observations were combined with boat census information taken at three drawbridges on the AIWW operated by the Corps Wilmington District. It was estimated that the Sneads Ferry and Swansboro sites are subjected to the wakes of about 25,000 boat passes per year.

7. Table A2 summarizes the magnitude and duration of waves produced by boat traffic in 1 year at these sites. The total time per year that these sites are subjected to boat wakes is about 8,400 min or about 140 hr per year.

Larger waves (greater than 30 cm) occur infrequently, about 200 min or about 3 hr and 20 min per year.

Wind-generated waves

8. The Coastal Engineering Research Center of the US Army Engineer Waterways Experiment Station gathered long-term synoptic weather data and employed wave hindcasting techniques to develop an estimate of the magnitude and duration of wind-generated waves at each of the three study sites. Table A3 summarizes the magnitude and duration of waves produced by winds at each of the three sites. Larger waves (greater than 30 cm) occur most frequently at the Harkers Island site, about 11,000 min or about 180 hr per year. At the more sheltered sites, Swansboro and Sneads Ferry, larger waves are much less frequent, 17 and 33 hr per year, respectively.

Comparison of boat and wind waves

9. It is apparent from the calculated hours of wave exposure that, even under very sheltered conditions (Swansboro - fetch less than 0.5 km) and high levels of boat traffic (25,000 boat passes per year), wind-generated waves are the dominant erosive force. At Swansboro, wind-generated waves impact the shore 40 times more frequently than boat-generated waves. Even in the category of waves larger than 30 cm, wind waves are 5 times more frequent. Overall, boat waves at the Swansboro site represent less than 5 percent of the total wave energy.

Growth of planted salt marsh

10. Growth of vegetation was monitored by making quarterly site visits for visual evaluation and photographs, and by sampling the vegetation near the end of the growing season in late September and early October. Six 0.25-m^2 quadrats were randomly selected from within replicate plots of planted smooth cordgrass at each site. Plants within each quadrat were harvested at the soil surface. Measurements were made of plant height, number of stems, and diameter of stems at the base. Living and dead plant material was separated, oven-dried at 70° C, and weighed. Belowground biomass was sampled by taking an 8.5-cm core, 30 cm deep, from each quadrat. The core was washed on a 2-mm screen, and the root and rhizome material remaining was dried and weighed.

11. Overall means of the growth measurements after two growing seasons are presented in Table A4. The aboveground growth was equivalent to similar natural marshes, but the belowground standing crop is lower than more mature marsh environments. These results are consistent with those given in Newling

and Landin (1985),* who compared biomass of planted and natural smooth cordgrass marshes at Bolivar Peninsula, Texas.

12. Table A5 compares plant biomass achieved during the first two growing seasons. Biomass increased substantially at all sites the second growing season, indicating continued growth and stability of the planted marsh.

Erosion and accretion

13. The Wilmington District has conducted quarterly elevational profiles in the three study areas. To date, only the first-year profiles have been analyzed; these are summarized in Table A6. Each of the three planted areas remained relatively stable, even during the first year of marsh development. The Swansboro site experienced a net vertical accretion of 4.8 to 5.6 cm along the planted portion of the profile. The Sneads Ferry and Harkers Island sites had some slight vertical erosion of 2.5 to 4.8 cm. Preliminary analysis of second-year profiles indicates the recovery of most profiles to preconstruction levels.

Summary and Conclusions

14. It appears that even on sites subjected to substantial boat traffic, wind-generated waves continue to be the primary erosive force. At the Swansboro site, where the average fetch is 0.5 km and the boat passes per year are 25,000, 85 percent of waves over 30 cm high are generated by the wind. At the Harkers Island site, where the average fetch is 6.0 km and where there is negligible boat traffic, waves over 30 cm high occur 9 times more frequently than at the Swansboro site.

15. Though some replanting of damaged areas was necessary after the first growing season, full plant cover was achieved by the second growing season. Each of the three shoreline environments examined in this study appears to be suitable for vegetative erosion control measures.

16. Elevational profiles at each test site indicate relatively stable conditions, even during initial establishment the first growing season. Although the profile data for the second growing season have not been thoroughly analyzed, onsite reports indicate increased stability on all test sites and evidence of accretion on portions of all sites.

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* See References at the end of the main text.

17. Vegetative stabilization appears to be a viable alternative to structural erosion control measures on coastal dredged material disposal areas with conditions similar to these sites. As a result, beneficial uses of dredged material such as habitat development and control of sediment can be achieved in a cost-effective way.

Table A1

Boat Wave Data

Vessel Type	Length m	Speed m/sec	Distance from Sailing Line 0-100 m	100-200 m
Motor-powered	0-5	0-5	5.5 cm (11)*	2.5 cm (12)
		6-10	7.7 cm (17)	7.6 cm (25)
		>10	10.0 cm (3)	3.0 cm (10)
	6-10	0-5	12.2 cm (9)	14.6 cm (11)
		6-10	11.2 cm (26)	10.8 cm (26)
		>10	13.3 cm (18)	9.4 cm (98)
	>10	0-5	30.0 cm (6)	20.9 cm (23)
		6-10	--	18.1 cm (16)
		>10	--	12.5 cm (4)
Sail-powered	0-5	0-5	--	10.0 cm (1)
		6-10	--	--
		>10	--	--
	6-10	0-5	5.0 cm (2)	6.0 cm (5)
		6-10	--	--
		>10	--	--
	>10	0-5	5.0 cm (6)	10.0 cm (9)
		6-10	--	--
		>10	--	--

* Values represent the mean wave height, in centimeters, and the number of observations (in parentheses).

Table A2

Boat-Generated Waves, Swansboro and Sneads Ferry, North Carolina

Wave Height cm	Cumulative Duration and Frequency 1,000 min/year	1,000 waves/year
0-15	6.6	197
15-24	1.3	38
24-30	0.3	8
>30	0.2	5

Notes: Each boat passage produces a group of about 10 waves; each wave within the group has an average wave period of 2 sec, as estimated from several observations of wave crest movement between two stationary points. Wave heights and numbers were measured by using the highest wave in each group.

Table A3

Wind-Generated Waves

Wave Height cm	Cumulative Duration and Frequency 1,000 min/year	1,000 waves/year
	Swansboro, North Carolina	
0-15	326	9,780
15-24	40	1,200
24-30	4	120
>30	1	30
	Sneads Ferry, North Carolina	
0-15	364	10,920
15-24	30	900
24-30	7	210
>30	2	60
	Harkers Island, North Carolina	
0-15	326	9,780
15-24	126	3,780
24-30	63	1,890
>30	11	330

Note: Average wave periods of 2 sec were estimated by observing wave crest movement of several waves between two stationary points.

Table A4

Second-Year Growth in Three Planted Marshes on Dredged Material Disposal Islands

Location	Height cm	Stems No./m^2	Basal Area cm^2/m^2	Aboveground Biomass Living g/m^2	Aboveground Biomass Dead g/m^2	Below-ground Biomass g/m^2
Sneads Ferry	125±4	382±17	122±7	946±71	168±29	946±91
Swansboro	126±2	369±12	114±5	739±30	122±9	813±57
Harkers Island	125±3	389±19	113±7	885±55	161±21	1,560±133

Note: Standard error shown as ± value; based on 48 replicates.

Table A5

Comparison of Biomass, First Versus Second Year of Growth, Smooth Cordgrass Plantings

Location	Dry Weight, g/m^2 Aboveground 1987	Aboveground 1988	Belowground 1987	Belowground 1988
Sneads Ferry	416	946	337	946
Swansboro	232	739	252	813
Harkers Island	764	885	337	1,560

Table A6

First-Year Average Vertical Erosion and Accretion in Three Planted Marshes on Dredged Material Disposal Islands

Location	Average Accretion/Erosion per Profile Segment, cm High Marsh*	Low Marsh**	Unplanted Low Intertidal†
Sneads Ferry	-2.5	-4.8	-4.0
Swansboro	+4.8	+5.6	+0.6
Harkers Island	+1.0	-4.8	-4.0

* Profile length = 10 m; planted with *Spartina patens*.
** Profile length = 20 m; planted with *Spartina alterniflora*.
† Profile length = 30 m; unplanted.

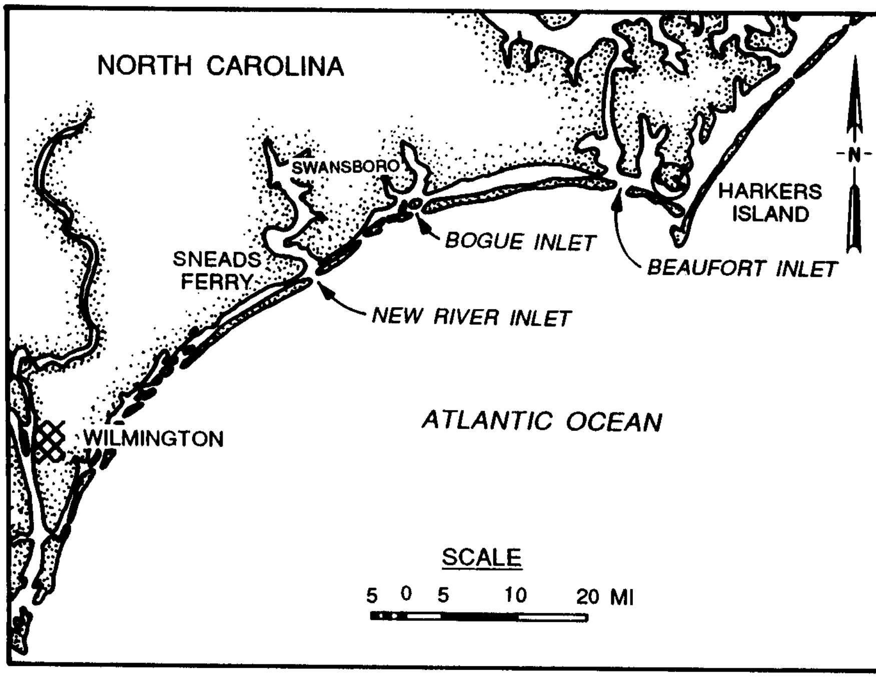

Figure A1. Marsh development sites adjacent to the Atlantic Intracoastal Waterway, North Carolina

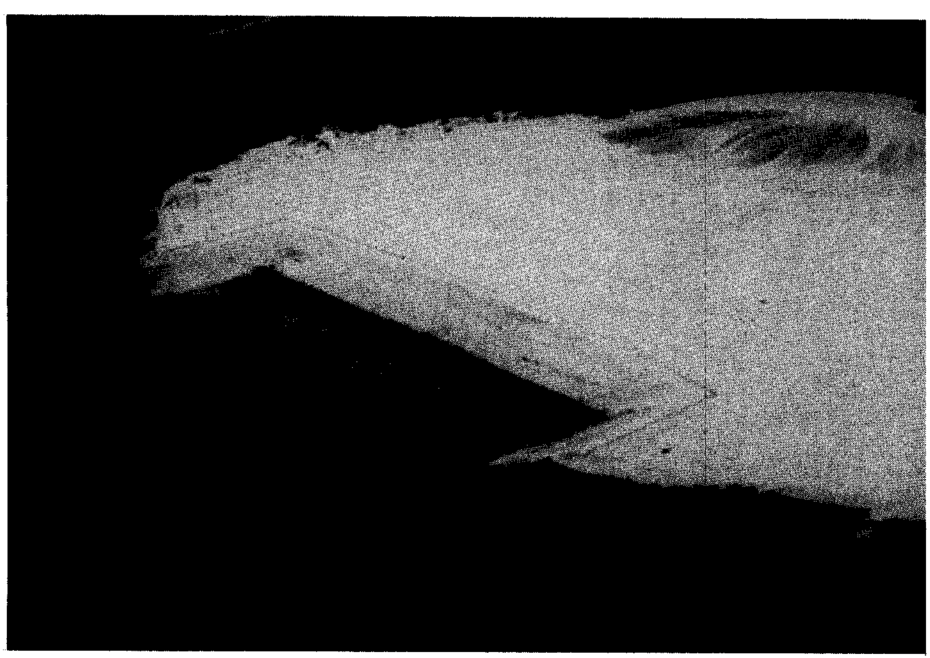

Figure A2. Sneads Ferry marsh development site

Figure A3. Swansboro marsh development site

Figure A4. Harkers Island marsh development site

APPENDIX B: SALT MARSH ESTABLISHMENT FOR DREDGED MATERIAL SHORELINE STABILIZATION, BOLIVAR PENINSULA, GALVESTON BAY, TEXAS*

Introduction

1. Erosion is a significant problem on many shorelines of the Galveston Bay complex, as well as other bays of the Gulf of Mexico. Erosion can be prevented by structural measures such as riprap and bulkheads, but shoreline structures often replace the marsh habitat that is important to various estuarine species (Woodhouse and Knutson 1982; Minello, Zimmerman, and Klima 1986).** Vegetation can often be established to prevent erosion and is less costly than traditional methods of shore protection (Allen and Webb 1983). Additionally, it often offers a more diverse and more species-rich habitat than use of traditional structures alone (Mock 1966). Plantings of smooth cordgrass, *Spartina alterniflora*, for shoreline marsh development have proven successful in low-wave energy areas in many parts of the United States (Lewis 1982), but high-wave energy areas require special plant protection methods during establishment (Lewis 1982; Webb and Dodd 1983; Allen, Webb, and Shirley 1984).

2. Wave break devices have been effectively used for plant establishment on shorelines with high wave energy. For example, floating tire breakwaters (FTBs) (Allen and Webb 1983) and two tiers of tires on cables (Webb and Dodd 1983) were successfully used as wave breaks to allow establishment of smooth cordgrass at sites located in Mobile Bay, Alabama, and East Bay, Texas, respectively. Although FTBs have been used successfully, any tires that break loose can create navigation hazards. Additionally, transport and handling of tires can be expensive and difficult in shallow-water and remote areas. Materials that are less hazardous to boat traffic, less costly, less labor intensive, and more easily transported than tires are still needed to improve plant establishment in moderate- to high-wave energy environments.

3. The major goal of this study was to test inexpensive, easily managed materials that have the combined effect of promoting plant establishment on dredged material shorelines with high wave energy, controlling erosion, and

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* This appendix was prepared by James W. Webb and Hollis H. Allen.
** See References at the end of the main text.

providing habitat. Field studies were conducted in 1984 and 1988 using various combinations of erosion-control mats and breakwaters to protect planted vegetation.

4. The study site consisted of dredged material taken from the Gulf Intracoastal Waterway (GIWW) and deposited on the Galveston Bay side of Bolivar Peninsula (see Figure 22 of the main text). The unconfined dredged material from the GIWW on Bolivar Peninsula typically forms fan-shaped plumes (Figure B1) on the bay shoreline, which erode as a result of wind-generated waves. The wind fetch to the west-northwest is over 30 km. The dredged material is primarily 90 to 99 percent sand (Lindau and Hossner 1981). Earlier studies on one of the plumes in 1976-1977 demonstrated that marsh establishment is possible with wave break devices (Figure B2) (Allen et al. 1978, Webb et al. 1978). Large sandbags used in that study were effective wave breaks, but they were relatively expensive because repeated maintenance was required.

5. Various treatments incorporating erosion control mats and plant wrappings have been tested to establish smooth cordgrass on bay shorelines (Allen, Webb, and Shirley 1984). The five most promising of these treatments were evaluated in small replicated demonstration plots at Bolivar Peninsula in 1984. In addition, two different configurations of tire breakwaters, a fixed tire breakwater and a FTB, were placed adjacent to the replicated treatment area for comparison of techniques (Figure B3). The fixed tire breakwater was a new design consisting of tires strung on poles, whereas the FTB had previously been used with success in Mobile Bay (Allen, Webb, and Shirley 1984).

6. After several years of monitoring, the best of the techniques, erosion control mats, were further tested on a larger scale in 1988 to evaluate the potential of this technique to be employed operationally. The technique was applied to 137 m of sandy dredged material along the bay shoreline of Bolivar Peninsula. This report describes those efforts in 1984 and 1988 and presents some conclusions and recommendations for stabilizing dredged material.

Methods

Erosion control treatments, 1984

7. In July 1984, five treatments were replicated four times in a randomized complete block design (Figure B3). The plant material used in each plot was smooth cordgrass. The treatments were (a) single rooted stems (sprigs); (b) plant rolls, which consisted of plant clumps with soil still attached to the roots and placed at 0.5-m intervals onto burlap strips, covered with sand, rolled into cylinders and fastened, and buried in the sediment; (c) multiple stems (plant clump) with attached roots and rhizomes; (d) burlap bundles, which consisted of individual multiple-stemmed plants with the roots wrapped with burlap, and (e) 5-cm-thick (carpetlike) erosion control mats (composed of horse hair, coconut fibers, and other fiber material bound together with latex rubber), secured to the substrate by burying the edges.

8. Plants were inserted into slits cut in the mat (Figure B4). Each plot was 6 by 9.1 m and was separated by 1.5 m of buffer. The long dimension of each paralleled the shoreline. Each plot was planted with single stems, multiple stems, burlap bundles, or plant rolls spaced at 0.5-m intervals. A total of 280 plants were placed in each plot.

9. In addition to the above replicated treatments, a modular FTB (see Figure 24 of main text) and a modular fixed tire breakwater (see Figure 25 of main text) were established on the western side of a dredged material plume. Each of these breakwaters enclosed a 6- by 30-m area to be planted. The areas were separated from each other and the replicated plots by 30 m (Figure B3). The FTB, which was modified from the Goodyear design (Gifford, Fisher, and Walton 1977), was constructed of two tiers of modules, each containing 18 tires (see Figure 24 of main text).

10. The tires and modules were linked together with rubberized nylon straps and anchored in place by utility pole screw anchors. The tires contained polyurethane foam for flotation. Modules also were placed at both ends to provide wave protection to the flanks of the plots. The FTB was placed in water just deep enough that the FTB was resting on bottom at low tide.

11. Each module of the fixed tire breakwater was constructed by placing tires on four 6-m-long, 15-cm-diam wooden poles. The poles were inserted into metal sleeves welded on plates at both ends and secured by bolting the poles to the sleeves (see Figure 25 of main text). Five of these modules were

placed parallel to the shoreline, and two additional modules were placed at each end. The modules were placed at the same topographic elevation as the FTB. The areas protected by the tire breakwater were also planted with smooth cordgrass on 0.5-m centers.

12. Evaluation of plant performance for each of the replicated plots and the area behind each breakwater consisted of observing transplant survival, stem density, and percent cover. Initially, survival and stem counts were determined in each area by counting all of the stems, but over time, density and cover increased and 0.25-m^2 frames were used to estimate density and percent cover. Percent cover was estimated ocularly as that percentage of the frame covered by plants.

Mat plantings, 1988

13. Two treatments, mats with plants and control plots (single-stemmed transplants without mats), were established and replicated on three dredged material plumes (Figure B5). The erosion control mats were like those used in the 1984 treatments described above. Each mat was 1.8 by 15 m. For each replication, 15 mats were joined to form a 7.8- by 45-m plot. A 7.8- by 15-m control treatment (no mat) was established for each of the three replications. The longest dimensions of the plots were oriented parallel to the shoreline. Placement of mats and planting occurred between 7 and 19 June 1988.

14. Because of a shortage of latex glue originally planned for constructing each large mat segment, a combination of methods was used for joining the mats together. In replications 1 and 3, 15 mats were overlapped (10 cm on edges) and sewn together by a 27-kg-test monofilament line, using upholstery needles, to form a 7.8- by 45-m mat (Figure B5). The outer free edges were buried to a 15- to 30-cm depth. In replication 2, the edges of each of 10 mats were overlapped, a single continuous bead of glue (eclectic 6000) was applied with a caulking gun, and the mats were pressed together. A 7.8- by 30-m mat segment was thus formed and the edges buried. The remaining five mats were not joined, and the edge of each mat was buried (Figure B5). Shovels or a water jet gun were used to bury mat edges below the sediment surface.

15. Single-stemmed sprigs of smooth cordgrass gathered from local borrow areas were inserted into slits cut in each mat on 0.5-m centers. The control treatments were 7.8- by 15-m plots located near the mats and consisted of single-stemmed sprigs transplanted on 0.5-m centers using shovels. They were transplanted without any mats or special protection.

16. Evaluation of treatments, plant performance, and establishment consisted of initially recording the survival of transplants, stem counts, and condition of mats at various dates over time. At first, survival and total stem counts were determined in each 1.8- by 15-m mat segment, but as plant density and cover increased, 0.25-m^2 frames (five per mat) were employed. Total stem counts were made in each control treatment throughout the monitoring period. In June 1989, these frames were used to estimate plant density and percent cover as described above for the 1984 treatments.

Results

Erosion control treatments, 1984

17. Three months after planting on 30 October 1984, transplant survival was relatively low, less than 26 percent for all treatments in the replicated study area (Table B1). Survival was not significantly different statistically among treatments despite the seemingly greater survival in the mats. By 3 January 1985, survival had decreased further in each treatment. No significant differences among treatments occurred, despite the fact that mean survival was 18.6 percent in mats, 10 percent in multiple stems, but less than 3 percent in the other treatments.

18. During a qualitative evaluation of the site in November 1985, about 1.5 years after planting, notable plant establishment was present only in two mat plots and one multiple-stem plot. In the two mat plots, the lower halves had good plant colonization, but the upper portions of the mats had washed away. The mats appeared to trap sand and hold plant roots in place (Figure B6). Only a few scattered plants remained in plots containing single stems, burlap bundles, or plant rolls. Despite the initial low survival, plants began to spread, and significant colonization of the shoreline occurred over time.

19. Approximately 2.5 years after planting on 20 November 1986, 6 of the original 20 plots had greater than 25 percent cover of smooth cordgrass. Plants had spread in three mat plots, two multiple-stem plots, and one burlap bundle plot (see Table B2 and Figures B7 and B8).

20. By 1 December 1987, plant establishment varied from complete coverage in one mat plot and one multiple-stem plot to less than 33 percent

coverage of plants in most other plots. Three of the four mat plots had 35- to 100-percent cover (Table B2, Figures B7 and B9).

21. The surviving plants continued to spread and, in 1989, the plants were far outside the original boundaries of the plots (Figure B7). However, the shoreline had receded behind the establishment stands, leaving the plots as islands.

Comparison of tire breakwaters

22. The plantings behind the FTB and fixed tire breakwater had poor initial survival. Failure of plants to survive immediately behind the tires appeared to be due to rapid sediment accumulation behind the tire breakwaters that buried some plants. Severe wave action in September 1984 also caused the top poles of the fixed tire breakwater to break. Both breakwaters sank into the sediment, and wave action over the breakwaters was severe enough to wash plants away. Although surviving plants spread rapidly during the summer, these areas were replanted at the end of July 1985 to further test breakwater protection after sediment accumulation had apparently stopped.

23. Two years after the initial planting, the plants behind the fixed tire breakwater had survived and spread to create a stand of smooth cordgrass behind the four more easterly modules, while wave action prevented plant establishment on the western side adjacent to the breakwater structure (Figure B10). The shoreline had receded 15.2 m from the western side of the plots. Erosion was occurring as a result of wave action over and around the fixed tire breakwater. By 26 June 1987, numerous tires were released since most of the remaining top poles had broken or worked free. Two thirds of the plants were removed by wave action on the western side. By June 1989, plants were confined to two small remnant stands within the fixed tire breakwater area. The lower poles and tires remained imbedded in the sand.

24. The FTB had excellent plant establishment in November 1986, about 2.5 years after the initial planting (Table B2 and Figure B10). Plants extended completely across the site. However, plants were not growing near the front line of tires, and plants had not colonized landward or seaward (Figure B11). Plant cover varied from 40 to 70 percent within the stand. By June 1989, plants had colonized down to the tires, which were solidly imbedded in the sediment, and completely covered the area within the wave protection of the tires. Plants had not colonized landward, apparently because of wave action and resulting erosion from the sides of the area that left it an island. The tires eventually filled with sediment and sank into the substrate

despite the presence of foam flotation. The plants did not colonize adjacent to the tire structure until the shifting of the tires ceased.

Mat plantings, 1988

25. On 13 September 1988, approximately 2.5 months after planting but before Hurricane Gilbert (described below), the mat plots (Figure B5) were in good condition except for some erosion at the upper edges. There was no erosion of the mat plots in replication 2 where the mat edges were buried and not exposed. Some portions of mats were covered with thin layers of shell fragments, sand, or silt. The percent survival of transplants was relatively low, 27.1 percent in the transplanted area compared to 23.8 percent in the control (Table B3). Survival was not significantly different between areas (control and planted plots) using a probability significance level of $P < 0.5$.

26. Goats were observed using the mats as loafing areas and may have influenced plant survival by crushing or eating plants. Other contributors to low survival may have been wave action and lack of rainfall, since 1988 was a record drought year. Percent survival was lowest in the mats at the highest elevation, followed by the next to highest (Table B4). The low survival at elevations above mean high water appeared to reflect the dry summer conditions of 1988.

27. Hurricane Gilbert generated harsh wave conditions in mid-September 1988. Despite the strong waves, the mats were intact when inspected on 15 October 1988. Erosion was notable along the top and bottom edges of mats in two replications, but the weight of sediment imbedded in mats appeared to hold them in place despite the exposure of edges. Wave action from Hurricane Gilbert only slightly reduced the percent survival in the mat treatments while the percent survival in the control treatments dropped from 23.8 to 10.8 percent (Table B3). The number of stems per planting unit and total stems in the transplanted area increased slightly from September to October despite the reduction in percent survival.

28. In June 1989, the mats were generally intact and in satisfactory condition. However, pieces of mats were torn away by wave action in a number of locations, particularly on corners. Sediment had generally redeposited to the elevation level of the mats. In replication 1, approximately 7.6 m of the western side had been torn loose by wave action. Part of this material was still attached and was being moved about by waves. The number of stems per square meter and the total number of stems in the mats had increased greatly,

and were significantly ($P < 0.05$) greater than the control areas (Table B3). Plants in control replications 1 and 3 were no longer present.

Cost analysis, 1988 mats

29. The cost of the fiber mats was the most expensive portion of the planting operation in 1988 (Table B5). Cost to purchase the fiber mat (5 cm thick by 15 m long by 1.8 m wide) was $3.34 per square meter. Installation of the mats took additional manpower compared to traditional planting methods using single stems. Considerable labor was expended in sewing the mats together. The original plan to glue the mats with natural latex rubber was not implemented because the vendor could not supply the glue in time to meet the planting schedule. Therefore, 30 mats were sewn together, 10 were glued, and 5 were buried individually. The sewing required 9 man-days of labor. Gluing of mats took much less effort, but the glue is relatively expensive. The waterproof adhesive was $4.50 per tube, which is enough to glue only two mats together.

30. Burying the edges of mats was perhaps the most difficult task. Hand labor was slow, and the water pump technique could be used only when water covered the edges of plots. The technique was generally effective when used. Water pumps can be purchased for $600. The labor to transplant is similar for both the mat and the control area. The major exception is that there is an additional effort in cutting the holes in the mat prior to transplanting and in locating the mat holes and placing the plant into the holes at the time of planting.

Discussion

31. The floating tire breakwater and the mats were the most successful of the techniques used. The fixed tire breakwater was a failure because of the pole breakage, release of tires, and poor plant establishment behind it. The 15-m-long poles presented two problems: (a) the structure was not able to move when hit by waves and was consequently battered apart and (b) the weight of the modules made handling of them difficult during construction. In contrast, the FTB remained intact, and plants established successfully behind the breakwater. The initial low survival appeared to be related primarily to sediment accumulation. Planting should be delayed until new deposition behind the FTB ceases; this delay could improve survival rates.

32. The mats were the most successful of the replicated treatments tried in 1984, but damage to some of the mats indicated that mat edges were vulnerable to erosion. Greater lengths of mat were placed parallel to the shoreline in 1988 than in 1984 to determine the effectiveness of mats when the ratio of mat edge to surface area was less. The longer mats laid down in 1988 were still intact in August 1989 except for the loss of one portion of one mat.

33. The mats provided the initial protection needed for establishment of plants in a high-wave energy climate. However, low survival occurred despite the presence of mats. The initial low survival probably occurred because of hurricane-generated waves, summer drought, and use of plots by feral goats. Since the mats were intact after low survival was determined, they could have been transplanted. They were not replanted in favor of monitoring the original transplant development. Since the mats have generally remained intact and plants have spread, the mats appear to have good potential for shoreline plant establishment.

34. Cost of the mat treatments could be reduced by focusing on cost-effective ways of fastening or placing the mats together, anchoring the edges into the substrate, and reducing material costs. Mats can be placed and anchored at the same time by using a mechanized ditch-digging device when the site is not flooded by tides. Then, edges of mats could be placed into the ditch and buried. When the site is flooded, a hydraulic jet pump could be used to bury the edges of the mat.

35. Severe erosion in the study area was primarily on the west-northwest side of each dredged material plume, the direction of longest fetch and most wave exposure. Wave exposure to the northwest (300-deg azimuth) was also documented as a direction of severe erosion at another Gulf of Mexico site (Webb, Allen, and Shirley 1984). Greater survival and spread of plants on the eastern side of the study area at Bolivar Peninsula (Figure B7) further indicates that a northwesterly exposure of plots can result in greater washout. The survival of some plants in burlap bundle and multistem plots very likely was influenced by protection from adjacent plots, tire breakwaters, and other plants to the west.

Summary and Conclusions

36. Five types of replicated vegetation treatments were tried in 1984 for shoreline erosion control on dredged material plumes deposited on Bolivar Peninsula. Erosion control mats, carpetlike in appearance, had smooth cordgrass inserted into them and were the most successful. This material was further investigated in larger plots in 1988. During the 1988 planting, the mat material remained intact, despite waves generated by Hurricane Gilbert and significant erosion of the site. Percent survival of plants, which was lower than expected, appeared to be associated with the extremely dry summer, the wave action generated by Hurricane Gilbert, and feral goat activity. The number of plants in the control treatments continued to decline, while the mat plots remained intact and plant coverage in those plots continued to expand throughout the monitoring period. The mats may provide a cost-effective technique for establishment of plants on high-wave energy shorelines without posing a problem to navigation. Further monitoring of these sites is encouraged to determine whether the plant community continues to establish and whether it provides long-term stability to the shoreline areas.

37. The area protected by the floating tire breakwater, despite some initial washout of plants, colonized successfully. The success of the FTB at this site once again demonstrated that FTBs in gulf coast climates are effective aids to shoreline marsh establishment. The fixed tire breakwater was a failure.

Table B1

Survival of 280 Transplants in Each of the Four Replicates of the Five Erosion Control Treatments Established July 1984

Treatment	No. of Plants Rep 1	Rep 2	Rep 3	Rep 4	Average No. Plants	Avg. % Survival
			30 Oct 1984*			
Mats	153	77	55	4	72.3	25.8
Multiple stems	13	61	113	28	53.8	19.2
Plant rolls	2	2	64	79	36.8	13.1
Burlap bundles	12	12	18	8	12.5	4.5
Single stems	3	3	18	38	15.5	5.5
			3 Jan 1985*			
Mats	138	19	51	0	52.0	18.6
Multiple stems	9	2	91	10	28.0	10.0
Plant rolls	0	0	11	18	7.3	2.6
Burlap bundles	7	7	8	4	6.5	2.3
Single stems	0	0	3	22	6.3	2.2

* There was no significant difference in survival between treatments as tested by analysis of variance ($P < 0.05$).

Table B2

Average Percent Plant Coverage of Plots and Density/m^2 of Plants in Erosion Control Experimental Plots at Bolivar Peninsula, Texas

Treatment	Rep 1 Cov	Rep 1 Stems	Rep 2 Cov	Rep 2 Stems	Rep 3 Cov	Rep 3 Stems	Rep 4 Cov	Rep 4 Stems
				20 Nov 1986				
Mats	0	0	99	228	25	108	66	192
Multiple stems	1	<1	90	148	33	80	00	00
Plant rolls	1	<1*	0	00	00	00	00	00
Burlap bundles	33	136	10	124*	00	00	6	64*
Single stems	0	0	6	136*	00	00	00	00
				1 Dec 1987				
Mats	0	0	100	315	35	162	60	228
Multiple stems	10	233	100	337	35	80	0	0
Plant rolls	33	233	0	0	0	0	0	0
Burlap bundles	75	322	40	315*	0	0	15	228*
Single stems	0	0	8	315*	2	160*	0	0
Floating tires	90	308						
Fixed tires	25	275						

* Plants were present, but coverage was due to encroachment from another treatment.

Table B3

Mean Percent Survival, Mean Stems per Plant, and Stems/m^2 in Fiber Mats and Control Plots, Bolivar Peninsula

Date	Percent Survival		Stems per Plant		Stems/m^2	
	Control	Mats	Control	Mats	Control	Mats
13 Sep 88	23.8	27.1	1.1	1.3	3.9	6.1
15 Oct 88	10.8	24.3	0.8	1.4	11.4	6.4
8 Jun 89					4.5a	35.0b

* Statistical differences (P < 0.05) between control and planted at that date.

Table B4

Plant Performance Measurements at Each Elevation of Mat Rows (13 Sep and 15 Oct 1988 and 8 Jun 1989)

Elevation	Percent Survival		Stems per Plant		Stems/m^2		
	Sep 88	Oct 88	Sep 88	Oct 88	Sep 88	Oct 88	Jun 89
Top	11.2	11.7	0.2	0.4	0.75c*	1.55c	11.6b
2nd	21.8	21.3	0.7	0.9	2.91c	3.90bc	45.8a
3rd	31.1	30.8	1.6	2.2	7.20ab	10.06a	66.0a
4th	37.2	29.9	2.5	1.8	12.01a	8.61ab	41.9a
Bottom	33.9	27.7	1.8	1.8	7.64ab	7.72ab	10.0b

* Statistical differences (P < 0.05) between elevations for that date. Elevations with different letters were significantly different by Student-Newman-Keuls' multiple range tests.

Table B5

Cost of Installation of Paratex Mats Planted in 1988

Fiber mats	- 45 rolls (1.8 m × 15 m × 5 cm	$6,600
Labor	- 490 hr at $6/hr	2,940
	- 100 hr at $15/hr	1,500
Both rental	- $50/day × 12	600
Truck and trailer rental		750
Equipment rental and use (pump, shovels, etc.)		150
		$12,540

Average cost per meter = $92

Approximate cost per square meter = $10.76/sq m

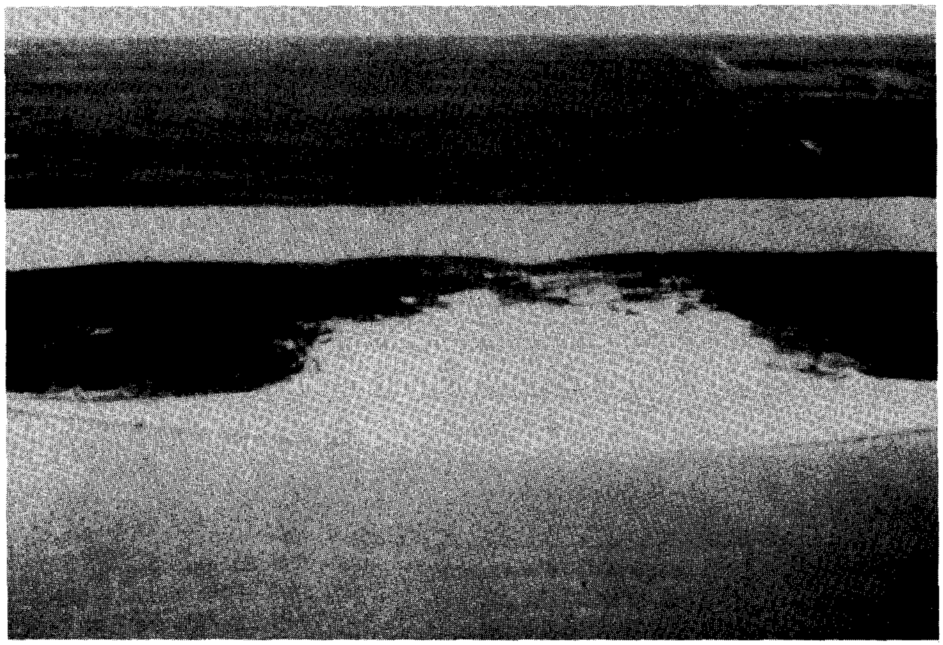

Figure B1. Fan-shaped plumes of dredged material typical of unconfined disposal operations in the Gulf Intracoastal Waterway at Bolivar Peninsula, Texas

Figure B2. Salt marsh developed in 1976-77 from use of a large sandbag breakwater. Photo shows marsh about 4 years after development

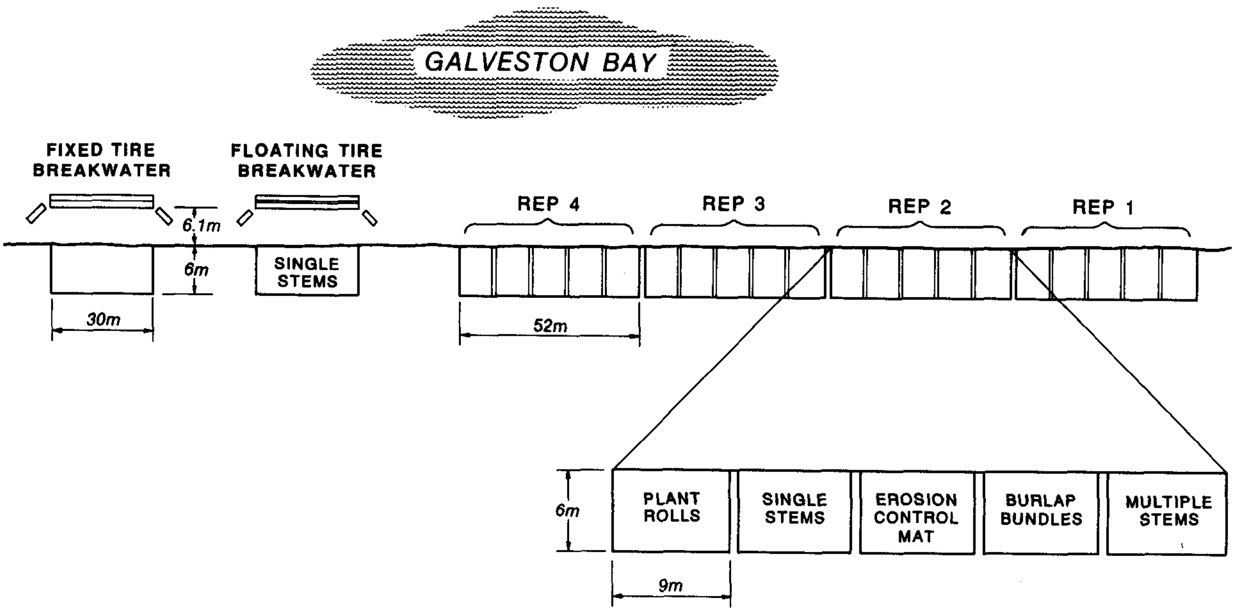

Figure B3. Field layout of 1984 salt marsh planting demonstration

Figure B4. Erosion control mat with plants inserted into slits

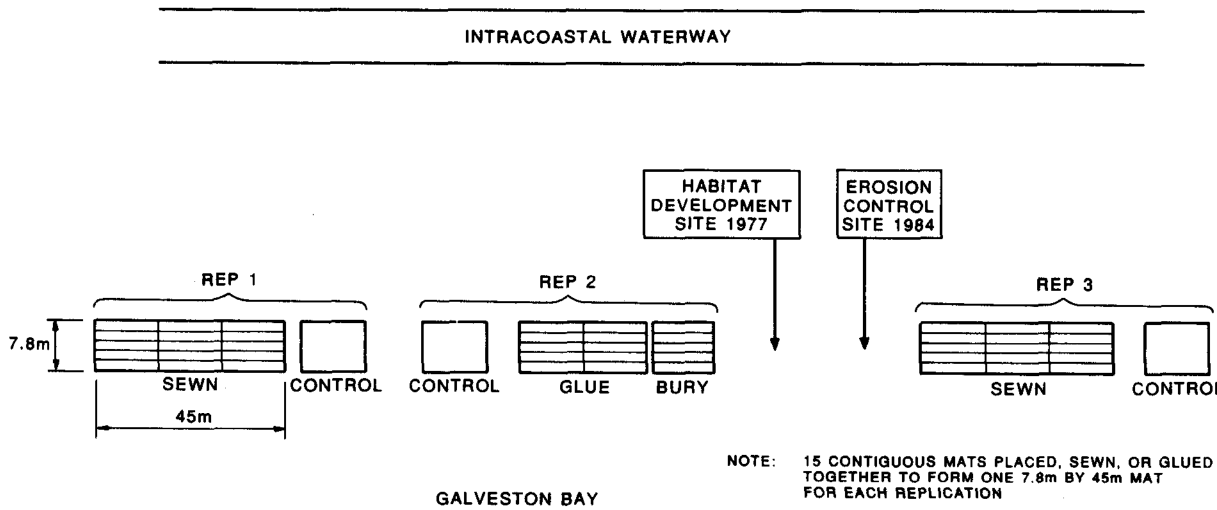

Figure B5. Field layout and design of erosion control mat plots in 1988

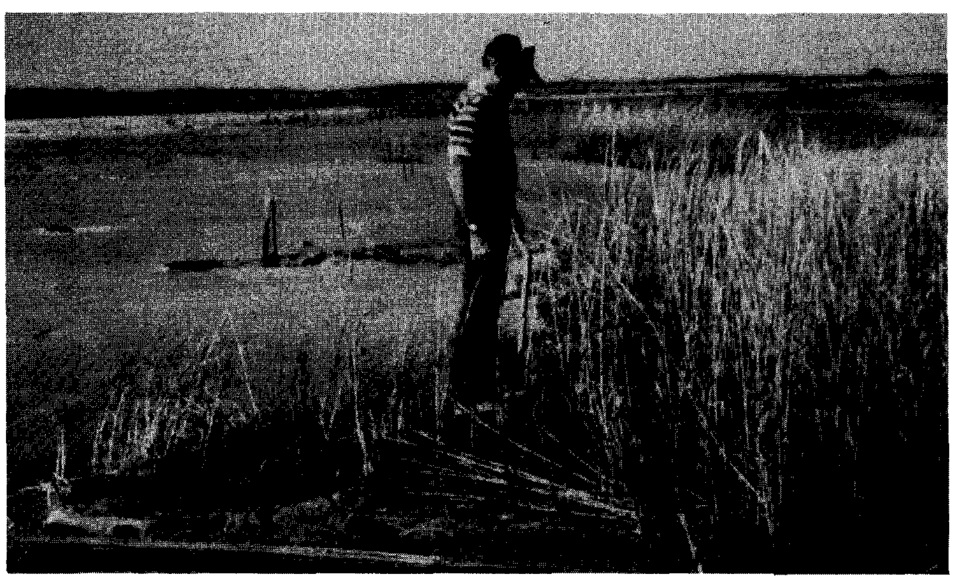

Figure B6. Erosion control mat plot in November 1985, about 1.5 years after planting

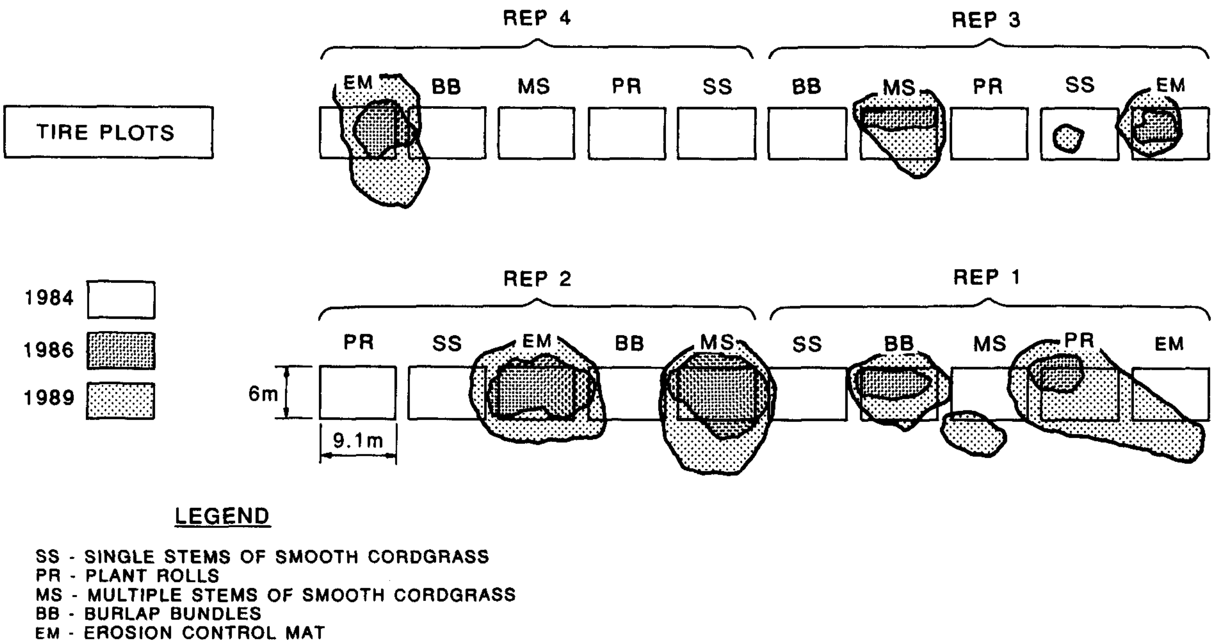

Figure B7. Plant presence (indicated by shaded areas) during two monitoring periods in the five 1984 experimental erosion control treatments

Figure B8. Plant spread in a mat plot as observed in November 1986, about 2.5 years after planting (tape shows edge of original plot)

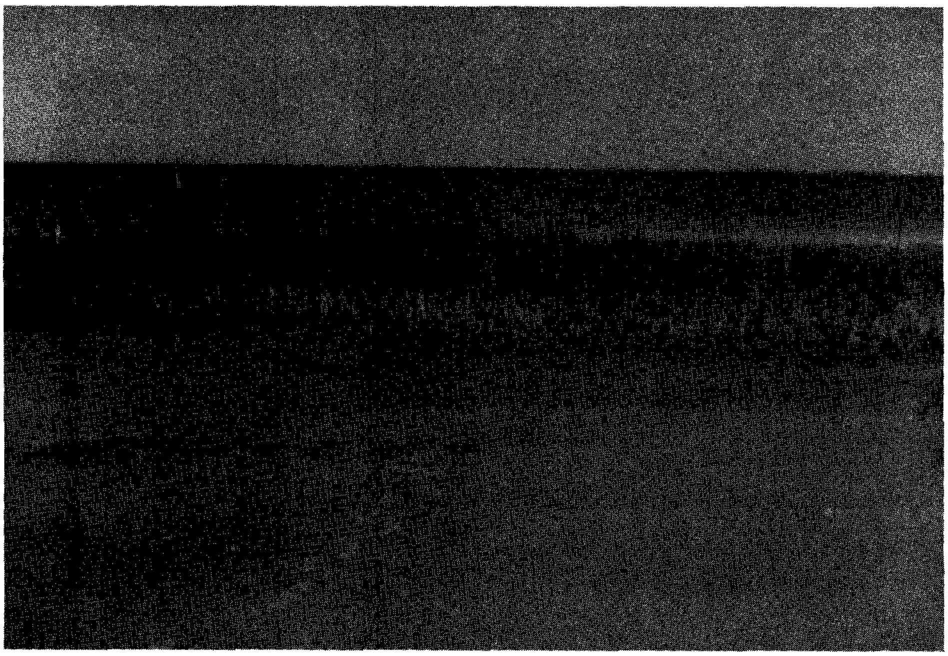

Figure B9. Erosion control mat as observed on 1 December 1987, about 3.5 years after planting

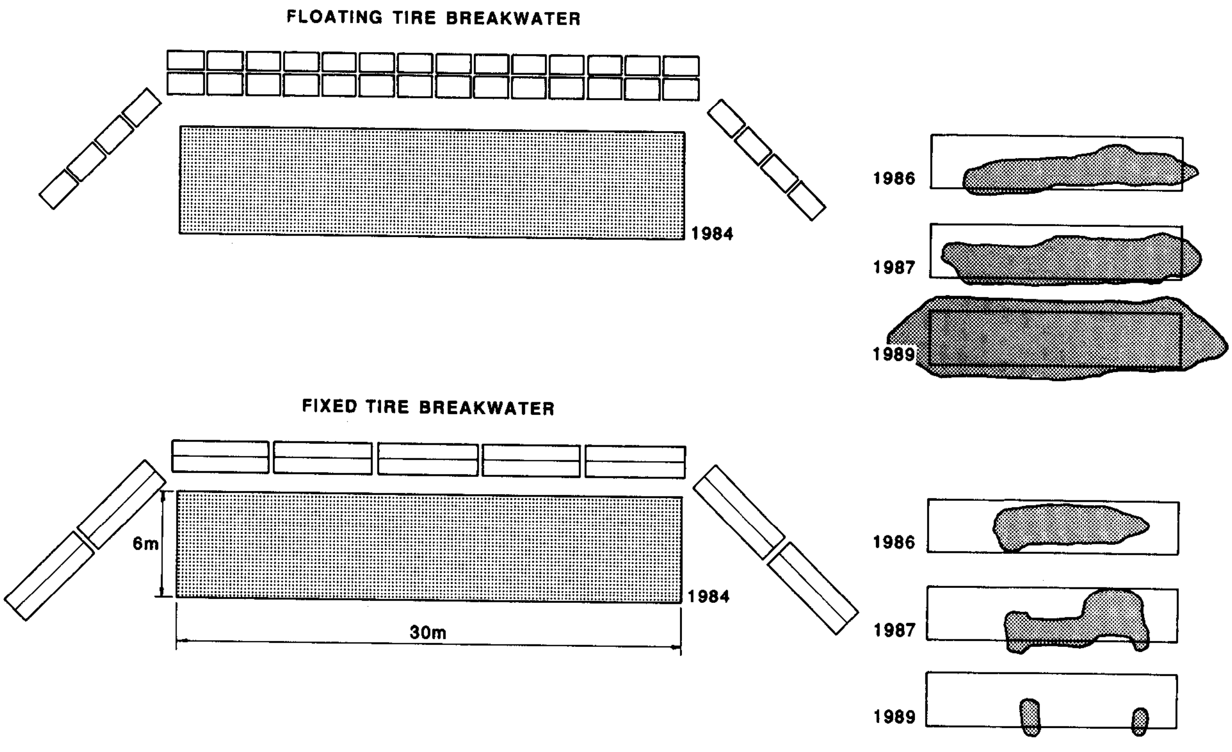

Figure B10. Plant establishment over time in the tire breakwater plots. (Note: A 6- by 30-m area shoreward of each breakwater was planted in 1984 with single-stemmed transplants of smooth cordgrass on 0.5-m centers. Shaded areas in the rectangles to the right represent plant cover in those same breakwater areas over time)

Figure B11. Floating tire breakwater area as observed in November 1986, about 2.5 years after planting