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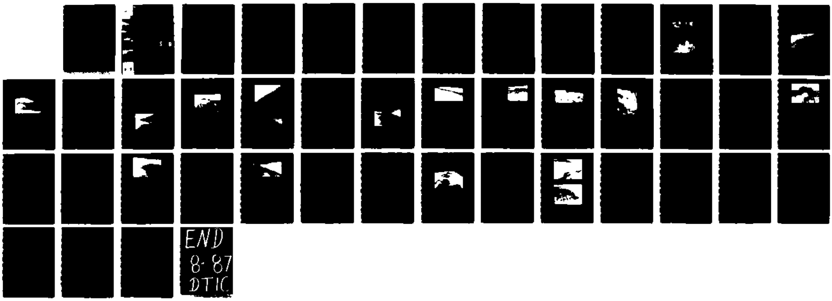

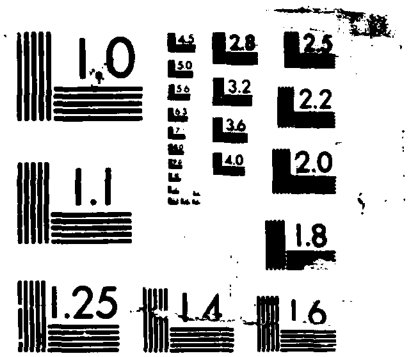

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ENVIRONMENTAL CONSIDERATIONS FOR DUNE-STABILIZATION PROJECTS

by

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Dune creation and stabilization are used by the US Army Corps of Engineers as an effective technique in storm and hurricane protection by providing a barrier to storm surges, by providing sand to eroding beaches, and in reducing maintenance and dredging requirements by stabilizing sand that could blow or erode into navigation channels and other project areas. Major dune stabilization projects along a barrier system should be preceded by an investigation of the role that the dunes and physical processes modified by dunes play in the overall dynamics of the system. This report provides the background needed to conduct these investigations.

During storms, dunes are a source of sand for beaches of any coastal type. Dune sand contributes to the beach profile by buffering or reducing the magnitude of beach change coincident with individual storm events. Dunes also act as barriers to prevent the penetration of waves and storm surges during some storm events.

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Dune systems along the gulf and Atlantic coasts of the United States are usually associated with barrier islands. Dune systems occur intermittently along the Pacific coast. They are usually found in association with sediments deposited by coastal rivers or captured in the lee of rocky headlands. Dunes around the Great Lakes form from glacial drift. Lowered water levels provide an increased sediment supply for dune building.

Perennial grasses are the primary plants used in efforts to stabilize dunes. The four grasses most commonly used are American beachgrass, bitter panicum, European beachgrass, and sea oats.

Two features of man-made dunes make them visually different from natural dunes. First, man-made dunes tend to be continuous and linear in configuration. Second, they tend to be dominated by the perennial grass that is initially planted, even after many years.

High dunes, natural or artificial, reduce erosion of the foreshore during storms. This process does not appear to affect long-term erosional or depositional trends on the shoreline.

The influence of dune stabilization, if any, on barrier island migration will often depend upon the type of barrier being stabilized. Upon relatively broad barriers, dune building will have little impact on migration processes. On narrow, eroding barriers, stabilization efforts may interfere with barrier migration.

The lack of plant diversity on man-made dunes is, typically, an unavoidable impact. The development of new dunes by planting or other means will change the microclimate of areas adjacent to the developing dunes. Whether or not these changes are viewed as ecologically positive or negative will depend upon the local importance and abundance of the habitats that are modified.

In some instances, stable dunes can be used to protect salt marshes from destruction by overwash and burial. However, on some barrier islands, overwash is important to the development of new marshes and the abatement of erosion on existing marshes.

Small, localized dune-stabilization efforts, particularly the planting of dune vegetation, can usually be considered as conservation measures. Dune-building techniques are used only when there is a need to protect existing facilities. Where such development exists, the absence of stable dunes can often be attributed to human activities; hence, dune building would be a restorative action.

Environmental impacts are not likely to be a major consideration even for relatively extensive dune-stabilization projects in mainland coastal areas. However, major efforts to build continuous dunes on barrier islands to provide protection to mainland areas from major storms and hurricanes will require more serious consideration. Projects of this magnitude may potentially alter the geological and ecological characteristics of the barrier system. Major dune-stabilization projects along a barrier system should be preceded by an investigation of the role that the dunes and the physical processes modified by dunes play in the overall dynamics of the system.

PREFACE

This report was sponsored by the Office, Chief of Engineers (OCE), US Army, as part of the Environmental Impact Research Program (EIRP), Work Unit 31533, entitled Beach and Foredune Ecology. The Technical Monitors for the study were Dr. John Bushman and Mr. Earl Eiker of OCE and Mr. David B. Mathis of the Water Resources Support Center.

This report was prepared by Mr. Paul L. Knutson, Coastal Ecology Group, US Army Engineer Waterways Experiment Station (WES) and Mr. Kenneth Finkelstein, Virginia Institute of Marine Science. Reviews and comments were provided by Dr. J. Allen, National Park Service; Dr. W. Hobson, Virginia Institute of Marine Science; Dr. Suzette Kimball, Coastal Engineering Research Center; Dr. Roger T. Saucier, WES; and Mr. E. Jack Pullen, WES. Mr. David A. Nelson was principal investigator for this report, under the general supervision of Mr. Pullen, Chief, Coastal Ecology Group; Dr. Conrad J. Kirby, Jr., Chief, Environmental Resources Division; and Dr. John Harrison, Chief, Environmental Laboratory. Dr. Saucier was the Program Manager of EIRP. This report was edited by Ms. Lee T. Byrne of the Information Products Division, Information Technology Laboratory, WES.

COL Allen F. Grum, USA, was the previous Director of WES. COL Dwayne G. Lee, CE, is the present Commander and Director of WES. Dr. Robert W. Whalin is the Technical Director.

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ENVIRONMENTAL CONSIDERATIONS FOR DUNE-STABILIZATION PROJECTS

PART I: INTRODUCTION

1. Dune creation and stabilization are used by the US Army Corps of Engineers as an effective technique in storm and hurricane protection by providing a barrier to storm surges, by providing sand to eroding beaches, and in reducing maintenance and dredging requirements by stabilizing sand that could blow or erode into navigation channels and other project areas. Major dune stabilization projects along a barrier system should be preceded by an investigation of the role that the dunes, and the physical processes modified by dunes, play in the overall dynamics of the system. This report will provide the background needed to conduct these investigations.

History of Human Efforts to Stabilize Coastal Dunes

2. Human efforts to stabilize and develop coastal dunes have more than a 200-year history in the United States. The earliest records of extensive dune-stabilization projects concern Cape Cod. Prior to European settlement, most of the Cape was thickly forested. Early settlers cleared areas of the forest for fuel, fence posts, fish weirs, and croplands. Some areas were burned annually to increase the blueberry crop, whereas others received grazing pressures. By the early 1700s, blowing sand threatened Provincetown and Provincetown Harbor at the northern tip of Cape Cod (Westgate 1904). As early as 1714 and again in the 1830s, colonists, recognizing their error, endeavored to stabilize damaged areas of the Provincelands with pine branches and the planting of beachgrass (Zak 1967). More than 400 ha were planted.

3. In about 1904, a group of Massachusetts duck hunters introduced the practice of sand stabilization to the Outer Banks of North Carolina. The Outer Banks had suffered from centuries of deforesting for firewood and boat making, as well as from grazing pressures. Blowing sand was filling in freshwater ponds and other prime waterfowl habitats. Members of a Massachusetts-owned hunting club on the Outer Banks began a major program to protect

thousands of hectares of the club's land. Pine branches were again used as well as "Cape Cod grass," brought from New England. The beachgrass that has been planted for more than two centuries is now referred to as American beachgrass (*Ammophila breviligulata*). Efforts at dune stabilization reached a peak on the Outer Banks in the 1930s. A Federal- and State-sponsored project utilized 1,500 Civilian Conservation Corps (CCC) and Works Progress Administration (WPA) laborers on 200 km of the Outer Banks shoreline. This project used more than 1,000,000 lin m of sand fence (slat-type fence) to capture sand. More than 1,200 ha of American beachgrass were planted (Stratton and Hollowell 1940).

4. The first stabilization efforts on the Pacific coast were not recorded until about 1900. The dune field that once covered San Francisco's Golden Gate Park was planted with beachgrass to control blowing sand, and the park's first trees were placed in the ground. The grass, European beachgrass (*Ammophila arenaria*), was imported from northern Europe, where it had long been used for sand stabilization and dune building (Federal Writers Project 1973). The value of this useful grass became known to the residents of Bodega Bay, 80 km north of San Francisco. Grazing and other activities had denuded major portions of the dunes that surrounded the bay. Wind erosion was rapidly filling the bay with sand. With plants obtained from Golden Gate Park, residents of Bodega began to stabilize critical areas of erosion. In 1952, with the help of the Soil Conservation Service, the last 400 ha of moving sand were brought under control (US Department of Agriculture 1967). CCC labor was also used to stabilize several areas of the Pacific Northwest (Figure 1). European beachgrass and sand fences were used to repair vast areas of barren sand created by improper grazing and foresting practices. For example, on the Clatsop Plains in Oregon, 1,200 ha of shifting sand were stabilized to protect a coastal highway, communities, and extensive pine forests (McLaughlin and Brown 1942).

5. Dune stabilization continues to be an important coastal engineering activity. In the past two decades, considerable emphasis has been placed on research to refine techniques of stabilization on the Atlantic coast (Gibbs and Nash 1961; Savage 1963; Zak 1965; Jagschitz and Bell 1966; Hawk and Sharp 1967; Woodhouse and Hanes 1967; Graetz 1973; Woodhouse, Seneca, and Broome 1976; and Knutson 1980) (Figure 2), the gulf coast (Gage 1970; Dahl et al. 1975; Dahl and Goen 1977), and the Pacific coast (Cowan 1975).

Figure 1. 1935 photo of dune plantings on the Clatsop Plains in Oregon (Soil Conservation Service)

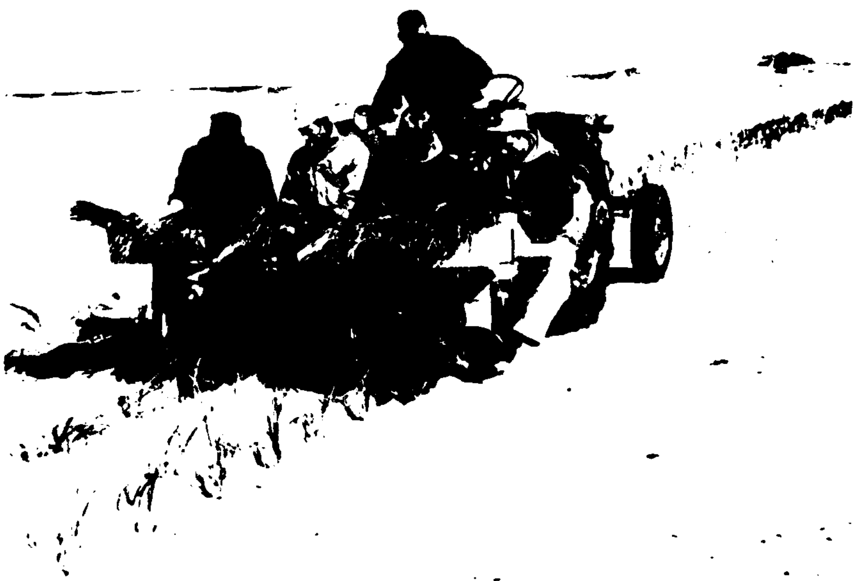

Figure 2. 1968 photo of dune planting experiments, Outer Banks, North Carolina (W. W. Woodhouse)

Report Objectives

6. Over the past two centuries, most dune-stabilization efforts have been attempts to restore coastal areas that have been adversely affected by one or more human activities. As such, dune-stabilization projects have been commonly regarded as conservation measures. Indeed, most stabilization activities are conservation measures. However, in recent years several arguments have been advanced against the unbridled use of this technology. The first arguments are geological in nature and deal with the potential impact of man-built dunes on coastal processes and barrier islands. Some researchers have suggested that stable dunes may actually accelerate erosion and may interfere with barrier island migration. Lastly, some ecologists have suggested that man-built dunes may change the character and habitat value of some coastal plant communities (Dolan, Godfrey, and Odum 1973; Godfrey and Godfrey 1973).

7. This report is intended as a summary of the major environmental issues that should be addressed in the planning and design of dune-stabilization projects. Part II reviews the role of dunes in shore processes. Parts III and IV describe the geomorphology and vegetation of natural dune systems and compare natural systems with man-made dune systems. Part V summarizes the potential impacts of dune-stabilization projects on shore and barrier island geological processes. Part VI summarizes potential biological impacts.

PART II: ROLE OF DUNES IN SHORE PROCESSES

8. Dune systems have two primary functions in shore processes. First, they act as levees to prevent the inland penetration of waves and surges during some storm events. Second, they provide a reservoir of sand to nourish eroding beaches during storms (US Army Coastal Engineering Research Center (CERC) 1984).

Overtopping

9. Foredunes, the first line of dunes landward of the beach, prevent storm waters from flooding low interior areas (Figure 3). Small increases in

Figure 3. Dunes under wave attack, Cape Cod, Massachusetts (Stephen P. Leatherman)

the elevation of the foredune crest result in large reductions in water overtopping. For example, it has been estimated that a 1.3-m-high dune on Padre Island, Texas, would prevent overtopping from water levels accompanying storms with an expected recurrence interval of 5 years (assuming that an increase in water level would not increase wave runup) (CERC 1984).

Sand Reservoir

10. During storms, erosion of the beach occurs, and the shoreline recedes. In a sense, the dynamic response of a beach under storm attack is a sacrifice of some beach to provide material for an offshore bar (Figure 4).

Figure 4. Dune erosion during severe storm, Cape Cod, Massachusetts (Stephen P. Leatherman)

This bar protects the shoreline from further erosion. Dunes can reduce the amount of beach loss occurring during a particular storm event by contributing sand to the upper beach and offshore bar system.

11. Recent investigations have estimated the volumes of sand eroded from beaches during storms. Losses from erosion during single storms on the shore of Lake Michigan (Fox 1970), on Jones Beach, New York (Everts 1973), and on Mustang Island, Texas (Davis 1972), have been estimated to be as high as 14,000, 17,000 and 31,000 m^3/km, respectively. Because much of the eroded sand is usually returned to the beach by wave action soon after the storm, these volumes are probably representative of temporary storm losses. Birkemeier (1979) studied poststorm changes on Long Beach Island, New Jersey. He found that about one half of the material eroded from the beach during the storm returned to the beach within 2 days. Volumes equivalent to those eroded during storms were trapped and stored in foredunes adjacent to the beach.

Foredunes constructed on Cape Cod, Massachusetts (Knutson 1980), Ocracoke Island, North Carolina (Woodhouse, Seneca, and Broome 1976), and Padre Island, Texas (Dahl et al. 1975), contained 60,000, 80,000, and 120,000 m^3/km of beach, respectively (CERC 1984).

12. Not all researchers agree that dunes reduce shore erosion during storm events. Some arguments to the contrary will be discussed in Part V.

PART III: DESCRIPTION OF NATURAL DUNE SYSTEMS

Geology of Natural Dunes

Dune processes

13. Sand dunes may occur where there is a large supply of sand, wind to move it, and a place in which it can accumulate (Goldsmith 1978). A precise physical discussion of the formation of dunes has been included in studies by Bagnold (1954) and Goldsmith (1978). Most coastal dune sediments are indirectly derived from reworked fluvial (river) and/or glacial material. The littoral transport system moves these sediments onshore and alongshore.

14. Coastal sand dunes may be divided into those that are vegetated and thus relatively fixed in place and those that are unvegetated. Vegetated coastal dunes of North America have primarily three different morphologies, as described below:

a. Foredune ridges are linear, low-amplitude ridges that parallel the beach (Hayes and Kana 1976). Most beaches along the Atlantic and gulf coasts are backed by foredune ridges (Figure 5).

Figure 5. High foredune ridge, Outer Banks, North Carolina

These ridges often occur either as a solitary ridge or in a series parallel or subparallel to each other. On accreting or stable beaches, organic and/or inorganic debris may collect in the backshore, forming a drift line. Plants establish on this drift line, capturing sand and forming incipient dunes, which can grow and form a continuous foredune ridge.

b. Parabolic dunes develop in sparsely vegetated areas and are common on the shorelines of Lake Michigan, Cape Cod, and northwest Florida. These dunes are U-shaped, with the open end generally oriented toward the direction of the prevailing wind (Figure 6). They form behind the foredune

Figure 6. Parabolic dune, False Cape, Virginia

ridge from an abundant sand supply and a strong unidirectional effective wind, under the increasingly stabilizing effects of vegetation (Goldsmith 1978).

c. Precipitation dunes may be sparsely vegetated or unvegetated and are so named because of the rapid landward movement or precipitation of sand. In some cases sand is blown into forested areas as the dune migrates landward (Figure 7). They are mostly, but not solely, found on the west coast of the United States (Cooper 1967).

15. Unvegetated dunes fall into three general categories: transverse dunes (perpendicular to wind), longitudinal dunes (parallel to wind), or sand hills (Figure 8). Transverse dunes are migrating dunes that lack vegetation to anchor the sediment, usually because of their rapid movement, and generally move landward in response to the prevailing wind. They are aligned normal to the resultant sand-transport vector and may be associated with vegetated dune fields such as those at Coos Bay, Oregon. A transverse dune has a single straight to sinuously shaped crest up to 1 km in length (Goldsmith 1978).

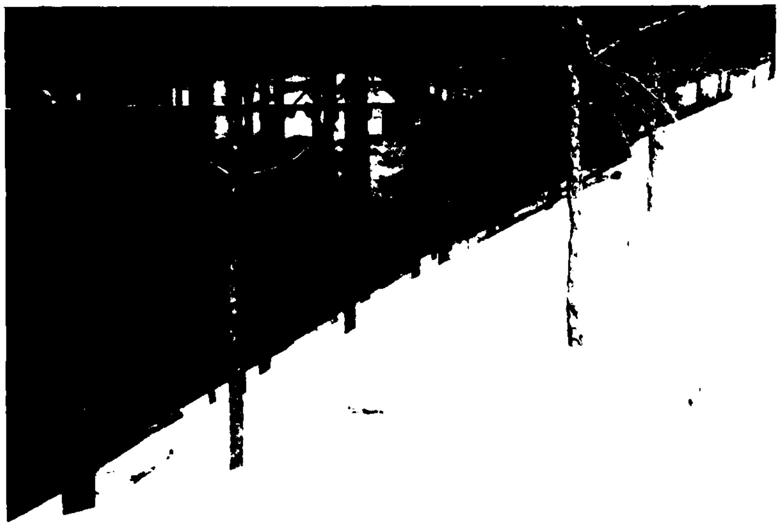

Figure 7. Precipitation dune, Dauphin Island, Alabama

Figure 8. Unvegetated dunes, Padre Island, Texas

Wind-parallel longitudinal dunes are also usually unvegetated and are characterized by an along-dune component of sand transport. A high, steep, unvegetated, isolated sand hill that may be tens of metres in height is called a "medano" (Goldsmith, Henninger, and Gutman 1977). Examples of medanos are at Currituck Spit, Virginia/North Carolina, and Coos Bay, Oregon. Long stretches of unvegetated dunes are also found along the coasts of Baja California and Alaska.

16. The most important single factor that determines coastal dune morphology is the density of vegetation. Other factors include the type of vegetation, the wind regime (which, although important, can be modified by vegetation), the topographic setting, and the local, coastal geology (Smith 1960). The latter determines the availability of sediments and changes in water level and shoreline position.

17. Onshore winds are primarily responsible for the building of dunes, particularly the foredune ridge. The relative height of the foredune line may depend upon the direction of prevailing and predominant winds relative to the orientation of the beach (Leatherman 1979a). Predominant and prevailing onshore winds tend to form large dunes, whereas regions where winds are offshore or alongshore are characterized by lower and more discontinuous dunes. Large foredunes are associated with onshore winds because the beach is often the primary source of dune sand. Sediment on the foreshore may be blown to the backshore and settle around organic or inorganic drift material, thus forming incipient dunes. Over the long term, the volume of sand transported from the beach to the dune is dependent upon wind direction and velocity and sediment availability (the amount of sand contributed to the beach by littoral processes). Rosen (1979) found that longshore transport contributed to the building of new foredune ridges on recently formed spit segments of the Tabusintac barrier system, New Brunswick, Canada. Overwash sands may also be a source of sand for dunes (Armon 1979, Rosen 1979). Overwash sands are transported to the dunes by longshore and offshore winds.

18. Wave climate and changes in shoreline position also influence dune morphology. Dunes are often larger on receding or stable shores than on prograding ones (Pye and Rhodes 1985). Prograding shorelines without the intervention of high storm waves will often have several or many prograding small foredune ridges. However, high wave activity from storms may destroy this progradation and prevent the formation of a series of low parallel dunes. Subsequent healing of the dunes after a high-energy event of this type may ultimately cause one relatively high foredune ridge to form even on a prograding beach.

Regional examples

19. Dune systems are common features along the gulf and Atlantic coasts of the United States and are usually associated with barrier islands. Longshore drift and onshore winds distribute sediments to the foredune ridge. Barrier beaches in New England are characterized by one or more dune ridges, often high. For example, dune ridges at Plum Island, Massachusetts, form several physiographic zones, all of which trend parallel to the present shoreline. Lying closest to the water is the foredune ridge, which is adjacent to the beach. A low interdune area occurs landward of the foredune ridge. A discontinuous backdune ridge is stabilized by shrubs and trees (Larson 1969).

20. Depending upon sediment availability, mid-Atlantic shores may exhibit many well-established dune ridges or may lack dunes altogether. For example, northern Assateague Island, Maryland, and southern Metomkin Island, Virginia (Figures 9 and 10), both starved of sand and frequently

Figure 9. Frequently overwashed portion of barrier island, Assateague Island, Maryland

overwashed, exhibit only small incipient dunes. Accreting shorelines may have a series of parallel dunes. For example, since 1904, 39 successive dune ridges have formed on a prograding spit, Fishing Point, in Virginia (Gawne 1966). Parramore Island, Virginia, a drumstick barrier island, exhibits several dune ridges on its accreting northern end (Hayes and Kana 1976).

Figure 10. Frequently overwashed portion of barrier island, Metomkin Island, Virginia

21. Gulf coast dune systems are largely affected by predominant onshore winds and severe tropical storms. The onshore winds encourage dune growth, whereas tropical storms often cause their destruction. In 1979, Hurricane Frederick caused extensive dune erosion on Dauphin Island, Alabama. Following the storm, sediments returned to the beach in the form of a landward-migrating bar (Penland, Nummedal, and Schram 1980). Subsequently, onshore winds moved sand to the backshore and dunes, facilitating the rebuilding of the foredune ridge. Similarly, when Hurricane Allen eroded 30 m of the dunes along Mustang Island, Texas, in 1980, the net effect was partially diminished by poststorm recovery (Nummedal 1982). Following the hurricane, beaches were covered with an almost continuous terrace, which was reworked into small, unvegetated dunes.

22. Dune systems occur intermittently along the Pacific coast. They are usually found in association with sediments deposited by rivers or captured in the lee of rocky headlands. For example, the Columbia River alone provides the sand source for thousands of hectares of extensive dunes on the Oregon coast (Figure 11). Cooper (1958) called Oregon's dunes oblique dunes because their direction of migration is oblique to both northwest and southwest winds. Though less abundant, Pacific dunes are often massive.

23. Dunes on the Great Lakes are largely confined to the shores of the states of Michigan and Indiana on Lake Michigan. Goldsmith (1978) notes that

Figure 11. Large dunes near mouth of Columbia River, Oregon

Lake Michigan sand dunes are similar in nearly every respect to other vegetative and precipitation coastal dunes. The source of sediment for these dunes is glacial drift. This material is moved by the longshore current to an area of accumulation where the wind picks it up and forms the dunes. Water levels in the Great Lakes go through extended periods (years) of lowering as a result of cyclical increases in evaporation and decreases in precipitation. The periods of fall in lake level accelerate the dune-building processes by exposing shore sediments to the wind.

Vegetation of Natural Dunes

24. As noted above, the formation and migration of coastal dunes are closely linked to the development of vegetation. Plant establishment is typically the first step in dune formation. Only a few species of plants are able to tolerate the beach environment. These plants must tolerate salt spray, sand abrasion, extremes in temperature and moisture, and occasional flooding. The plants that invade the upper beach have been called "dune initiators" or "strand-line plants" (Woodhouse 1978). The sand captured by these plants seldom forms more than small hummocks, but these hummocks provide an environment for the invasion of the more formidable "dune-building" plants. Common examples of the initial colonizers are sea rocket (*Cakile edentula*) and Russian-thistle (*Salsola kali*) on the Atlantic, sea-purslane (*Sesuvium portulacastrum*)

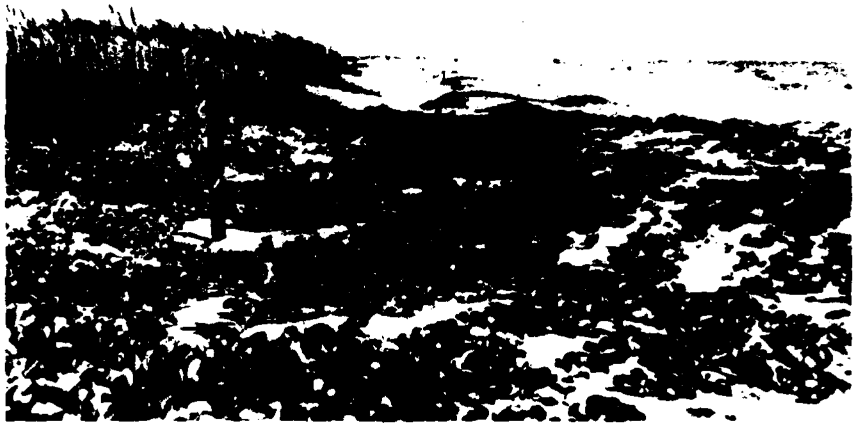

Figure 12. Railroad vine (foreground), a dune initiator, Padre Island, Texas (Bill E. Dahl)

and railroad vine (*Ipomoea Pes-caprae*) (Figure 12) on the gulf, sandverbena (*Abronia latifolia*) and sea fig (*Carpobrotus aequilaterus*) on the Pacific, and seaside spurge (*Euphorbia polygonifolia*) and sea rocket on the Great Lakes coasts.

25. Though the invasion of the upper beach by the strand-line species is often the first step to dune building, the bulk of the sand is captured by a distinctly different group of plants. While dune initiators avoid wind exposure by maintaining a low profile, the dune builders obstruct the flow of wind with their erect posture (Figure 13). They lower wind velocity near the ground, causing sand to accumulate. Again, the number of plant species that can survive on a newly forming dune is very limited. In addition to the stresses of the beach, dune builders must tolerate continual sand burial. Each region of the United States has one or more perennial grasses that are able to withstand and even thrive under these conditions. American beachgrass (*Ammophila breviligulata*) is the dominant dune builder in the north Atlantic coast from Maine to North Carolina and along the Great Lakes. From North Carolina to Texas, two additional species dominate, sea oats (*Uniola paniculata*) and bitter panicum (*Panicum amarum*). Panicum is of greater importance in the southern half of this range. American dunegrass (*Elymus mollis*) is the native dune pioneer in the Pacific Northwest (also found in the Great Lakes).

Figure 13. American beachgrass, a dune builder, Ludington, Michigan

However, American dunegrass has been largely displaced in the Pacific Northwest by the nonindigenous European beachgrass (*Ammophila arenaria*). Though European beachgrass was also introduced to California, dunes there still often lack a perennial grass component. They are often hummocky in appearance and support low-lying, strand-type vegetation.

26. As dunes develop, they form a physical barrier to many of the environmental stresses encountered on the backshore. Behind developing dunes, salt spray is reduced, flooding is lessened, and the effects of wind and sand burial are moderated. If the area remains stable over a period of several years, soil development begins. Topographically these protected areas may be either flat plains or dune ridges. The diversity of plants in these areas generally increases with distance from the oceanic stresses and also increases over time if the area remains undisturbed. Dune-building plants decline in

importance landward of the primary dunes. In some instances this decline is associated with a decrease in the rate of burial. In other cases the lessening of environmental stresses simply increases competition. Secondary dune areas that are periodically flooded during severe storms may never support a diversity of vegetation. For example, frequently overwashed flats on the mid-Atlantic coast tend to be dominated by saltmeadow cordgrass (*Spartina patens*) (Oosting and Billings 1942, Godfrey 1977). However, where dunes preclude periodic flooding, many other forbs, additional grasses, and even shrubs and trees may invade the secondary dune area.

PART IV: DESCRIPTION OF MAN-MADE DUNE SYSTEMS

Dune-Building Techniques

27. The perennial grasses referred to in the previous section as dune builders are the primary plants used in dune-stabilization efforts. The four grasses most commonly used are American beachgrass, bitter panicum, European beachgrass, and sea oats. Each of these grasses is easy to grow and plant, and each is an efficient trap for sand. Stems of these plants are usually planted in early spring on 1/2- to 1-m centers in a band about 15 m wide and parallel to the shore. If plantings are flooded with salt water during the growing season, they are usually destroyed. For this reason, a small elevated dune is often created prior to planting.

28. The most common method of creating a small dune prior to planting is with the use of sand fencing. Wooden or fabric fences create a region of low wind velocity, causing sand deposition. After a mound of sand has been captured by one or more lifts of fencing, the ridge is usually planted with beachgrasses.

Morphology of Man-Made Dunes

29. Several features of man-made dunes make them visually different from natural dunes, at least during the early stages of dune development. Natural dunes are formed by a series of chance events. They begin as small individual hummocks, usually of assorted shapes and sizes. The hummocks may coalesce over time, and the resultant dune will be irregular in elevation and in its location with respect to the shore. Regardless of stabilization procedure, man-built dunes tend to be linear (Figure 14). Indeed, dunes can be designed with a zigzag or other pattern, but for practical reasons they usually are not. First, straight dunes require the least effort and materials to construct. Second, if an irregular pattern is used on an eroding shoreline where the purpose of the dune is to prevent overwash, the portion of the dune closest to the shore will be the first area to erode. The flood protection provided by a dune system is limited to the protection provided by the weakest portion of that system. The same line of thinking can be used to discourage the use of an irregular dune-crest elevation. Because of these

Figure 14. Linear-shaped planted dunes, Outer Banks, North Carolina (R. P. Savage)

considerations, man-made dunes typically will be more regular in appearance and more continuous than natural dunes.

30. Man-made dunes can be made to conform to natural dune contours in other respects. The selection of stabilization technique may influence the final shape of the dune. Knutson (1980) observed in Cape Cod experiments that planted dunes produced lower and wider dunes than fence-built dunes. In North Carolina, researchers found that decreasing the spacing of plants both landward and seaward from the dune crest increased dune width and reduced the seaward slope of the dune from about 10 to 5 percent (Savage and Woodhouse 1968).

Vegetation on Man-Made Dunes

31. When planted in favorable environments, the dune-building beachgrasses provide rapid vegetative cover. The stabilizing role of these plants provides new habitat for other invading species. However, because of the formidable advantage that planting provides the beachgrasses and because of their aggressive nature, the invasion of other species is likely to be slow. Dahl and Goen (1977) observed only six invading species on monospecific beachgrass plantings over an 8-year period in south Texas. As noted earlier, other plants (dune initiators) may precede the beachgrasses in the stages of natural

dune development. Dahl and Goen (1977) concluded that when natural dunes develop, some species remain on the dune from previous successional stages.

32. California is a rather special case in dune stabilization. Apparently no perennial grass functioned as a dune-building beachgrass prior to the human introduction of European beachgrass. Many researchers consider dunes planted with this grass in California as being unnatural. For this reason Cowan (1975) and others have conducted experiments on stabilizing California dunes with native forbs such as the sea fig (*Carpobrotus aequilaterus*), beach sagewort (*Artemisia pyenocphala*), and sandverbena (*Abronia latifolia*). Because these native species are not commercially available and often require specialized treatment such as hydromulching and irrigation, attempts to stabilize dunes in this manner are very costly.

PART V: GEOLOGICAL CONSIDERATIONS IN DUNE-STABILIZATION PROJECTS

Shore Erosion

33. On an eroding coast, a stabilized dune will slow but not prevent erosion. Dunes can serve effectively as barriers to high-energy surf, but eventually storm waves will undermine or overtop the dunes with a subsequent net loss of sediment from the original dune. The lifetime of a particular foredune line is a function of the rate of shoreline erosion, dune height, and dune width. Large, well-developed dunes commonly withstand moderate storms and, often, relatively severe ones. However, where beach erosion is rapid, artificial stabilization will result in dunes of limited size and short lifespan. Stabilization of dunes on such a coast will provide only temporary protection to backdune structures or facilities.

34. Dolan (1972) proposed that during storm conditions the swash erodes the continuous foredune line. Breaking wave energy is confined to the zone seaward of the dune line. Dolan believed much wave energy would then be expended upon the beach, winnowing the finer material to offshore areas. This wave activity would result in a coarser beach texture and steeper beach profile. Subsequently, the steeper beach profile would increase wave reflection and turbulence. The end product would be more beach erosion.

35. The impact of dunes on beach processes has been reviewed in detail by Leatherman (1979b), who disputed the Dolan hypothesis and argued that much of the material removed from the dune and beach reforms as one or more nearshore bars. Wave reflection off the nearshore bars causes diminution of the incident waves and eventually reduces dune erosion. Seaward development of nearshore bars during high-wave storm events and of the resulting dissipative surf zone (Figure 15) with shoreward decay of incident waves is explained by Wright et al. (1979). It should also be noted that major storms and high waves tend to flatten the foreshore profile rather than steepen it.

36. The nearshore bar exhibits a cyclic behavior. During fair weather conditions, the bar migrates landward and after several weeks may weld onto the foreshore. This process of onshore bar migration after a storm event because of decreasing wave power has been shown by Short (1979).

37. Erosion of dunes by storms is a natural occurrence. This material provides a source of sand for the beach. As offshore sediments return to the

Figure 15. Dissipative surf conditions during storm, Outer Banks, North Carolina

foreshore to reestablish the original beach profile, onshore winds return sediment to the eroded dune. This is not to say that dunes will revert to their former size; that depends on the local sand budget and wind conditions. If more sediment is leaving a local coastal zone than entering it, dunes will exhibit continual erosion. Where dunes are breached or undermined, dunes will reestablish naturally, but usually landward of the original dune line. Sea-level rise may also contribute to dune erosion. However, if an adequate supply of sediment is available, the dune may migrate landward with the shoreline, as suggested by Bruun (1983).

38. High dunes, natural or artificial, may reduce foreshore erosion during storms because much of the dune sand is transported seaward, ultimately to an outer bar, and thereby contributes to dissipating wave energy. Rather, stable dunes buffer rapid changes in the beach associated with these severe storm events.

Barrier Island Migration

39. Barrier islands are elongated islands that for the most part parallel the mainland shores of the gulf and Atlantic coasts. The coastal plain and continental shelf are broad and gently sloping. In response to sea-level rise, the coastal plain is being submerged. If barrier islands were to occupy

a fixed position on the continental shelf, they would be eventually submerged by sea rise. However, for the most part, these barriers migrate landward up the continental shelf, maintaining a relatively constant elevation with respect to sea-level rise. Retreat of the seaward shore is accomplished by shore erosion, whereas the landward shore is extended by sediments transported between and around the island by tidal inlets and sediments transported over the islands by overwash and wind.

40. Considering that the objective of most dune-stabilization projects is to reduce the frequency of overwash and flooding, barrier island migration is an issue that should be addressed on a case-by-case basis. Though overwash processes have been shown to dominate some small microtidal barriers, most barriers appear to be too wide to migrate as a result of overwash. For example, Everts, Battley, and Gibson (1983) have shown that North Carolina barrier islands have narrowed, not migrated, over the past 130 years. Beach sands carried by overwash rarely reach the lagoonal side of most barrier islands, though after the barrier island narrows to a critical width, overwash events may contribute to landward migration. Leatherman (1976) estimated that the critical maximum width for overwash to be an effective transport mechanism on Assateague Island, Maryland, was between 100 and 200 m (Figure 9).

41. The impact of small, localized dune-stabilization projects on barrier migration does not warrant extensive discussion. The techniques used to encourage dune growth mimic the natural dune-building processes that are at work on all barrier systems. Typically, these techniques are used only when there is a need to protect existing man-made structures. Where such development exists, the absence of stable dune systems can often be attributed to human activities. Vehicle passes across foredunes often result in devegetation and blowouts; these pathways can serve as channels for overwash during storms (Figure 16). In addition, vehicles traveling over existing washovers prevent the reestablishment of vegetation. Dune stabilization can repair areas damaged by human activities.

42. The issue of barrier migration, however, may be raised when dune-stabilization efforts are employed to restabilize areas damaged by storm events. In this case, it should be recognized that the project, if successful, will accelerate dune establishment and will, for a period of time, reduce the frequency of overwash. The influence of this reduction in overwash, if any, on barrier island migration will often depend upon the type of barrier

Figure 16. Vehicle path through foredune, Warrenton, Oregon

being stabilized. Upon relatively broad barriers, where the likelihood of an overwash traversing the entire barrier is remote, dune stabilization will have little impact on barrier migration. As noted earlier, most US barriers are too broad for overwash to affect their migration significantly. On narrow, eroding barrier islands, overwash will frequently be critical to migration processes. Fortunately, dune-stabilization projects are not commonly proposed for narrow, frequently overwashed barriers.

43. Though barrier migration will not prove to be a major environmental concern for most dune-stabilization projects, understanding dune migration can be of great practical value. Dunes keep pace with the landward movement of the barrier in response to both aeolian and overwash processes. Nordstrom and McCluskey (1983) measured substantial aeolian transport over the dune crest, contributing to dune migration on Fire Island, New York. Stabilized dunes, as well as shorefront development, can diminish winds and slow dune migration. On migrating barriers, overwash is often the primary mechanism by which dunes keep pace with the landward movement of the barrier. High, vegetated dunes have been shown to reform landward continuously as a result of severe storm overwash and subsequent recovery on Plum Island, Massachusetts (Jones and Cameron 1977), and at the Malpeque barrier system, Prince Edward Island, Canada (McCann 1979). Zaremba and Leatherman (1984) monitored material deflated from a large overwash fan on Cape Cod over an 18-month period. They

found that approximately half of the deflated material was incorporated into the landward portion of dunes adjacent to the overwash. Dunes maintained in a fixed position (i.e., fully stabilized in the attempt to prevent all aeolian transport and overwash) fail as the shore retreats. The project life of the stabilized dune will be no greater than the dune setback (distance between dune and shore) divided by the shore erosion rate, and frequently it will be much less. Permitting dune migration may extend the project life. This can be accomplished by allowing gaps in the stabilized line of dunes in noncritical areas.

PART VI: BIOLOGICAL CONSIDERATIONS IN DUNE-STABILIZATION PROJECTS

Dune Vegetation

44. Human efforts to stabilize coastal dunes usually entail planting aggressive, perennial beachgrasses in monospecific stands. As noted earlier, the planted species remain dominant on the dune for many years after planting. Dahl and Goen (1977) found that, when a dune forms naturally with the pioneering plants available to the area, some species remain from previous successional stages and are a natural component of the mature dune plant community. However, planting of beachgrasses bypasses some of the pioneering successional stages, resulting in less plant diversity on the mature, planted dune. This lack of plant diversity is, typically, an unavoidable impact on man-built dunes. Plant diversity is associated with slow and protracted dune development, which is contrary to the objectives of most dune-stabilization projects.

Secondary Dune Vegetation

45. Based upon experiments conducted on the Outer Banks of North Carolina, some investigators have suggested that dune-stabilization projects adversely impact coastal plant communities (Dolan, Godfrey, and Odum 1973; Godfrey and Godfrey 1973). They contend that high, continuous dunes form an effective barrier to storm waves, thus reducing the amount of salt spray and preventing overwash. Reducing salt spray and saltwater flooding can result in major changes in coastal plant communities. At Cape Hatteras, North Carolina, continuous, impenetrable thickets 3 to 5 m high have formed in the lee of protective dunes. The National Park Service has resorted to controlled burnings to counter these changes. (As noted earlier, North Carolina was the site of extensive stabilization efforts during the 1930s.) However, scattered shrub and even forest communities are common on many Atlantic barrier islands that have not been the focus of stabilization efforts. The excessive development of shrub communities in association with dunes is not an ecological issue in New England (Zaremba and Leatherman 1984) and has not been reported to be a problem in other regions. Indeed, in heavily visited recreational areas, shrubs may be important in protecting dunes from pedestrian impacts.

46. The changes associated with artificial development of dunes are often considered ecologically beneficial. For example, plantings were made on Padre Island, Texas, following Hurricanes Carla and Beulah in 1967. Much of the island was unvegetated, hurricane-planed backshore and barren, migrating dunes. By 1976 the island's soil adjacent to the planted dunes was measurably less arid than other portions of this south Texas island (Figure 17). The

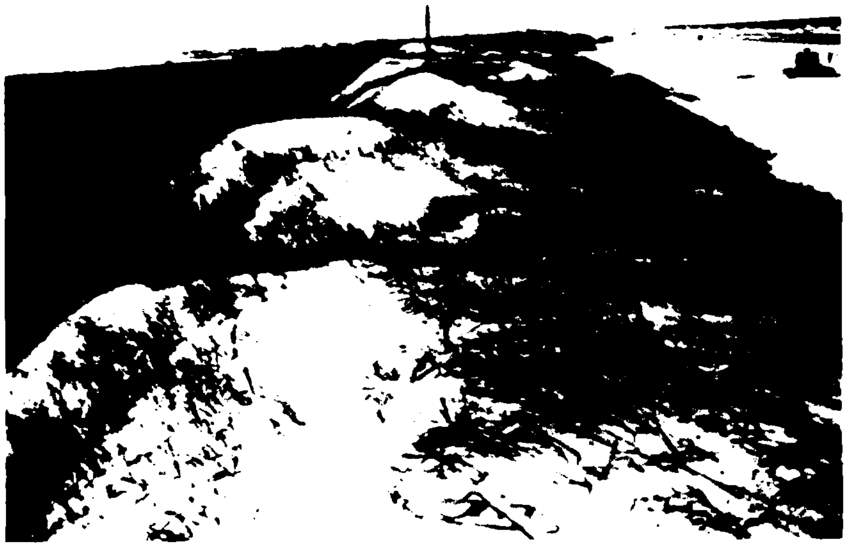

Figure 17. Vegetation landward (left on photo) of artificially stabilized dunes, Padre Island, Texas (Bill E. Dahl)

mesic (moist) microclimate bayward of the planted dunes is believed to be due to the damming effect provided by the resultant dunes. These dunes retain rainwater in the mid-dune area, providing a more favorable habitat.

47. The development of new dunes by planting or other means will change the microclimate of areas adjacent to the developing dunes. Whether or not these changes are viewed as ecologically positive or negative will depend upon the local importance and abundance of the habitats which are modified. Areas that are frequently stressed (for example, by overwash) either lack vegetation or are colonized by a limited number of grasses and forbs. Developing dunes provide a measure of stability to adjacent areas by reducing flooding and salt spray. This stability makes the environment suitable for a greater diversity of plant species. If stable for a sufficient length of time (10 to 50 years), shrubs will invade and later dominate the plant community (Dolan, Godfrey, and

Odum 1973; Zaremba and Leatherman 1984). If stability continues, mature forests can develop in 50 to 100 years.

48. The shrub and forest communities represent an improved habitat for terrestrial animals and many bird species, principally songbirds, though herons and egrets also use coastal shrubs for nesting. Conversely, bare sand and grass areas on the coast are the primary nesting sites for many colonial nesting birds, particularly gulls and terns.

Coastal Salt Marshes

49. The coastal salt marshes of the United States are considered to be a major environmental resource. They are important contributors to the primary production of the coastal zone and are essential nursery grounds for sport and commercial fishery species. Some researchers contend that dune stabilization can have a negative impact on salt marshes (Godfrey and Godfrey 1973).

50. Salt marshes are intertidal plant communities found on the Atlantic and gulf coasts and, to a lesser extent, on the Pacific coast. Two processes are of particular importance in creating shallow, marine environments in which marshes may establish: (a) flooding as a result of sea-level rise and/or subsidence of land and (b) sediment deposition. Salt marshes are often associated with deltas. The Mississippi River Delta is a spectacular example of the constructive impact of sediment deposition on marsh development. This delta system forms nearly half of the nation's coastal marshes. Deltas are also responsible for the development of the majority of Pacific coast marshes.

51. On the gulf and Atlantic coasts, however, deposition of barrier island sediment is important to marsh development. Active and remnant flood-tidal deltas behind these barriers are commonly the focus of marsh development (Godfrey and Godfrey 1973) (Figure 18). On some barriers, marshes are altogether absent, except where there is evidence of inlet activity (Leatherman and Joneja 1980). Overwash may have either a negative or a positive impact on marshes. When stable marshes are present landward of the barrier, overwash events may destroy the marsh through burial or may change its ecological character by raising its elevation (Zaremba and Leatherman 1984) (Figure 19). Conversely, overwash may widen a narrow, eroding marsh or may encourage the

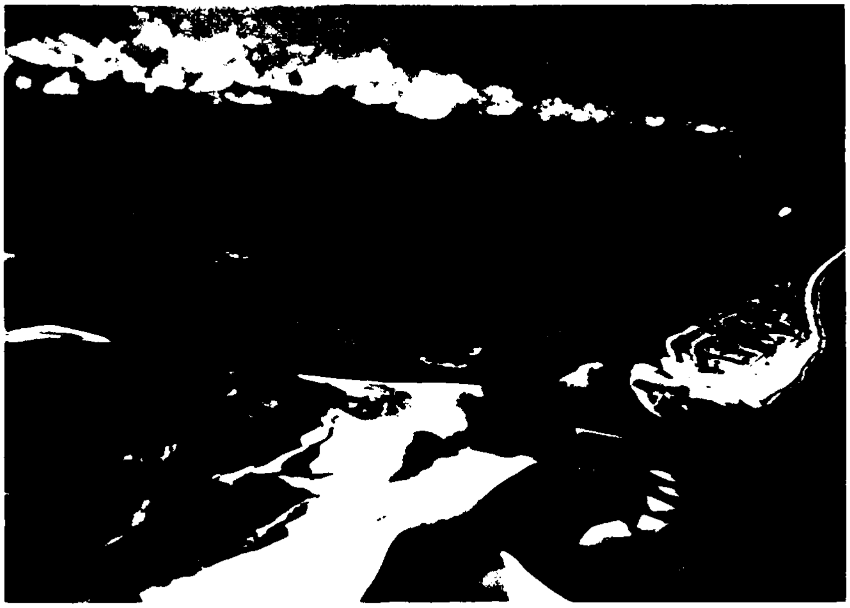

Figure 18. Salt marshes landward of barrier island systems, Murrell's Inlet, South Carolina

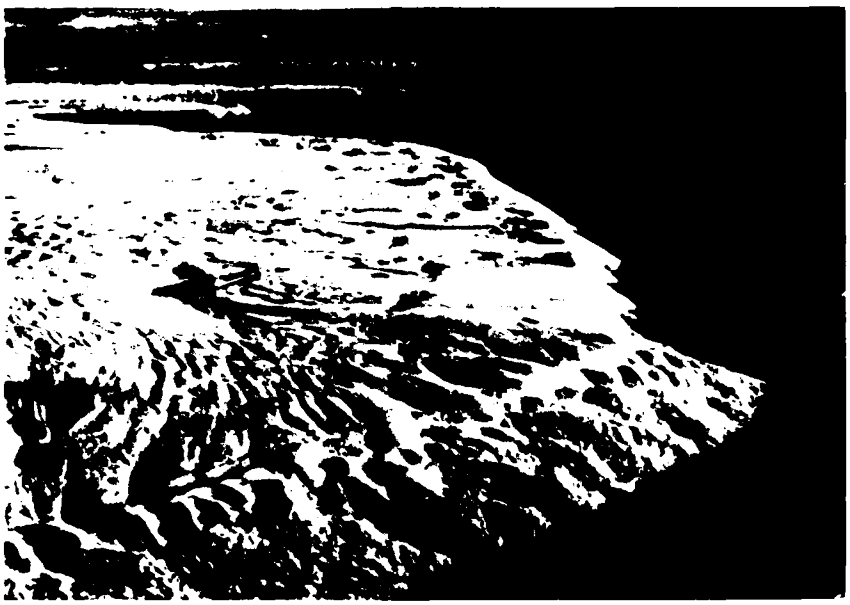

Figure 19. Overwash burial of salt marshes, Cape Cod, Massachusetts (Stephen P. Leatherman)

growth of new marshes on barren areas by creating a broad, gradually sloping, intertidal plain (Godfrey and Godfrey 1974).

52. To evaluate fully the potential impact of a particular dune-stabilization project on marsh development, two factors must be considered. First, back barrier marshes will be impacted only when the elevated width of the barrier is traversed by overwash or when the entire barrier is breached by an ephemeral inlet. Therefore, marsh impacts will be a concern only where events of this magnitude can be reasonably expected to occur within the anticipated life of the project. Second, the current condition of the marshes landward of the barrier should be evaluated. The impact on marsh development will be a project issue if barren shore or eroding marshes are present in the back barrier area.

PART VII: SUMMARY

Roles of Dunes

53. During storms, dunes are a source of sand for beaches of any coastal type. The contribution of dune sand to the beach profile buffers or reduces the magnitude of beach change coincident with individual storm events. Dunes also act as barriers to prevent penetration of waves and storm surges during some storm events.

Natural Dunes

54. Dune systems along the gulf and Atlantic coasts of the United States are usually associated with barrier islands.

55. Dune systems occur intermittently along the Pacific coast. As a rule, they are found in association with sediments deposited by coastal rivers or captured in the lee of rocky headlands.

56. Dunes around the Great Lakes form from glacial drift. Lowered water levels provide an increased sediment supply for dune building.

Man-Made Dunes

57. Perennial grasses are the primary plants used in efforts to stabilize dunes. The four grasses most commonly used include American beachgrass, bitter panicum, European beachgrass, and sea oats.

58. Two features of man-made dunes make them visually different from natural dunes. First, man-made dunes tend to be continuous and linear in configuration. Second, they tend to be dominated by the perennial grass that is initially planted, even after many years.

Geological Considerations

59. High dunes, natural or artificial, reduce erosion of the foreshore during storms.

60. The influence of dune stabilization, if any, on barrier island migration will often depend upon the type of barrier being stabilized. Upon

relatively broad barriers, dune building will have little impact on migration processes. On narrow, eroding barriers, stabilization efforts may interfere with barrier migration.

Biological Considerations

61. The lack of plant diversity on man-made dunes is, typically, an unavoidable impact.

62. The development of new dunes by planting or other means will change the microclimate of areas adjacent to the developing dunes. Whether or not these changes are viewed as ecologically positive or negative will depend upon the local importance and abundance of the habitats that are modified.

63. In some instance, stable dunes can be used to protect salt marshes from destruction by overwash and burial. However, on some barrier islands, overwash is important to the development of new marshes and to the abatement of erosion on existing marshes.

Overview

64. Small, localized dune-stabilization efforts, particularly the planting of dune vegetation, can usually be considered as conservation measures. Dune-building techniques are used only when there is a need to protect existing facilities. Where such development exists, the absence of stable dunes can often be attributed to human activities; hence, dune building can be a restorative action.

65. Major efforts to build continuous dunes on barrier islands to provide protection to mainland areas from major storms and hurricanes may potentially alter the geological and ecological characteristics of the barrier system. Major dune-stabilization projects along a barrier system should be preceded by an investigation of the role that the dunes and the physical processes modified by dunes play in the overall dynamics of the system.

REFERENCES

Armon, J. W. 1979. "Landward Sediment Transfers in a Transgressive Barrier Island System, Canada," Barrier Islands, S. P. Leatherman, ed., Academic Press, New York, pp 65-80.

Bagnold, R. A. 1954. The Physics of Blown Sand and Desert Dunes, William Morrow and Co., New York.

Birkemeier, W. A. 1979 (Jan). "The Effects of the 19 December 1977 Coastal Storm on Beaches in North Carolina and New Jersey," Shore and Beach.

Bruun, P. 1983. "Review of Conditions for Uses of the Bruun Rule of Erosion," Coastal Engineering, Vol 7, pp 77-89.

Cooper, W. S. 1958. "Coastal Dunes of Washington and Oregon," Geological Society of America Memoir 72, Waverly Press, Baltimore, Md.

________. 1967. "Coastal Dunes of California," Geological Society of America Memoir 104, Waverly Press, Baltimore, Md.

Cowan, B. 1975 (Jul). "Protecting and Restoring Native Dune Plants," Fremontia, the Journal of the California Native Plant Society, Vol 3, No. 2.

Dahl, B. E., et al. 1975 (Sep). "Construction and Stabilization of Coastal Foredunes with Vegetation: Padre Island, Texas," Miscellaneous Paper 9-75, US Army Coastal Engineering Research Center, Fort Belvoir, Va.

Dahl, B. E., and Goen, J. P. 1977. "Monitoring of Foredunes on Padre Island, Texas," Miscellaneous Paper 79-8, US Army Coastal Engineering Research Center, Fort Belvoir, Va.

Davis, R. A., Jr. 1972. "Beach Changes on the Central Texas Coast Associated with Hurricane Fern, September 1971," Contributions in Marine Science, Marine Science Institute, University of Texas, Port Aransas, Tex., Vol 16, pp 89-98.

Dolan, R. 1972. "Barrier Dune Systems Along the Outer Banks of North Carolina: A Reappraisal," Science, Vol 176, pp 286-288.

Dolan, R., Godfrey, P. J., and Odum, W. E. 1973. "Man's Impact on the Barrier Islands of North Carolina," American Scientist, Vol 61, pp 152-162.

Everts, C. H. 1973. "Beach Profile Changes in Western Long Island," Coastal Geomorphology, Proceedings of the Third Annual Geomorphology Symposia Series, pp 279-301.

Everts, C. H., Battley, J. P., and Gibson, P. N. 1983. "Shoreline Movements, Cape Henry, Virginia to Cape Hatteras, North Carolina, 1949-1980," Technical Report 83-1, US Army Coastal Engineering Research Center, Fort Belvoir, Va.

Federal Writers Project. 1973. San Francisco, the Bay and Its Cities, rev. ed., Works Progress Administration for Northern California, New York Hastings House, New York.

Fox, W. T. 1970. "Anatomy of a Storm on the Lake Michigan Coast," Conference on Effects of Extreme Conditions on Coastal Environments, unpublished paper, Western Michigan University, Kalamazoo, Mich.

Gage, B. O. 1970 (Jan). "Experimental Dunes of the Texas Coast," Miscellaneous Paper 1-70, US Army Coastal Engineering Research Center, Washington, DC.

Gawne, C. E. 1966. "Shore Changes on Fenwick and Assateague Island, Maryland and Virginia," Bachelor's Thesis in Geology, University of Illinois, Urbana, Ill.

Gibbs, R. F., and Nash E. 1961. "Beach and Sand Dune Erosion Control at Cape Hatteras National Seashore," Transactions of the American Society of Agricultural Engineers, pp 122-127.

Godfrey, P. J. 1977. "Climate, Plant Response, and Development of Dune on Barrier Beaches Along the U.S. East Coast," International Journal of Biometerology, Vol 21, pp 203-216.

Godfrey, P. J., and Godfrey, M. M. 1973. "Comparisons of Ecological and Geomorphic Interactions Between an Altered and Unaltered Barrier Island System in North Carolina," Coastal Geomorphology, D. R. Coates, ed., State University of New York, Binghamton, N. Y., pp 239-258.

__________. 1974. "The Role of Overwash and Inlet Dynamics in the Formation of Salt Marshes on North Carolina Barrier Islands," Ecology of Halophytes, R. A. Reimold, ed., Academic Press, New York, pp 407-427.

Goldsmith, V. 1978. "Coastal Dunes," Coastal Sedimentary Environments, R. A. Davis, ed., Springer-Verlag, New York, pp 171-235.

Goldsmith, V., Henninger, H. F., and Gutman, A. L. 1977. "The VAMP Coastal Dune Classification," Coastal Processes and Resulting Forms of Sediment Accumulation, Currituck Spit, Virginia/North Carolina, V. Goldsmith, ed., SRAMSOE No. 143, Virginia Institute of Marine Science, Gloucester Point, Va., pp 26-1 to 26-20.

Graetz, K. E. 1973 (Feb). Seacoast Plants of the Carolinas for Conservation and Beautification, UNC-SG-73-06, Soil Conservation Service, Raleigh, N.C.

Hawk, V. B., and Sharp, W. C. 1967 (Jul-Aug). "Sand Dune Stabilization Along the North Atlantic Coast," Journal of Soil and Water Conservation, Vol 22, No. 4, pp 143-146.

Hayes, M. O., and Kana, T. W. 1976. "Terrigenous Clastic Depositional Environments: Some Modern Examples," AAPG Field Course Guidebook and Lecture Notes, Technical Report No. 11-CRD, Part 1, Coastal Research Division, Department of Geology, University of South Carolina, Columbia, S. C.

Jagschitz, J. A., and Bell, R. S. 1966 (Jan). "Restoration and Retention of Coastal Dunes with Fences and Vegetation," Agricultural Experiment Station Contribution No. 1149, Bulletin No. 382, University of Rhode Island, Kingston, R. I.

Jones, J. R., and Cameron, B. 1977. "Landward Migration of Barrier Island Sands Under Stable Sea Level Conditions: Plum Island, Massachusetts," Journal of Sedimentary Petrology, Vol 47, pp 1475-1482.

Knutson, P. L. 1980 (Aug). "Experimental Dune Restoration and Stabilization, Nauset Beach, Cape Cod, Massachusetts," Technical Report 80-5, US Army Coastal Engineering Research Center, Fort Belvoir, Va.

Larson, F. D. 1969. "Aeolian Sand Transport on Plum Island, Massachusetts," Coastal Environments, Coastal Research Group, University of Massachusetts, Amherst, Mass., pp 356-367.

Leatherman, S. P. 1976. "Barrier Island Dynamics: Overwash Processes and Aeolian Transport," Proceedings of the 15th International Coastal Engineering Conference, Honolulu, Hawaii, pp 1958-1974.

__________. 1979a. Barrier Island Handbook, The Environmental Institute, University of Massachusetts, Amherst, Mass.

__________. 1979b. "Barrier Dune Systems: A Reassessment," Sedimentary Geology, Vol 24, pp 1-16.

Leatherman, S. P., and Joneja, D. 1980. "Geomorphic Analysis of South Shore Barriers, Long Island, New York," Report Number 47, Phase I, National Park Service Cooperative Research Unit, University of Massachusetts, Amherst, Mass.

McCann, S. B. 1979. "Barrier Islands in the Southern Gulf of St. Lawrence, Canada," Barrier Islands, S. P. Leatherman, ed., Academic Press, New York, pp 29-63.

McLaughlin, W. T., and Brown, R. L. 1942 (Sep). "Controlling Coastal Sand Dunes in the Pacific Northwest," US Department of Agriculture Circular No. 660, Washington, DC.

Nordstrom, K. F., and McCluskey, J. M. 1983. "The Effects of Houses and Sand Fences on the Eolian Sediment Budget at Fire Island, New York," Journal of Coastal Research, Vol 1, pp 39-46.

Nummedal, D. 1982. "Hurricane Landfalls Along the Northwest Gulf Coast," Sedimentary Processes and Environments Along the Louisiana-Texas Coast, D. Nummedal, ed., pp 63-78.

Oosting, H. J., and Billings, W. D. 1942. "Factors Affecting Vegetational Zonation on Coastal Dunes," Ecology, Vol 23, No. 2, pp 131-142.

Penland, S., Nummedal, D., and Schram, W. E. 1980. "Hurricane Impact at Dauphin Island, Alabama," Proceedings of the Coastal Zone 1980 Conference, American Society of Civil Engineers, Hollywood, Fla., pp 1425-1449.

Pye, K., and Rhodes, E. G. 1985. "Holocene Development of an Episodic Transgressive Dune Barrier, Ramsay Bay, North Queensland, Australia," Marine Geology, Vol 64, pp 189-202.

Rosen, P. S. 1979. "Aeolian Dynamics of a Barrier Island System," Barrier Islands, S. P. Leatherman, ed., Academic Press, New York, pp 81-98.

Savage, R. P. 1963. "Experimental Study of Dune Building with Sand Fences," Proceedings of the Eighth Conference on Coastal Engineering, Mexico City, Mexico.

Savage, R. P., and Woodhouse, W. W., Jr. 1968 (Sep). "Creation and Stabilization of Coastal Barrier Dunes," Proceedings of the 11th Conference on Coastal Engineering, American Society of Civil Engineers.

Short, A. D. 1979. "Three Dimensional Beach-Stage Model," Journal of Geology, Vol 87, pp 553-571.

Smith, H. T. U. 1960. "Physiography and Photo Interpretation of Coastal Sand Dunes," ONR Final Report, Geology Department, University of Massachusetts, Amherst, Mass.

Stratton, A. C., and Hollowell, R., Jr. 1940 (Jul). "Sand Fixation and Beach Erosion Control," North Carolina Beach Erosion Control Project, NC-LD 13, National Park Service, Department of Interior, Washington, DC.

US Army Coastal Engineering Research Center (CERC). 1984. Shore Protection Manual, 4th ed., Vols I and II, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

US Department of Agriculture. 1967. "Sand Dune Control Benefits Everybody," Soil Conservation Service, Portland, Oreg.

Westgate, J. M. 1904. "Reclaimation of Cape Cod Sand Dunes," Bureau of Plant Industry Bulletin No. 65, US Department of Agriculture, Washington, DC.

Woodhouse, W. W., Jr. 1978 (Sep). "Dune Building and Stabilization with Vegetation," SR-3, US Army Coastal Engineering Research Center, Fort Belvoir, Va.

Woodhouse, W. W., Jr., and Hanes, R. E. 1967 (Aug). "Dune Stabilization with Vegetation on the Outer Banks of North Carolina," TM 22, US Army Coastal Engineering Research Center, Washington, DC.

Woodhouse, W. W., Jr., Seneca, E. D., and Broome, S. W. 1976 (Dec). "Ten Years of Development of Man-Initiated Coastal Barrier Dunes in North Carolina," Bulletin 453, Agricultural Experiment Station, North Carolina University, Raleigh, N. C.

Wright, L. D., et al. 1979. "Morphodynamics of Reflective and Dissipative Beach and Inshore Systems: Southeastern Australia," Marine Geology, Vol 32, pp 105-140.

Zak, J. M. 1965 (Jul-Aug). "Sand Dune Erosion Control at Provincetown, Massachusetts," Journal of Soil and Water Conservation, No. 4, pp 188-189.

__________. 1967 (Mar). "Controlling Drifting Sand Dunes on Cape Cod," Bulletin No. 563, Massachusetts Agricultural Experiment Station, University of Massachusetts, Amherst, Mass.

Zaremba, R. E., and Leatherman, S. P. 1984. "Overwash Processes and Foredune Ecology, Nauset Spit, Massachusetts," Miscellaneous Paper EL-84-8, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

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