Barrier Dune System along the Outer Banks of North Carolina: A Reappraisal

Abstract. *Barrier dune development has been encouraged by man along the Outer Banks of North Carolina to stabilize the barrier islands. This modification of a delicately balanced natural system is leading to severe adjustments in both geological and ecological processes.*

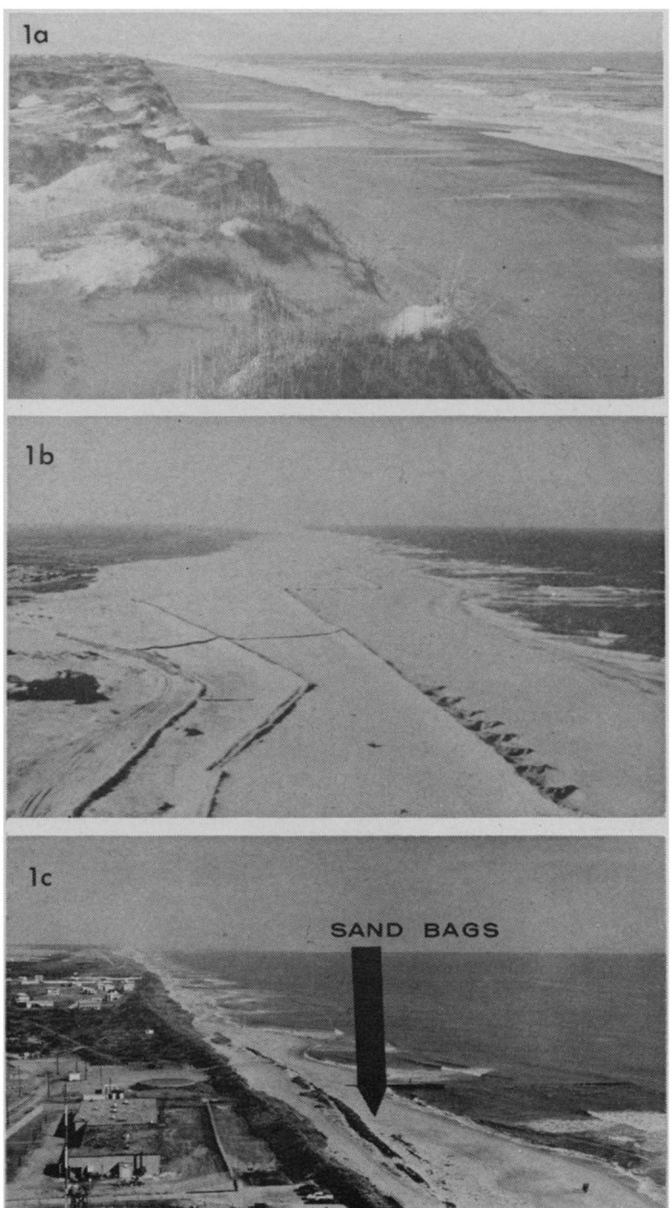
In the early 1930's the barrier islands of North Carolina were in what might be called a natural or equilibrium state. Changes were rapid, but the system was well adapted to accommodate powerful natural forces. The first steps to stabilize the islands were taken by the Works Progress Administration–Civilian Conservation Corps (WPA-CCC) in the 1930's by encouraging sand accumulations with brush fences. This was followed by extensive dune stabilization by the National Park Service in the 1950's. In building the high coastal dunes along the Outer Banks (Fig. 1), man has created a new state in the beach system that may be detrimental to the long-range stability of the barriers and may become more difficult and costly to manage than the original natural system.

In an article in *Science*, Houston (*1*), a National Park Service biologist, said,

> . . . Criteria for management of a park ecosystem must, of necessity, differ from criteria for other uses of land, since park management involves preventing or compensating for the influence of man. The objectives for natural areas appear to be ecologically feasible if it is recognized that these areas have a finite capacity for absorbing man's consumptive and disruptive influences.

In the case of the barrier dunes, man's disruptive influence is linked, most directly, with geological processes; however, Godfrey (*2*), also a biologist with the National Park Service, has established an important coupling of the geological and ecological implications of barrier dune stabilization.

The "natural condition" for the mid-Atlantic barriers is simply a wide range of sand deposit responses to various wave conditions. Like fluvial systems, in which streams adjust in cross section to accommodate the water flow, beaches adjust in cross section to accommodate wave run-up. When the wave run-up



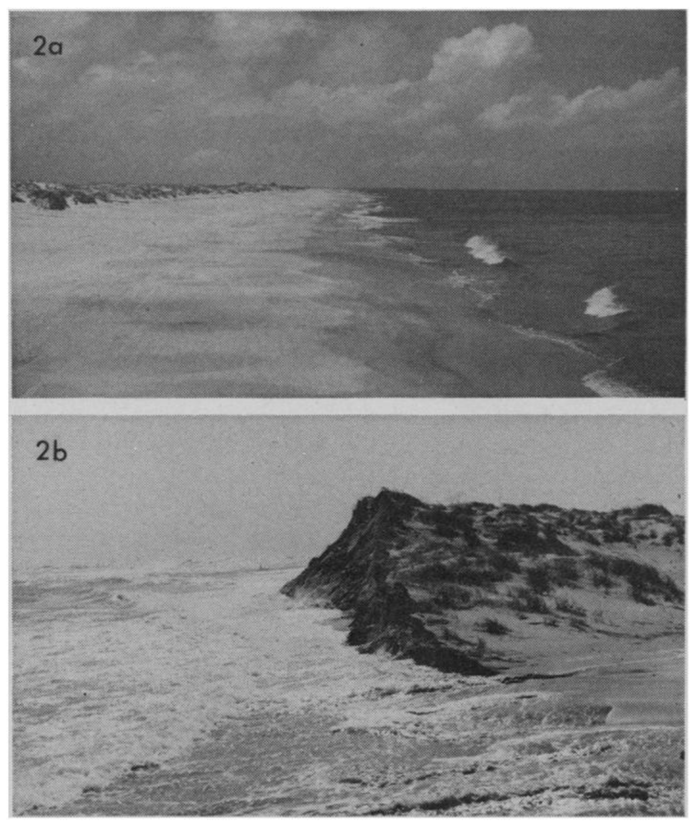


Fig. 1 (left). The coastal barrier dunes of the Outer Banks of North Carolina. These dunes were originally developed by man in the 1930's and have since been encouraged and expanded with sand fences and grass plantings. (a) General view on Bodie Island (1969). The sharp line between the active beach and the stabilized dune complex is a 3-m erosional scarp. During severe winter northeasters the dunes are commonly eroded back, up to several meters. (b) Some of the original WPA-CCC sand fencing near Cape Hatteras (1936–1937). (c) Sandbag revetment and stabilized dunes near Cape Hatteras. This is the same area as in Fig. 1b, but 25 years later. Fig. 2 (right). (a) Beach system under moderate wave attack. (b) Beach system under severe wave attack. Comparison of Figs. 1a and 2a shows how man's activities have altered the characteristics of these zones.

of the surf zone is high, as during storms, the active beach expands, both landward and seaward. When the run-up is low, as during the summer months, the active beach zone contracts.

Most of the time this process of expansion and contraction is of minor significance, geologically or economically, because it is confined to the central part of the active zone, where little change in the sand deposit is involved. Under these conditions, the cross section required to accommodate the wave run-up is analogous to the stream cross section at low river stage. In the fluvial system the flow is confined within the system's natural levees most of the time, so the bed can easily accommodate the stream discharge. In the beach system, the berm serves as the topographic constraint for wave run-up most of the time (Fig. 2a).

During extreme events, such as hurricanes or winter northeasters, the beach cross section must make major adjustments to lengthen the distance of the run-up and thus dissipate the increased energy. In the offshore region this is manifested as an extension of the active zone beyond the outer bar. At the subaerial end of the profile, if the increased energy level is high enough, the wave run-up extends into the zones normally associated with eolian processes and eolian landforms—namely, the sand dunes and adjacent sand flats (Fig. 2b).

Man's efforts to stabilize the beach system naturally focus on the area that is (i) only occasionally penetrated by storm surge, (ii) suitable terrain for permanent development, and (iii) amenable to simple modification. The active beach does not fit any of these criteria, but the dune area can be controlled. Although intuition suggests that by stabilizing the dunes one succeeds in stabilizing the entire beach system, the dunes are, unfortunately, a response element of the system, not a forcing element.

The rationale behind the construction and stabilization of barrier dunes is that the dunes confine the upper limit of the wave uprush within the swash zone and prevent the undesirable effects of overwash and channel development. For permanent stabilization, this requires a beach system that is stable through time. Erosion of the barrier islands is, however, a well-understood geological process (*3*). Beach stability, for any period of time, is a function of sea level and the amount of sedimentary material supplied to the coast. If the sea level rises or the amount of material required to sustain the system is reduced, the beach system migrates landward, with areas of backshore becoming foreshore and areas of dune becoming backshore. If the dune areas are stabilized, the new system must adjust to any changes that occur in the barrier itself. That is, if the sea level rises and the beach zones shift landward, the dunes must also shift, or the beach sector of the system is reduced in width, the energy dissipation process is changed, and the entire system is forced out of equilibrium.

Table 1. Changes along the Outer Banks of North Carolina since high barrier dunes were constructed.

Topographic zones	Ratio × 100 (%)	
	January 1945	August 1969
Beach to active sand zone	51.5	54.5
Beach to island width	20.2	10.9
Active sand zone to island width	42.1	22.0
Dune to island width	21.9	11.2

The most important changes brought about by dune stabilization and beach narrowing are associated with the restriction and consequent steepening of the run-up profile, which forces the process of energy dissipation to take place in a limited cross section of the beach, so that more energy is dissipated per meter of beach cross section. If the energy dissipation ratio is 5 : 1, a certain combination of slope, width, and sand size of the beach will result. If the width of system is reduced by 20 percent and the ratio becomes 4 : 1, a greater amount of energy is being dissipated per meter of beach profile. The material deposited across the upper limit of the swash zone, about 10 m wide along the Outer Banks, is the finest material within the beach system. This is a consistent pattern that has been established by years of beach sampling (*4*). When the system is compressed, it is the finer materials, in the upper part of the swash zone, that are most vulnerable to winnowing processes.

Coarser beaches are steeper, and if they become steep enough to initiate wave reflection a new set of interactions is triggered, which may result in a concentration of the energy dissipation process in narrower zones. The increased stress and turbulence across the narrower beach results in higher attrition and winnowing rates for the sand grains and leads to accelerated losses of fine sand (0.25 mm). This is an important process that accounts for a major loss of beach material (*5*).

In the 13 years since the National Park Service initiated its major effort to stabilize the dunes and beaches along the Outer Banks of North Carolina, a process of beach narrowing, relative to the dune system, has been underway. Originally, the distance from the dune fields to the shoreline was about 100 to 125 m; since then, erosion has reduced this distance by 30 to 40 m, leaving beach widths of 70 to 100 m in most areas.

Figure 3 illustrates a set of measurements taken from several strips of aerial photographs dated between 1945 and 1969, and Table 1 provides estimates of the changes that have occurred along the Outer Banks since the high barrier

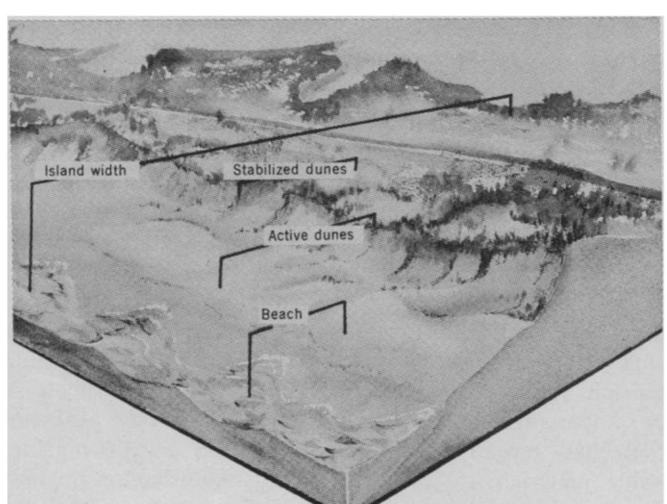


Fig. 3. Measurements taken from aerial photographs to determine the degree of change in the beach and dune systems. The barrier islands can be divided into three distinct biophysical zones, the beach, the zone of active sand dunes, and the stabilized zone, which extended to the sound-side shoreline.

dunes were constructed. The topographic zones in Table 1 include the beach and the active dunes, and these are collectively called the active sand-movement zone. The active sand zone can easily be detected on aerial photographs, since the dense cover of the dune grasses usually marks a sharp transition between the stable and the active areas of the barrier islands.

The results in Table 1 show that in 1945 the beach represented 51.5 percent of the active sand-movement area and by 1969 it represented 54.5 percent. The reason for this increase is that when the dune system is stabilized, the active sand zone, which is critical to the long-term equilibrium of the barrier system, is no longer a dynamic element of the system. When the dunes are reduced to essentially an inactive state, the actual beach becomes the only dynamic element of the system. It can also be seen that during this period the beach width was reduced by 9.3 percent, the active sand zone was reduced by 20.1 percent, and the dune area was reduced by 10.7 percent. The latter figure is highly significant as it indicates that although extensive dune areas have been stabilized, new dune areas are not developing to replace those being eroded on the ocean side of the barrier.

Since it is impossible to move the stabilized system inland with each reduction in the beach profile, which does, in effect, occur in a natural system, the inevitable has taken place. The beaches are narrower, steeper, and coarser, and wave reflection is common. The sediment most vulnerable to these changes is the fine materials (0.20 to 0.40 mm) that are the natural supply for renourishment of the native dune system. This sediment is associated with the uppermost limit of the uprush on an altered beach (*4*).

With little prospect for a reversal of the trend of the sea level to rise, and little hope for a change in the sediment balance, it appears that although the densely vegetated barrier dunes reduce the amount of windblown sand and overwash material, this continued effort to stabilize the beaches and dunes may be detrimental to the long-term equilibrium of the barrier islands themselves. Major amounts of fine sand are being lost by winnowing to the offshore and by increased attrition within the swash zone. Equally important, the National Park Service has recently started using immovable materials to protect some beach areas (Fig. 1c). Sandbags and revetments cause a great deal more swash reflection than even the oversteepened beaches. The loss of sand is a costly price to pay for temporary stabilization.

With the rapid deterioration of the barrier dune systems along the Outer Banks of North Carolina in recent years and the large expenditures of resources necessary to reestablish or maintain them, or both, this research suggests that this is an appropriate time for the National Park Service and the Corps of Army Engineers to review the basic concept of dune construction in light of the geological and ecological implications. This is not to suggest that we should simply return the barrier island to nature and adjust to the whims of the elements, but rather that we should consider very carefully the long-term implications of our present decisions. This is particularly desirable now that the National Park Service has nine large seashore areas within its control (*6*), and several others may be added in the near future.

ROBERT DOLAN
Department of Environmental Sciences, University of Virginia, Charlottesville 22903

References and Notes

1. D. B. Houston, *Science* **172**, 648 (1971).
2. P. J. Godfrey, *Oceanic Overwash and Its Ecological Implications on the Outer Banks of North Carolina* (Office of Natural Science, National Park Service, Washington, D.C., 1970).
3. D. B. Stafford and J. Langfelder, *Photogramm. Eng.* **37**, 565 (1971).
4. R. Dolan, *Prof. Geogr.* **18**, 210 (1966).
5. P. H. Kuenen, *Sedimentology* **3**, 29 (1964).
6. Cape Cod, Fire Island, Assateague Island, Cape Hatteras, Cape Lookout, Cumberland Island, Gulf Islands, and Padre Island.
7. Supported by the Office of Natural Science, National Park Service.

24 August 1971; revised 8 November 1971

Groundwater Contamination by Road Salt: Steady-State Concentrations in East Central Massachusetts

Abstract. *The average steady-state contamination of groundwater by road salt in the suburban area around Boston, on the assumption that current rates of application of salt will continue, is about 160 milligrams of sodium chloride per liter of water (100 milligrams of chloride per liter). This value is compared with values of 50 to 100 milligrams of chloride per liter found rather commonly now in town wells in eastern Massachusetts. These salt concentrations may be of concern to persons on low-sodium diets and to persons who obtain water from wells in the vicinity of major highways where salt concentrations could be several times higher than average.*

Salt, mainly NaCl, has been used in increasing amounts in recent years to remove ice and snow from roads in northern areas. The rate of application of salt to Massachusetts state highways is now about 20 metric tons of total salt ($NaCl + CaCl_2$) per lane mile per year (*1*). Relatively little salt was used prior to 1955 in Massachusetts, especially on town roads.

One consequence of the use of salt on roads is the inadvertent contamination of water supplies (*1–3*). The situation encountered in the town of Burlington, Massachusetts, over the past several years represents a good example of the contamination of groundwater by road salt (*4*). Chloride concentrations in water from town wells increased over several years prior to 1970 and reached values exceeding 100 mg per liter of water in 1970, with one well showing peak concentrations in excess of 200 mg/liter. The use of salt in Burlington on town roads was subsequently suspended. Recent surveys reveal that wells in at least 14 other communities in eastern Massachusetts produce water containing > 100 mg of chloride per liter (*5*). These findings may imply a more general future contamination of water supplies in the heavily populated areas of east central Massachusetts.

We attempt here to estimate the steady-state concentrations of salt that may be expected in groundwater in the suburban area around Boston if present rates of application of salt are continued. For our calculations we consider several contiguous towns lying north and west of Boston in an area which includes Burlington. The towns are representative of suburban communities around Boston with respect to population densities and salt use (*6*). Data concerning land use and rates of application of salt are given in Table 1, from which a yearly value of 107 metric ton/km^2 (10.7 mg/cm^2) is obtained over the total area considered.

Salt is applied during a 3-month