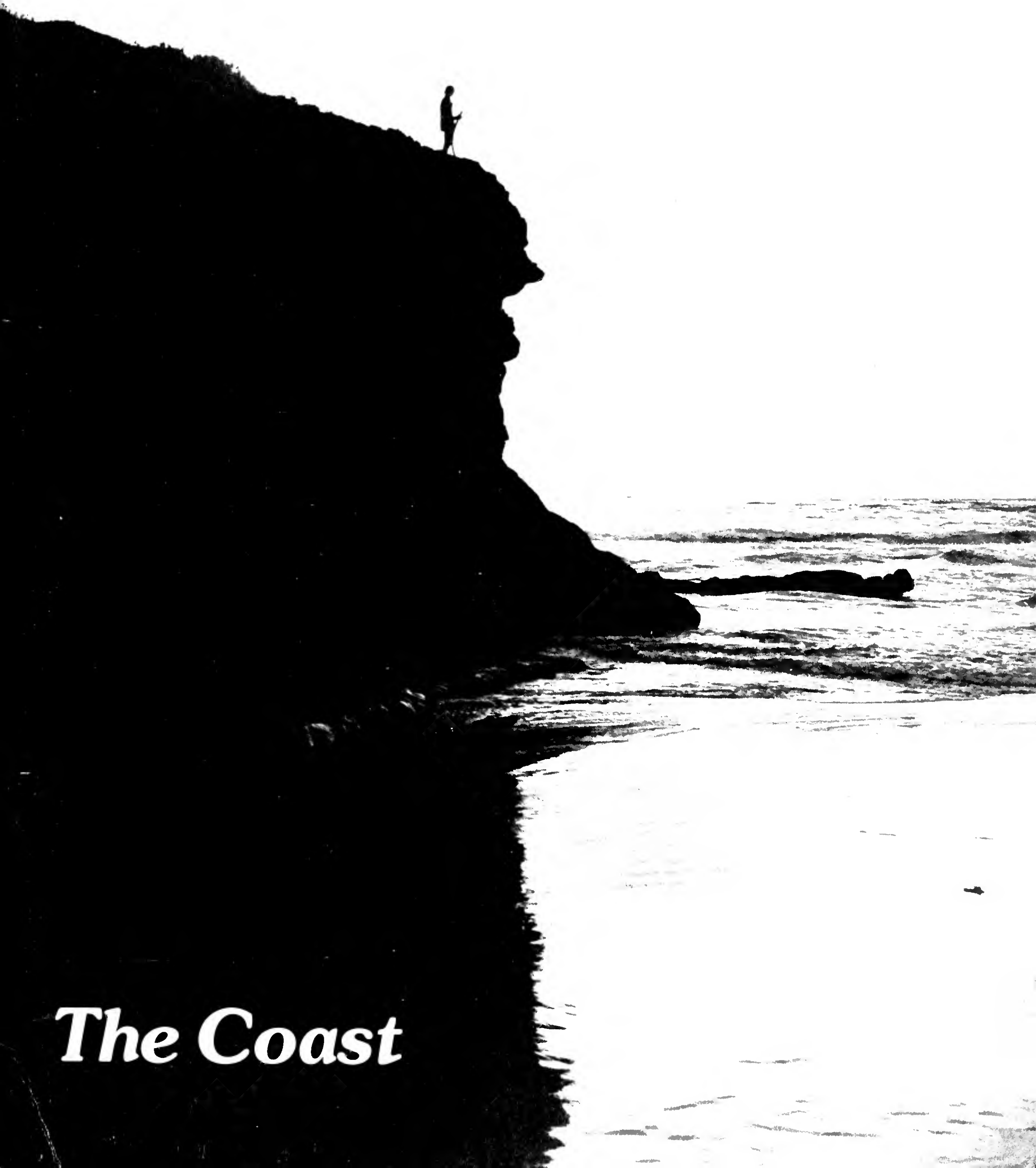
Oceanus

Volume 23, Number 4, Winter 1980/81



The Coast

Oceanus®

The International Magazine of Marine Science

Volume 23, Number 4, Winter 1980/81

William H. MacLeish, *Editor*
Paul R. Ryan, *Managing Editor*
Deborah Annan, *Assistant Editor*

Editorial Advisory Board

Edward D. Goldberg, *Professor of Chemistry, Scripps Institution of Oceanography*
Charles D. Hollister, *Dean of Graduate Studies, Woods Hole Oceanographic Institution*
Holger W. Jannasch, *Senior Scientist, Department of Biology, Woods Hole Oceanographic Institution*
Judith T. Kildow, *Associate Professor of Ocean Policy, Department of Ocean Engineering, Massachusetts Institute of Technology*
John A. Knauss, *Dean of the Graduate School of Oceanography, University of Rhode Island*
Robert W. Morse, *Senior Scientist, Department of Ocean Engineering, Woods Hole Oceanographic Institution*
Ned A. Ostenso, *Deputy Assistant Administrator for Research and Development; and Director, Office of Sea Grant, at the National Oceanic and Atmospheric Administration*
Allan R. Robinson, *Gordon McKay Professor of Geophysical Fluid Dynamics, Harvard University*
David A. Ross, *Senior Scientist, Department of Geology and Geophysics; Sea Grant Coordinator; and Director of the Marine Policy and Ocean Management Program, Woods Hole Oceanographic Institution*
Derek W. Spencer, *Associate Director for Research, Woods Hole Oceanographic Institution*
Allyn C. Vine, *Senior Scientist Emeritus, Department of Geology and Geophysics, Woods Hole Oceanographic Institution*

Published by Woods Hole Oceanographic Institution

Charles F. Adams, *Chairman, Board of Trustees*
Paul M. Fye, *President of the Corporation*
Townsend Hornor, *President of the Associates*

John H. Steele, *Director of the Institution*

The views expressed in *Oceanus* are those of the authors and do not necessarily reflect those of Woods Hole Oceanographic Institution.

Editorial correspondence: *Oceanus*, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543. Telephone (617) 548-1400.

Subscription correspondence: All subscriptions, single copy orders, and change-of-address information should be addressed to *Oceanus* Subscription Department, 1172 Commonwealth Avenue, Boston, Mass. 02134. Urgent subscription matters should be referred to our editorial office, listed above. Please make checks payable to Woods Hole Oceanographic Institution. Subscription rate: $15 for one year. Subscribers outside the U.S. or Canada please add $2 *per year* handling charge; checks accompanying foreign orders must be payable in U.S. currency and drawn on a U.S. bank. Current copy price, $3.75; forty percent discount on current copy orders of five or more. When sending change of address, please include mailing label. Claims for missing numbers will not be honored later than 3 months after publication; foreign claims, 5 months. For information on back issues, see page 68.

Postmaster: Please send Form 3579 to *Oceanus*, Woods Hole, Massachusetts 02543.

expand [illegible]
and share [illegible]
[illegible]

Oceanus

Oceanus [illegible]

The Illustrated Magazine
of Marine Science
Published by Woods Hole
Oceanographic Institution

Please make checks payable to Woods Hole Oceanographic Institution. Checks accompanying foreign orders must be payable in U.S. currency and drawn on a U.S. bank.
Outside U.S. possessions [illegible] Canada [illegible]

Please enter my subscription to OCEANUS for:
☐ one year at $15.00 ☐ payment enclosed
☐ please renew my subscription for one year ☐ bill me

Please send MY Subscription to: Please send a GIFT Subscription to:

Name (please print) Name (please print)

Street Address Street Address

City State Zip City State Zip

Donor's Name ______

Address ______

Oceanus [illegible]

The Illustrated Magazine
of Marine Science
Published by Woods Hole
Oceanographic Institution

Please make checks payable to Woods Hole Oceanographic Institution. Checks accompanying foreign orders must be payable in U.S. currency and drawn on a U.S. bank.
Outside U.S. possessions [illegible] Canada [illegible]

Please enter my subscription to OCEANUS for:
☐ one year at $15.00 ☐ payment enclosed
☐ please renew my subscription for one year ☐ bill me

Please send MY Subscription to: Please send a GIFT Subscription to:

Name (please print) Name (please print)

Street Address Street Address

City State Zip City State Zip

Donor's Name ______

Address ______

HAVE THE
SUBSCRIPTION
COUPONS
BEEN DETACHED?

If someone else has made use of the coupons attached to this card, you can still subscribe. Just send a check — $15 for one year ($17 overseas) — to this address . . .

Oceanus
Woods Hole Oceanographic Institution
Woods Hole, Mass. 02543

PLACE
STAMP
HERE

Please make check payable to:
Woods Hole Oceanographic Institution

Oceanus
Woods Hole Oceanographic Institution
Woods Hole, Mass. 02543

Remember — You can make your Marine Science Library complete with back issues!

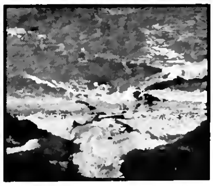
PLACE
STAMP
HERE

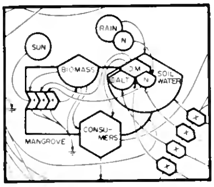
see inside back cover

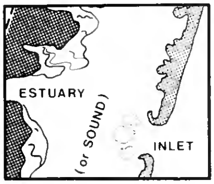
Oceanus
Woods Hole Oceanographic Institution
Woods Hole, Mass. 02543

1930 - 1980

Contents

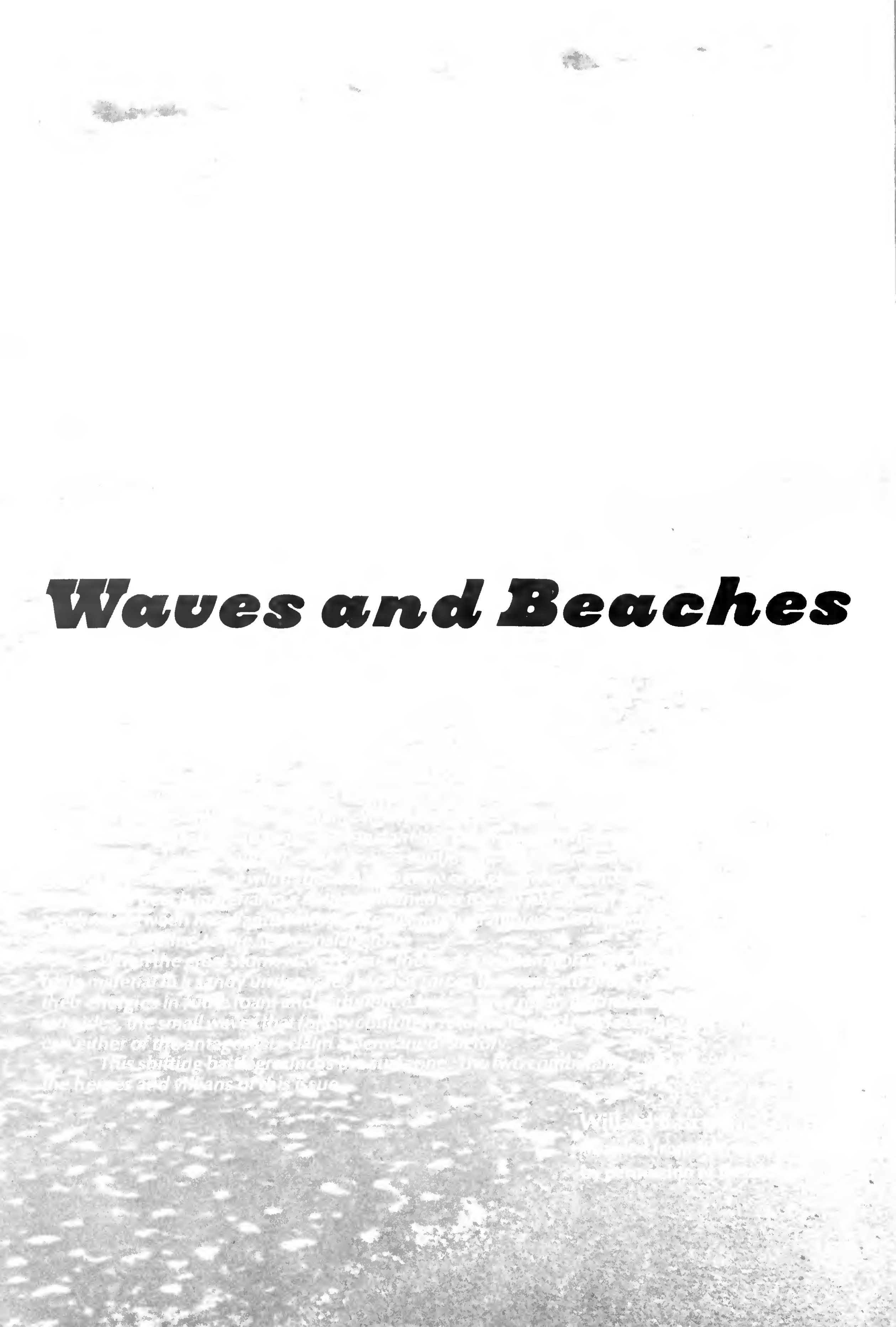






FRONT AND BACK COVER: Coastal scene at Natural Bridges State Park, Santa Cruz, California. Photo by Alexander Lowry, PR.

Oceanus (ISSN 0029-8182) is published quarterly by Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543. Second-class postage paid at Falmouth, Massachusetts, and additional mailing points.



Waves and Beaches

[illegible] When the [illegible] [illegible] beach material [illegible]

When the great storm waves [illegible] beach material in a sandy underwater bar [illegible] their energies in [illegible] foam and [illegible] the small waves that follow build [illegible] on either of the antagonists claim a permanent victory.

This shifting battleground [illegible] the two combatants, the heroes and villains of this issue.

Wil[illegible]

Going to the Beach

This has been the Year of the Coast, an effort principally by environmentalists to focus national attention on the more than 80,000 miles of American fringe lands. It's about time, and it may be way past time.

On a recent assignment for *Smithsonian*, I had occasion to travel a fair section of the coast — starting at Galveston and working east from Mobile around the thumb of Florida and north through the Outer Banks of North Carolina to New York. There are still plenty of wild stretches, miles we have left lonely. But generally where development has occurred, it has been fast and formless. The west coast of Florida has semblances of style — a domino skyline, a sweep of bay bridge — but the net effect is surfeit. The Outer Banks are protected as a national seashore, but where protection stops, a kind of fancy, second-home shantytown begins. Prices are phenomenal, particularly on barrier islands; a thousand dollars a shoreline foot is often asked and gotten, sometimes two thousand. "People are going to live on the coast," the mayor of an Alabama beach resort told me. "And they're not making any more coast."

The national centrifuge has spun three of four Americans out to within a hundred miles of some coast, oceanic or lacustrine. By the end of the decade, three out of four will be living within 50 miles of the sea, some predictors say. If they are right, the pressures on some of our most beautiful, delicate, and productive areas will be placed under severe stress. The trends are there: we have drained, filled, or otherwise lost about 40 percent of our wetlands, and the process continues at the rate of some 300,000 acres a year; that shrinkage, plus pollution of nursery bays and estuaries, has caused sharp drops in local shell and finfish harvests.

The risk is not entirely to the environment. Sea level is rising, a fact the buying public does not seem to have grasped. Precise measurements are difficult, but most scientists will settle for a mean value of about one foot a century worldwide. As the sea rises, coasts submerge — except in areas of glacial rebound — and coastlines retreat inland. We can armor choice shorelines with sea walls and groins, but even these brutally expensive structures can't give property owners more than a few decades of protection.

Curiously, the beach boom has been going on during a lull in hurricanes. More than a hundred of them have come ashore since the start of the century, but the incidence is down now. The result is that around eight out of ten Americans living on the coast have had no experience with really heavy weather; many of them tell poll takers they don't pay much mind to killer storms. That insouciance simply is not healthy. Few people know, or seem to care, that the worst natural disaster by far in this country occurred when a hurricane slammed into the barrier island of Galveston, Texas, in 1900, killing 6,000 in the city and another 2,000 or so nearby. Today, experts say, if a big storm like Camille, rated five on a scale of five, were to come ashore in a heavily urbanized area like, say, Miami, the results would dwarf Galveston.

Scientists and government officials are paying much more attention today to coastal processes and their interaction with social stresses of coastal crowding. Nearshore oceanography tends to be difficult work: tides and topography can make a washing machine out of the inshore ocean. But as the articles in this issue indicate, we are learning. We are beginning to understand how the sea shapes beaches, how to predict where storms may open inlets, how to spot high-hazard areas. We are beginning to understand the effects on the coastal biota of at least some pollutants, including oil and some heavy metals. We can, upon occasion, identify and correct the causes of dangerous siltation or variation in the salinity of lagoons and estuaries.

Equally important, we are facing up to the impact of governmental policies on shoreline development. Much of the infrastructure of that development is underwritten to a degree by federal programs. Those would include roads and bridges, sewage treatment facilities, flood control, and hurricane protection. Coastal communities meeting flood-related building standards are eligible for federal insurance at bargain premiums. Revision of these programs may not halt our rush to the salt, but it could make it more likely that the costs of living in harm's way will be more equitably apportioned.

William H. MacLeish

Crescentic bars occurring off Nauset Inlet on Cape Cod, Massachusetts, in May, 1953. The bars extend for at least 5 kilometers, with a spacing of hundreds of meters. A complex wave pattern exists in the lee of these crescentic bars. (Courtesy U.S. Coast and Geodetic Survey)

Ou amic Coastline

by David G. Aubrey

The coastlines of the world represent one of the most variable and complex regions of our globe. They form the unique interface between the earth's three major constituents: the land masses, the oceans, and the atmosphere. The oceans and atmosphere are constantly changing, a behavior scientists are diligently trying to decipher. In response to this variability, the coastlines change over a spectrum of time scales, trying to achieve an equilibrium with those forces shaping it. The activity of our shorelines is of great human concern because nearly two-thirds of the world's inhabitants live along the ocean margins.

Considering the variability and fragility of the world's coastlines, we clearly need to understand the forces sculpting shorelines and how these fragile boundaries respond. Our knowledge of the complex interactions between the atmosphere, oceans, and land masses is incomplete. Our ability to predict variability in this system is woefully inadequate at times (the most common example of this is the media weatherman, who opens himself to violent criticism with each broadcast). Coastal zone management must rely heavily on scientific knowledge to be effective in protecting and preserving the nation's shorelines, while minimizing the adverse impact on man and his cultural relicts along the coasts. Only by understanding the dynamic nature of the coastal zone can we intelligently manage the limited and fragile resource separating the continents from the oceans.

Most of our nation's coastline includes a thin border of beach sand or other clastic material, backed by either sea cliffs, more water, or low-lying plains. Stretches of shoreline lacking beaches generally have sea cliffs plunging directly to the water's edge. Both beaches and sea cliffs serve to buffer the continents from the oceans' fury. Some regions are highly successful, others fail alarmingly. Beaches on the south shore of the island of Martha's Vineyard, Massachusetts, are receding at the rate of 3 meters per year. The Atlantic-facing shores of Cape Cod, Massachusetts, are backed by sea cliffs eroding at a rate of 1 meter per year. Lighthouses and other structures have been relocated inland to avoid the tenacious reclamation of land by the sea.

The major forces modifying beaches on a brief time scale are winds, waves, tides, storm surges, and man. On geological time scales, the slow sea-level rise along much of the nation's coast causes beaches to migrate landward and to contract. Hurricanes and winter storms provide vivid demonstrations of the frailty and vulnerability of beaches; this, combined with local sea-level rise, dooms many of our beaches to recede, accelerating coastal damage during hurricanes and storms.

Barrier beaches represent a special type of shoreline, bordered on one side by an ocean, sea, or gulf, and on the other by a protected body of water (Figure 1). These beaches may be completely separated from land, in which case they are called barrier islands. Barriers attached on one side to land are called barrier spits. When completely enclosing an embayment with only a single channel to the ocean, they are known as baymouth bars. In this article, these classifications are implied in the general term barrier beach. The distinction among these different structures is often temporary, as storms often remold shorelines into a different form within a few hours.

All beaches, including barrier beaches, are in many ways similar in their response to nature's forces. Storm waves, most frequent in winter months, erode beaches, whereas more quiescent waves return sediment shoreward and rebuild beaches. Waves approaching at an angle move sand along the beach. This longshore transport may have no net effect on the appearance of the beach, or it may accrete or erode the beach, depending on whether equal or unequal amounts of sand enter

Cliffs of clay at Gay Head, Martha's Vineyard, move back about 3 meters per year through wave action and wind erosion. (Photo by Jan Hahn)

Figure 1. Barrier beach systems are composed of a thin vegetated beach separating a major body of water from a protected bay and adjacent land mass.

and leave a particular coastal stretch. Beaches may be long or short, straight or sinuous, depending on the forces modifying them and the available sediment. Two major processes are unique to barrier beaches: tidal inlet changes (both their formation and migration), and overwash processes. During storm conditions, these processes can control the poststorm barrier beach configuration, far outweighing other agents that are modifying the beach at that time.

Geological Factors

The shape and characteristics assumed by a stretch of coastline reflect a myriad of geological forces and present-day processes. A major geological factor controlling shoreline features appears to be plate tectonics (see *Oceanus*, Vol. 17, No. 3), which influences the width and bathymetric detail of the continental shelf as well as the local rise or fall of sea level. The rate of denudation of inland regions coupled with the supply of sediment to the coastline are other factors. The local conditions of some shorelines mirror river drainage patterns, faulting, and slumping, as well as biological processes (such as on coral beaches or mangrove beaches). Wind patterns, climate, and tidal range all contribute to the complex nature of shorelines.

Sea-level changes, both eustatic (worldwide) and local, play an important role in long-term beach development. A eustatic sea-level change results from glacial activity; as glaciers melt, worldwide sea level tends to rise, while as glaciers enlarge, worldwide sea level tends to fall. Since the world is currently in an interglacial period, sea level is relatively high. A schematic sea-level curve for the eastern United States (Figure 2) shows a sea-level stillstand near 15,000 years before present (BP), followed by a relatively rapid rise up to 5,000 years BP, when sea level was approximately 5 meters below the present level. Sea-level rise since then has averaged approximately one millimeter per year, gradually encroaching on the continents.

Superimposed on the eustatic sea-level curve are other sea-level fluctuations that result in nonuniform rates of relative sea-level rise around the world. The primary forces causing noneustatic relative sea-level changes are tectonism (such as along the Pacific coast), glacial rebound resulting from land masses gradually readjusting to removal of glacial loading (such as in Scandinavia), and seasonal changes in sea level that are the result of freshwater inflow and heating and cooling cycles in the ocean (steric effects). Tide gauge records from the United States over the last 40 years show the entire mainland coast submergent relative to the oceans, with rates ranging from 3 millimeters per year in New England to about 15 millimeters per year

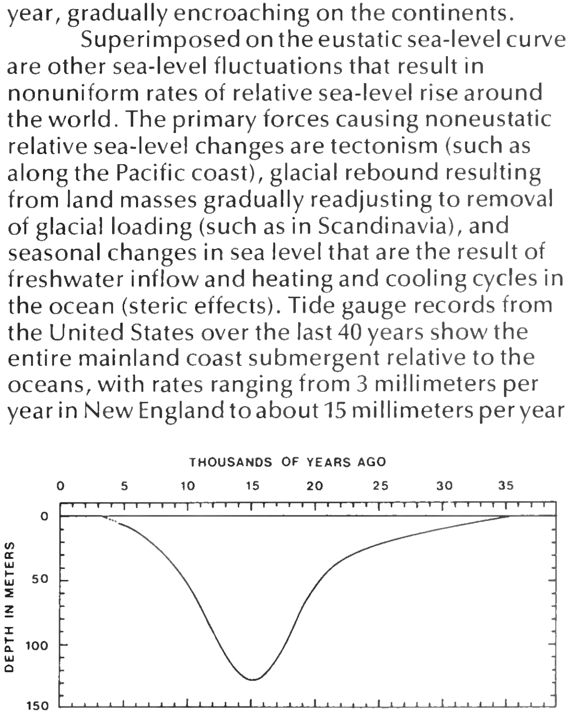


Figure 2. A sea-level curve for the last 35,000 years clearly shows the rise and fall of sea level associated with worldwide glaciation. (After Milliman and Emery, Science *1968)*

along the Gulf coast. Clearly both eustatic and local effects are important factors in determining relative rates of sea-level rise, and the ultimate fate of beaches.

Nearshore Hydrodynamics

Besides the geological factors, water motions impinging on beaches in large part control the behavior of the shoreline. The major events modifying beaches are hurricanes and winter storms. Hurricanes often have dramatic effects on coastal regions, bringing with them large waves, storm surges, and devastating winds. Hurricane Frederic in September, 1979, caused approximately $1 billion in damages along the Gulf coast (see page 47). The last major hurricane to devastate the Atlantic coast was Donna in 1960. Many coastal and atmospheric scientists believe a major hurricane will strike a populated U.S. coastal region in the next few years, and will surely cause widespread damage.

Winter storms also are responsible for extensive coastal destruction, often affecting much greater stretches of coastline than a single hurricane. Large waves, winds, and storm surges are also associated with these winter storms. The Ash Wednesday storm of March 7, 1962, caused millions of dollars of damage along the eastern seaboard. Each year, nearly a hundred such storms along the U.S. coast shape and modify the beaches.

The mean circulation in the nearshore zone can be schematically represented by a generalized circulation cell (Figure 3). Waves approach the shore at an angle, driving a longshore current in the direction of wave propagation, interrupted periodically by seaward-flowing rip currents. This simple model illustrates the major components of nearshore circulation, but obscures the complexity of the mutual interactions of these various flow fields. To understand how a beach responds to a hurricane, storm, or calm-weather wave field, we first need to know how waves behave as they approach the shoreline.

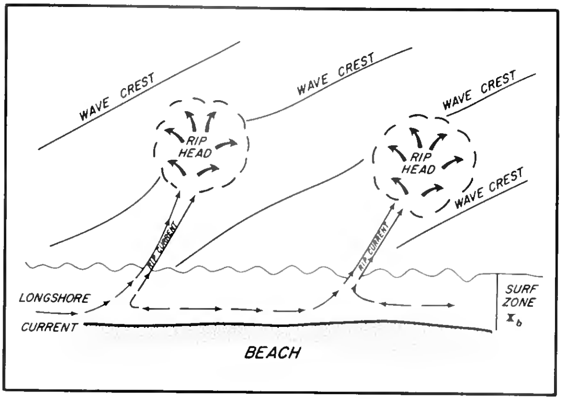


Figure 3. Nearshore circulation cell consisting of incident waves, wave-driven longshore currents, and seaward-flowing rip currents.

Surface gravity waves, which are the waves we observe on the sea surface, are fueled by winds blowing over the oceans. As waves propagate across the open ocean, they lose some energy, but can remain coherent over distances of thousands of miles. Once the waves reach shallow water,* however, they begin to transform and lose energy more rapidly. The loss of wave energy in shallow water is primarily through bottom friction; as waves pass over the bottom, energy is dissipated in the bottom boundary layer. Some of the dissipated energy results from moving sediment, the rest goes into the production of turbulence which eventually is dissipated as heat.

The bottom boundary layer is the transition region near the seabed where the wave and current motions decay to zero. The detailed structure and dynamics of this boundary layer are as important as they are complex; to understand the mechanics of near-bottom sediment transport (both bedload, which is material transported along the bed, and suspended load, which is material transported off the bed), we must improve our modeling of the boundary layer.

The changes that waves undergo as they move shoreward or shoal are complex and not entirely understood. The simplest transformation predicts no changes in wave symmetry or period, only changes in height and wavelength. Except for dissipation, a shoaling wave conserves its rate of flow of energy (energy flux) from deep water up to the breaker point. As it shoals, the wavelength constantly decreases; since the period remains the same, the wave speed (wavelength divided by period) also decreases. The wave height initially decreases as shoaling occurs, then increases shoreward. This linear shoaling model predicts symmetrical wave forms and symmetrical near-bottom wave motions.

Waves can change direction as they move shoreward; this phenomenon, called wave refraction, is analogous to optical refraction. As waves propagate into shallower water, their direction changes such that wave crests become more parallel to shore; in very shallow water waves break nearly parallel to the shoreline. Other wave shoaling effects are diffraction and reflection, where the seafloor changes the wave properties because of sudden bottom irregularities, steep bottom slopes, or longshore bathymetric discontinuities.

Field observations show that the linear shoaling model does not adequately represent

---

*Shallow water here is roughly defined as water depth less than half the deep-water wavelength, approximately 175 meters for a 15-second wave or 38 meters for a 7-second wave.

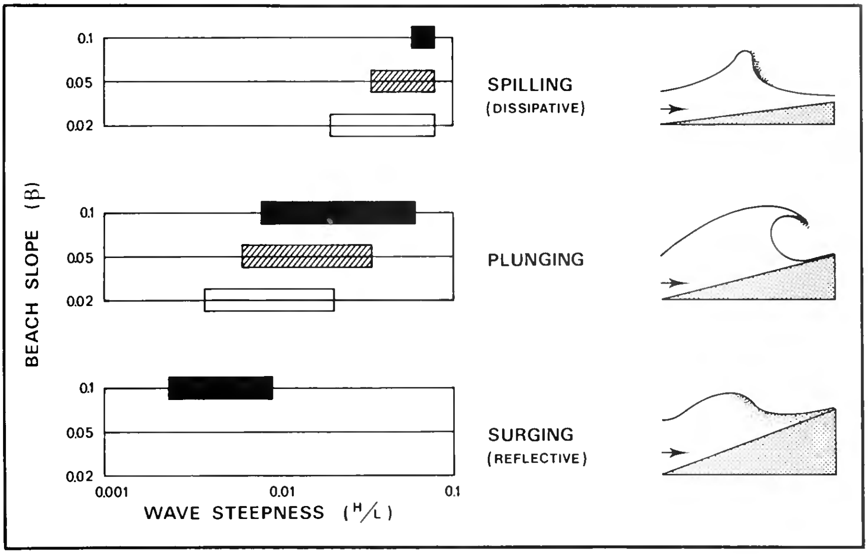


Figure 4. The three primary types of breaking waves are classified according to beach slope and wave steepness (wave height divided by wavelength, H/L). The breaker type influences the nature of water and sand motions near the surf zone.

shallow-water wave behavior. As waves progress shoreward, they steepen and become asymmetrical, with steep, high crests and broad, low troughs. Wave orbital motions become asymmetrical as well, imparting unequal movement to sediment in the onshore and offshore directions, resulting in a net movement of sediment or a finite beach slope. The description of nonlinear wave shoaling, with increased wave asymmetry and transfer of energy between waves of different periods, is of supreme importance in nearshore sediment transport; studies are under way to model and observe this process more thoroughly.

The shoreward propagation of waves is accompanied by variations in the momentum of water waves as well as changes in energy. The resulting force, termed the radiation stress, has widespread ramifications for nearshore processes. Wave set-up and set-down are two results of this radiation stress. As waves shoal, there is an initial slow decrease in wave height, followed by more rapid increase in wave height up to the breakpoint (if dissipation is low enough).

Accompanying the increase in wave height is a tilting of the mean water level down toward the shoreline; this is wave set-down. If the waves were absent, this effect would not occur. Landward of the breaker zone, the wave height decays toward shore; this decay is accompanied by an increase in the mean water level in the swash zone known as wave set-up. Again, this effect is the result of the presence of waves. Wave set-down does not have profound ramifications in beach stability; wave set-up is important, however, as it contributes to the maximum water levels reached during storms and can increase erosion. Radiation stresses also are responsible for generating longshore currents; these are strong currents (up to 2 meters per second) moving parallel to the coast in the direction of wave advance, confined in most part between the breaker point and the shore.

The most dramatic phase of wave shoaling is wave breaking, when the wave becomes so steep and asymmetrical it is unstable. The breaker type is dependent on beach slope and wave steepness (wave height divided by wave length — see Figure 4). Spilling breakers occur with shallow beaches and steep waves, surging breakers occur with steep beaches and waves of low steepness, while plunging breakers result from steep beaches and waves of intermediate steepness. The steepness of the beach has a direct influence on nearshore hydrodynamics, and consequently on beach sand movement. This influence has two major expressions: it affects the transfer of energy from wave motions to long-period motions in the surf zone; and it correlates with run-up patterns in the surf zone.

Field observations have shown that energy is transferred from incident wave periods to long-period motions within the surf zone. This transfer shows up in surf zone measurements of both run-up of waves on beaches and of swash velocities. This transfer of energy could have several causes; one might be the excitation of long-period waves by incoming swell. Theoretical work has demonstrated the possibility of taking energy from incoming surface waves and pumping it into longer-period fluctuations called "edge waves." These edge waves have a longshore periodicity and amplitudes decaying exponentially offshore, whose energy is trapped against the shoreline by refraction. Energy is supplied by incoming ocean waves, and is lost through bottom friction or other dissipation.

Field and laboratory observations are consistent with theories about nearshore edge waves, suggesting their importance in nearshore sand movement. These longshore periodic waves may influence rip current formation and even the beach configuration itself.

Storm systems affect beaches other than just through waves. Storm surges can raise the mean water level near the coast, enabling destructive waves to erode the beach at higher and higher levels. Storm surge is composed of several components. The first is an "inverse barometer" effect, where sea level rises in response to lowered atmospheric pressure associated with storms. A drop in atmospheric pressure of 2 millimeters of mercury is equivalent to a sea-level rise of 3 centimeters. Combined with this barometric effect, a wind blowing onshore during a storm can raise sea level by several meters. The combined storm surge can significantly contribute to storm damage along coasts, and the development of overwashes and inlets along barrier beaches. Other water motions also may influence beach processes, but generally to a lesser degree. Internal waves, shelf circulation patterns, Gulf Stream eddies, and other low-frequency motions may influence any particular beach in an intricate fashion.

Beach Response

Our understanding of how beaches respond to waves and tides is largely empirical, although significant theoretical advances have increased our knowledge of the physics of sediment transport. The U.S. National Oceanic and Atmospheric Administration's Sea Grant program recently has been sponsoring a major effort to better understand how beaches work; this program is called the Nearshore Sediment Transport Study (NSTS). Approximately 10 scientists serve as principal investigators on this project, designed to "perfect relations for the prediction of sediment transport by waves and currents in the nearshore environment." The study emphasizes field measurement of nearshore wave and current behavior at three different sites, as well as theoretical and empirical modeling of surf zone hydrodynamics and sediment transport. This study is contributing to our understanding of the behavior of different beaches as they are exposed to various driving forces.

Although beaches change in a complex manner, some aspects of their behavior can be correlated with particular aspects of the forcing conditions. The most obvious example is the gradual encroachment of the sea onto beaches, responding in part to local sea-level rise. As sea level rises, beaches retreat landward, often leaving peat deposits, tree stumps, and other coastal forest remnants exposed on the open-ocean beaches. Accompanying this shoreward migration may be a narrowing of the beaches and consequently a reduction in their capacity to act as buffers to ocean storms and waves. This beach retreat and narrowing is not a result of sea-level rise alone; it also reflects fluctuations in the availability of sediment in the nearshore zone as well as variations in storm and wave climates.

The movement of sediment along a beach is conveniently divided into on/offshore sand transport and longshore sand transport. Although this division is arbitrary and ignores the very real mutual interactions between these modes, on/offshore and longshore transport do respond generally to different features of the incident wave field. Both modes of transport can be responsible for patterns of beach erosion or accretion at a particular location; it is important to distinguish which mechanism is responsible for coastal change whenever shoreline stabilization methods are considered.

On/offshore transport results from shoaling asymmetrical waves, moving sediment both landward and seaward, alternately acting with and against the influence of gravity. Wind- and wave-induced currents within the surf zone may modify this transport pattern. Field and laboratory experiments suggest that long, low waves build up a beach to a "berm profile," whereas steep, short waves erode the beach face, causing a "bar profile." Since coastal wave climates have a seasonal variability, beach changes also have a seasonal character to them. To better understand the mechanics of on/offshore sediment movement, we need to better understand nonlinear wave shoaling, nonlinear surf zone energy transfers, wave breaking phenomena, wave boundary layer structure, and the bedload/suspended sediment transport transfer functions.

As waves approach and break along a shoreline at an angle, driving a longshore current within the surf zone, sediment moves alongshore in the direction of wave advance. Surf zone structures and tidal inlets interrupt this littoral drift, causing modifications of downdrift beaches. If more sediment enters a coastal area than leaves through longshore transport, the beach accretes. If more longshore drift leaves an area than enters, erosion results. There are many notable examples of longshore sand starvation caused by structures, and the subsequent beach erosion (Figure 5).

Tidal inlets interrupt littoral drift, forcing sand to bypass either by moving in and out of the inlet, or along an offshore delta. When new inlets are formed during storms, sand is taken from the nearshore sand budget to build flood and ebb tide deltas. Once these features are well developed, bypassing of sediment to the downdrift barrier beach can occur by natural processes. If the inlet is modified by jetties, bypassing may be more difficult and often must be accomplished by further human intervention.

Figure 5. Santa Barbara, California, presents a notable example of longshore sand entrapment by a coastal structure and resultant severe erosion of downdrift beaches.

Storms can damage coasts severely over very short time intervals. Because of the larger wave energies present during storms, much more sand is moved than during quiescent conditions, both alongshore and on/offshore. The effects of rapid storm erosion were measured at Santa Barbara, California, in February, 1980, by the author and R. J. Seymour of Scripps Institution of Oceanography, as part of the NSTS (Figure 6). Vertical beach changes of up to 2.5 meters occurred over a period of several days. In contrast, the recovery of the subaerial beach to its prestorm configuration will take months or years, emphasizing the mismatch of time scales for erosion and accretion of beaches.

Storms acting on barrier beaches often modify them by two additional processes: overwash and inlet formation (Figure 7). Overwash occurs when the combined effects of erosion, wave set-up and run-up, and storm surge, cause the water to overtop the barrier beach, channeling sand and water into the bay. The overwash process has several major effects. It helps to push sand shoreward, causing the barrier to migrate toward shore. It also destroys the protective dune structure and vegetation, thereby temporarily weakening the barrier and making it more susceptible to future overwash events. Finally, it partly fills the bay (hence reducing the volume of water exchanged by the bay and ocean through tides), and can kill existing vegetation and shellfish.

Tidal inlets, or breakthroughs, can be formed on barrier beaches during storms, often as a result of overwash events. These new inlets can change the flushing characteristics of bays, as well as interrupt longshore sand transport, robbing the nearshore of valuable protection. Inlets may remain open for long periods of time, either coexisting with or replacing former inlets. In many cases, storm inlets close after a short period, leaving tidal flushing to the prestorm inlets. These two processes are instrumental to the shoreward migration and evolution of barrier beach systems; their long-term benefits partly offset the immediate removal of sand from the local sand budget.

In addition to the general on/offshore and longshore transport of sand, nearshore water motions also result in the creation of periodic beach forms; this periodicity may be in either the longshore direction (oblique forms) or shore normal direction (parallel forms). These periodic bed structures most likely result from a periodicity in the driving forces; researchers have been only partly successful in isolating the mechanisms generating these features. One common type of periodic form is the multiple parallel offshore bar (Figure 8): these forms have wavelengths of tens or hundreds of meters and heights of approximately one meter. As with most nearshore features, multiple parallel bars can be formed in a number of ways. One documented sequence consists of the

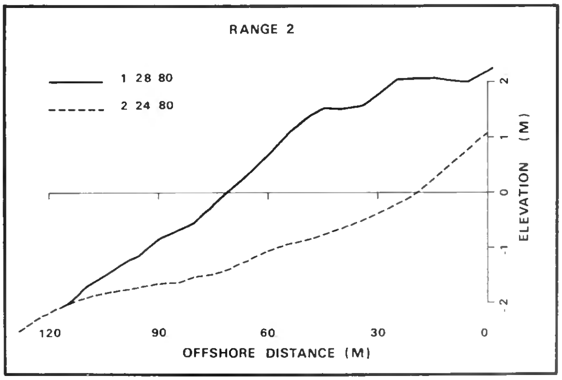


Figure 6. Beach erosion resulting from a series of storms battering Santa Barbara, California, in February, 1980, causing vertical cuts in the beach of up to 2.5 meters, and horizontal beach retreat of up to 60 meters.

Figure 7. Overwash event and inlet formation occurred in February, 1978, on Monomoy Island, Massachusetts, separating a barrier island into two distinct islands. Strong tidal flows between the Atlantic Ocean and Nantucket Sound keep the inlet open.

Figure 8. Multiple parallel offshore bars located off Truro, Cape Cod, Massachusetts, along Cape Cod Bay, where the tidal range is approximately three meters. The bars intersect the shoreline to the north where they become sinuous; bar spacing increases with distance offshore.

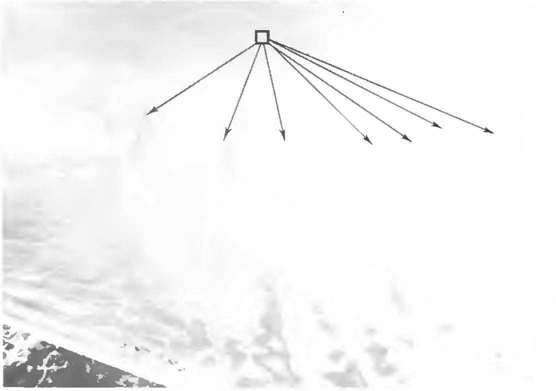


Figure 9. Multiple oblique nearshore bars are superimposed on numerous, smaller-wavelength parallel bars off Wellfleet, Cape Cod, Massachusetts, where the tidal range in Cape Cod Bay is approximately 3 meters. The spacing between oblique bars is several hundred meters.

Figure 10. Multiple bars exposed at low tide off El Golfo, Sonora, Mexico, in the Gulf of California, where the tidal range is approximately ten meters. The bars form a confused pattern with both oblique and parallel bars separated by short distances.

formation of a submerged bar under a breaking wave (a breakpoint bar), which moves shoreward under favorable conditions, eventually to weld onto the shoreline as an accretionary feature. As one bar is migrating shoreward, a second breakpoint bar may form, which in turn migrates shoreward. This sequence occurs in both tidal and tideless seas, although it is more common in the latter.

Multiple oblique bars also exist along coastal regions (Figure 9). Their existence is often ascribed to shallow longshore tidal currents; they can exist superimposed on multiple parallel bars that may be wave related. Sometimes oblique bars and parallel bars of the same scale cover the same coastline (Figure 10); although wave forcing is believed responsible for this feature, tidal flows are often contributory (the tidal range in Figure 10 is approximately 10 meters). Crescentic bars often form offshore, with distinct cusps and horns. Their occurrence has been linked by A. J. Bowen and D. L. Inman (1971) to standing edge waves trapped between two longshore features (such as headlands). The region (see introductory photo) has no apparent trapping mechanisms, so other forcing may control the spacing and occurrence of these crescentic bars.

Other longshore periodic features of similar spatial scales include shore-attached hooked bars, with hooks pointing in the direction of longshore transport (Figure 11). The hooked ends of the bars are in the zone of most active longshore transport, averaged over a tidal cycle. These features originally may have been bars separating longshore periodic rip currents. If the shore-attached hooked bars result from periodic rip currents, then the origin of periodic rip currents needs to be explained.

Edge waves are frequently blamed for many of these longshore periodic bedforms. Indeed, R. Dolan, B. Hayden, and C. Jones (1979) have even postulated large-scale edge waves as sculpting the numerous false capes along the eastern seaboard. R. T. Guza and Inman (1975), among others, have suggested subharmonic edge waves as a generating mechanism for beach cusps, with some field evidence to support this association. Edge waves are convenient because they have a longshore periodicity and have an infinite number of modes (hence wavelengths). It is straightforward to match the spacing of any longshore periodic feature to some edge-wave mode. Carefully planned, well-instrumented experiments are needed to assess the role of edge waves and other long waves in nearshore hydrodynamics. Other alternative mechanisms, such as surf zone instabilities, need to be explored in greater detail as well.

A Look to the Future

The beaches of the United States, which include the most extensive barrier beaches in the world, constitute a valuable and delicate resource that must be managed intelligently to avoid loss of their recreational benefits, storm protection, and aesthetic appeal. Beaches are complex systems: they are forced by complex atmospheric and oceanic behavior and respond in an equally complex manner.

Our scientific understanding of beaches in some respects is not sufficient to meet the requirements of coastal zone management in establishing beach policies and guidelines. Active research in beach processes in general, including barrier beach systems, must continue in order to fill this need. In addition to continued research, the scientific community must work closely with the public, educating them and communicating the various scientific alternatives available for managing our nation's beaches. The public in turn must become concerned and better informed if we wish to most effectively and least destructively utilize our valuable beaches.

David G. Aubrey is an Assistant Scientist in the Department of Geology and Geophysics, Woods Hole Oceanographic Institution.

All photos taken by the author, unless otherwise noted.

Figure 11. Multiple, shore-attached hooked bars stretching from Provincetown, to points further south along the Atlantic shore of Cape Cod, Massachusetts. The hooks point in the direction of longshore transport, and occur with a spacing of hundreds of meters.

References

Bowen, A. J., and D. L. Inman. 1971. Edge waves and crescentic bars. *Journal of Geophysical Research* 76: 8662-71.

Dolan, R., B. Hayden, and C. Jones. 1979. Barrier island configuration. *Science* 204: 401-402.

Dolan, R., B. Hayden, and H. Lins. 1980. Barrier islands. *American Scientist* 68: 16-25.

Guza, R. T., and A. J. Bowen. 1975. The resonant instabilities of long waves incident on a beach. *Journal of Geophysical Research* 80: 4529-34.

Guza, R. T., and R. E. Davis. 1974. Excitation of edge waves by waves incident on a beach. *Journal of Geophysical Research* 79: 1285-91.

Guza, R. T., and D. L. Inman. 1975. Edge waves and beach cusps. *Journal of Geophysical Research* 80: 2997–3012.

Inman, D. L., and C. E. Nordstrom. 1971. On the tectonic and morphologic classification of coasts. *Journal of Geology* 79: 1-21.

Wright, L. D., J. Chappell, B. G. Thom, M. P. Bradshaw, and P. Cowell. 1979. Morphodynamics of reflective and dissipative beach and inshore systems: Southeastern Australia. *Marine Geology* 32: 105-140.

The Apalachicola Experiment:

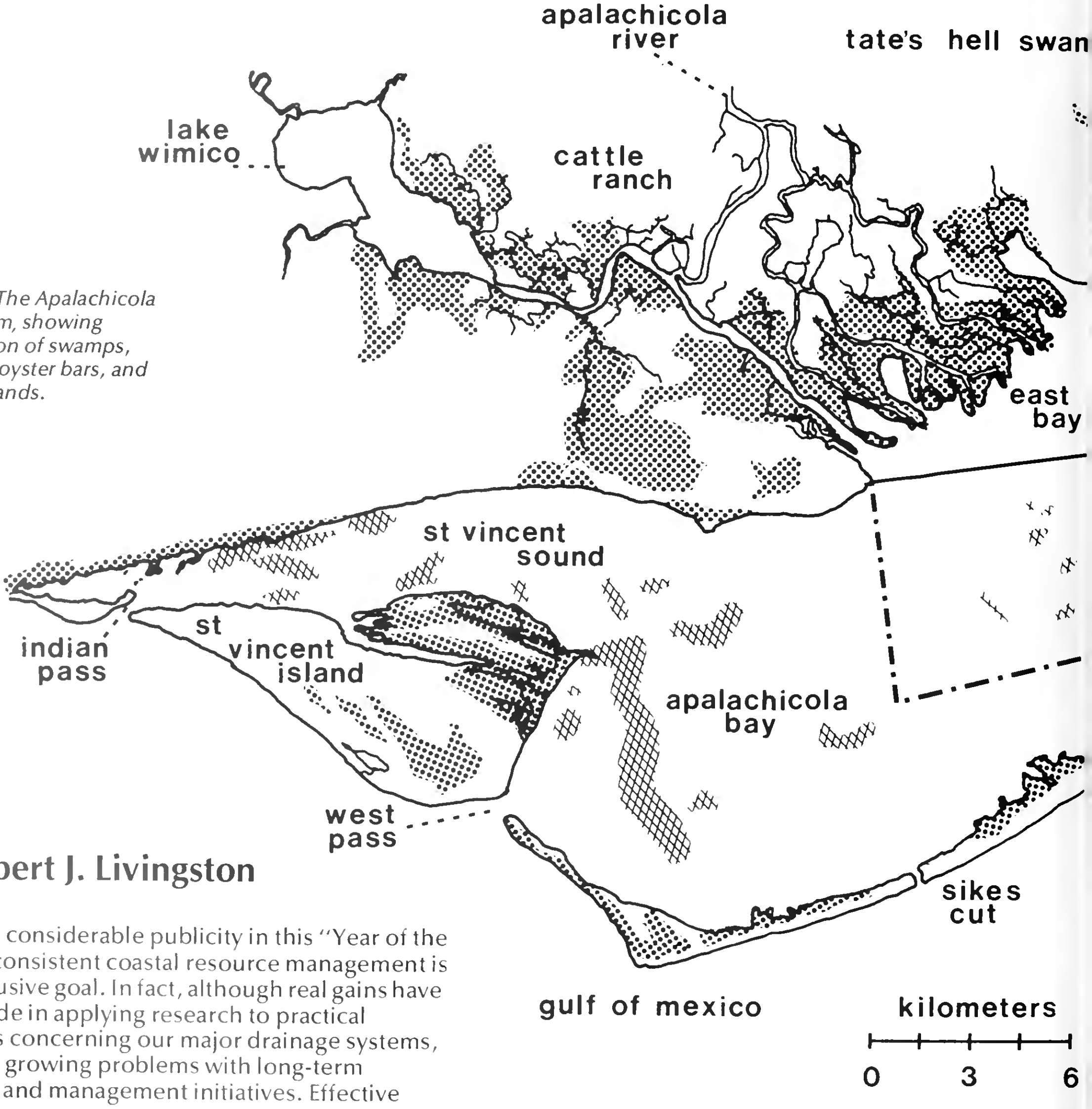


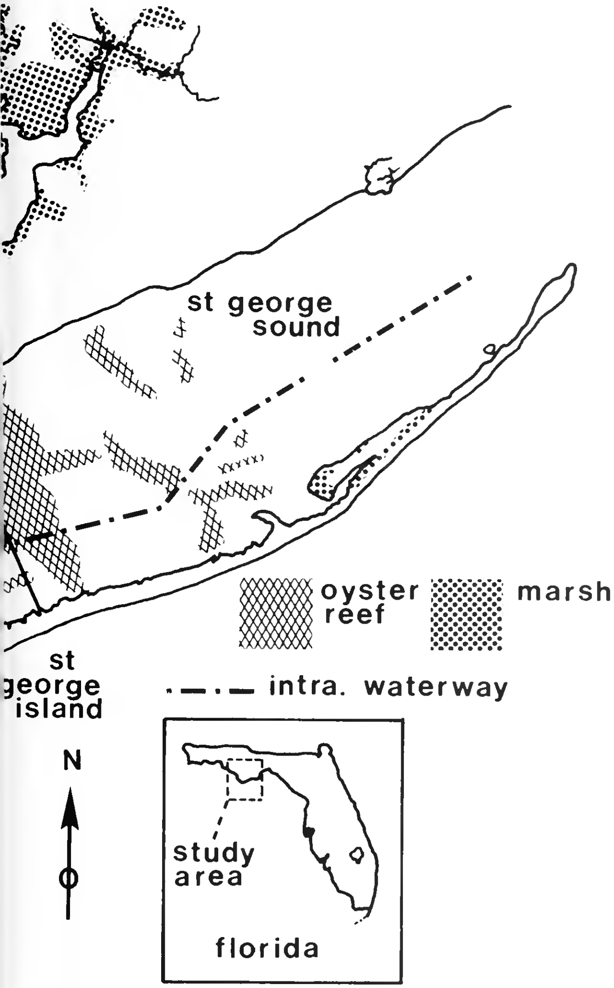
Figure 1. The Apalachicola Bay system, showing distribution of swamps, marshes, oyster bars, and barrier islands.

by Robert J. Livingston

Despite considerable publicity in this "Year of the Coast," consistent coastal resource management is still an elusive goal. In fact, although real gains have been made in applying research to practical decisions concerning our major drainage systems, there are growing problems with long-term planning and management initiatives. Effective resource management requires more than a superficial understanding of the ecological system in question. Unfortunately, few environmental scientists are willing to participate in the long-term, multidisciplinary research programs, which are necessary for such understanding. There are several reasons for this situation. Funding for systems-oriented projects in coastal and marine areas is almost nonexistent. The handful of federal agencies that have the funds and the mandate to carry out such research have often discouraged long-term investigation. There are usually few publications during the early years of a project, and universities, with the tenure system and the publish-or-perish ethic, do not encourage such work.

Our coastal systems, central to the productivity of the seas, remain under intensifying pressure from development and pollution. Millions of acres of productive coastal shellfish beds have been condemned or destroyed because of pollution. Public education and general knowledge of the environment are still lacking. In short,

Research and Management



despite a vague public perception of the importance of the environment, the underlying ecological mechanisms of our major drainage areas are still poorly understood. Consequently, the systematic application of such understanding to the administration of this dwindling resource is haphazard and fragmented.

Since 1971, a continuous, multidisciplinary research program has been carried out in two bay systems in northern Florida, Apalachee Bay and Apalachicola Bay.

The Apalachicola Drainage System

The Apalachicola system is located along the sparsely populated Gulf coast of northern Florida (Figure 1). It is an anachronism in the sense that it remains relatively free of the municipal and industrial waste discharges that characterize many of our major drainage systems. The upland drainage area (19,500 square miles) includes three major rivers (the Flint, the Chattahoochee, and the Apalachicola) in three states — Alabama, Georgia, and Florida (Figure 2).

As part of the tri-river system, the Apalachicola River is one of the last major "unimproved" rivers in the country. The flood plain is an extensive network of freshwater and brackish wetlands. The particular hydrological features of the system, together with the almost unbroken wetlands, form the ecological basis for the incredible natural productivity of the Apalachicola estuary (Figure 3). This bay system provides 80 to 90 percent of Florida's oysters. It serves as a nursery for the bulk of the "Big Bend" (northern Florida) shrimp, crab, and finfish fisheries. The river wetlands provide habitats for various freshwater, brackish, and marine species. Freshwater runoff from upland wetlands and the physiography of the area (for example, the barrier-island system) provide the basis for various sports and commercial fisheries. In a sense, the Apalachicola River provides the cultural and economic basis for the entire region.

Although the Apalachicola flood plain is largely intact, it is not uniformly pristine. Six miles above the bay, a 33,000-acre cattle ranch was established during the early 1970s. Massive clearing, ditching, and diking projects altered the wetlands, and the effluents were routinely pumped over the dikes without meaningful interference from state or federal regulatory agencies. Any attempts to rectify the problem were somehow blocked. However, industrial and commercial land use remained minimal (around 0.2 percent) in the valley, with forestry as the dominant local industry. Our long-term research indicated that forestry activities in wetlands, including clearing, draining, and associated processes, had adversely affected hydrological and water-quality features of receiving systems. However, with appropriate controls and safeguards, such impact could be minimized. Forestry contributed in a positive way to maintaining aquatic productivity since it prevented widespread municipalization and industrialization of the flood plain, which almost certainly would have permanently altered the natural system.

Shipping and industrial interests in Georgia and Alabama, subsidized by state and federal funds, have applied continuous pressure to maintain the authorized 9-foot navigation channel from the Gulf of Mexico to upland ports in Georgia and Alabama (Figure 4). Such efforts led to proposals for massive

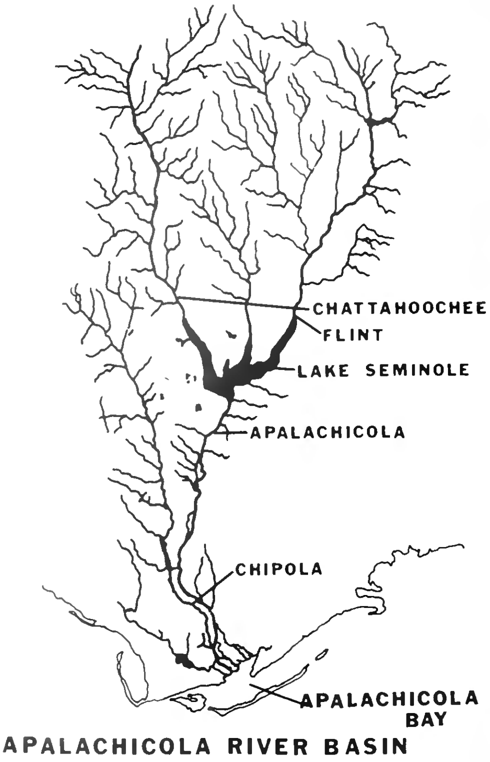


Figure 2. The Apalachicola drainage system and the major tributaries of the tri-river area.

Figure 3. Flood-plain vegetation has been linked to the productivity cycles of the Apalachicola drainage system. (Photo by author)

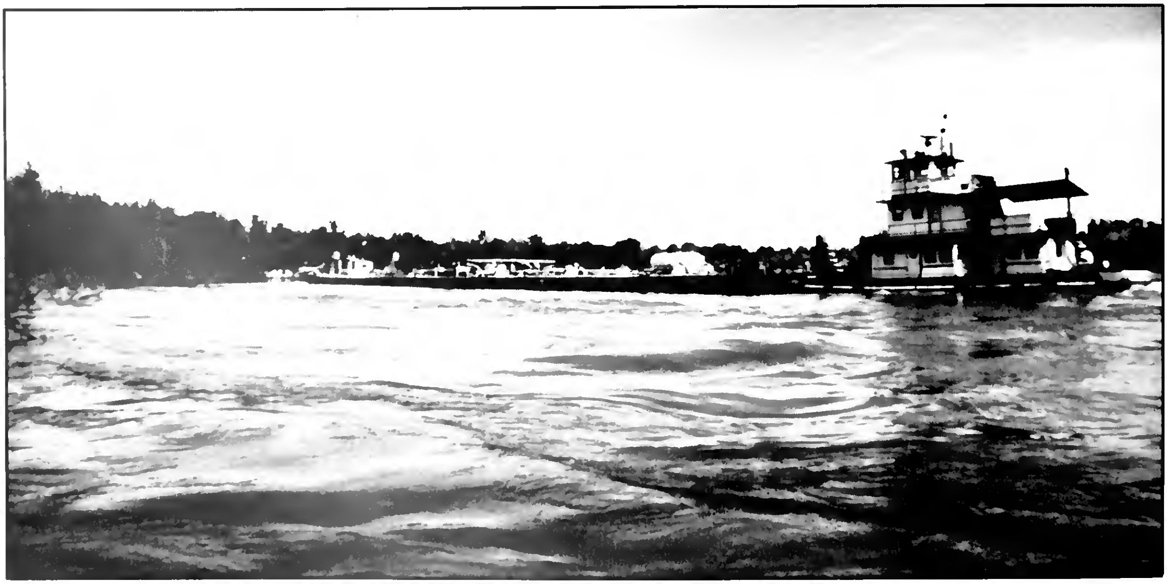


Figure 4. Barge and industrial interests in Georgia have continuously opposed the Apalachicola Estuarine Sanctuary and other constructive management proposals in their effort to turn the Apalachicola River into the "Ruhr of the South." (Photo by author)

damming projects along the Apalachicola River. So far, the projects have been blocked by various Florida interests since changes brought about by damming the river system would have had negative economic effects in Florida. In fact, the application of hundreds of millions of federal dollars to damming and navigation of the tri-river systems has been found to be neither economically feasible nor environmentally sound according to a series of studies on the subject. The 13 established hydroelectric dams on the Chattahoochee River, together with industrial and municipal waste disposal, have already taken a toll on the water quality in this region. The rapid growth of metropolitan Atlanta has become a threat to the water supply of the entire system, and remains the single most important concern to all interests. Yet, despite the importance of the tri-river system to the region, not one comprehensive study has been carried out to weigh the overall impact of ongoing and proposed projects, and to provide an objective basis for future development. Although a "Level B" study has been proposed, the controversial issue of water use will play an increasingly important role in maintaining the natural productivity along the tri-river system.

St. George Island, forming the gulfward perimeter of large areas of Apalachicola Bay, is of critical importance to the productivity of the estuary (Figure 5). This barrier island, as a physiographic feature of the system, controls the water quality and salinity regime of the bay. However, considerable portions of St. George are privately owned.

High-priced island real estate was created by another publicly financed project, the construction of a bridge in 1965 linking the island to the mainland. The entire range of problems associated with the development of barrier islands (see page 38) is related to the spectacular increase in land values after construction of bridges. Road and marina construction, dune destruction, septic tank wastes, and sheer overpopulation of an exceedingly fragile island system may soon affect the Franklin County oyster industry. This, together with continuing sewage and storm water runoff problems in other areas of the county, makes the need for a comprehensive land management plan even greater.

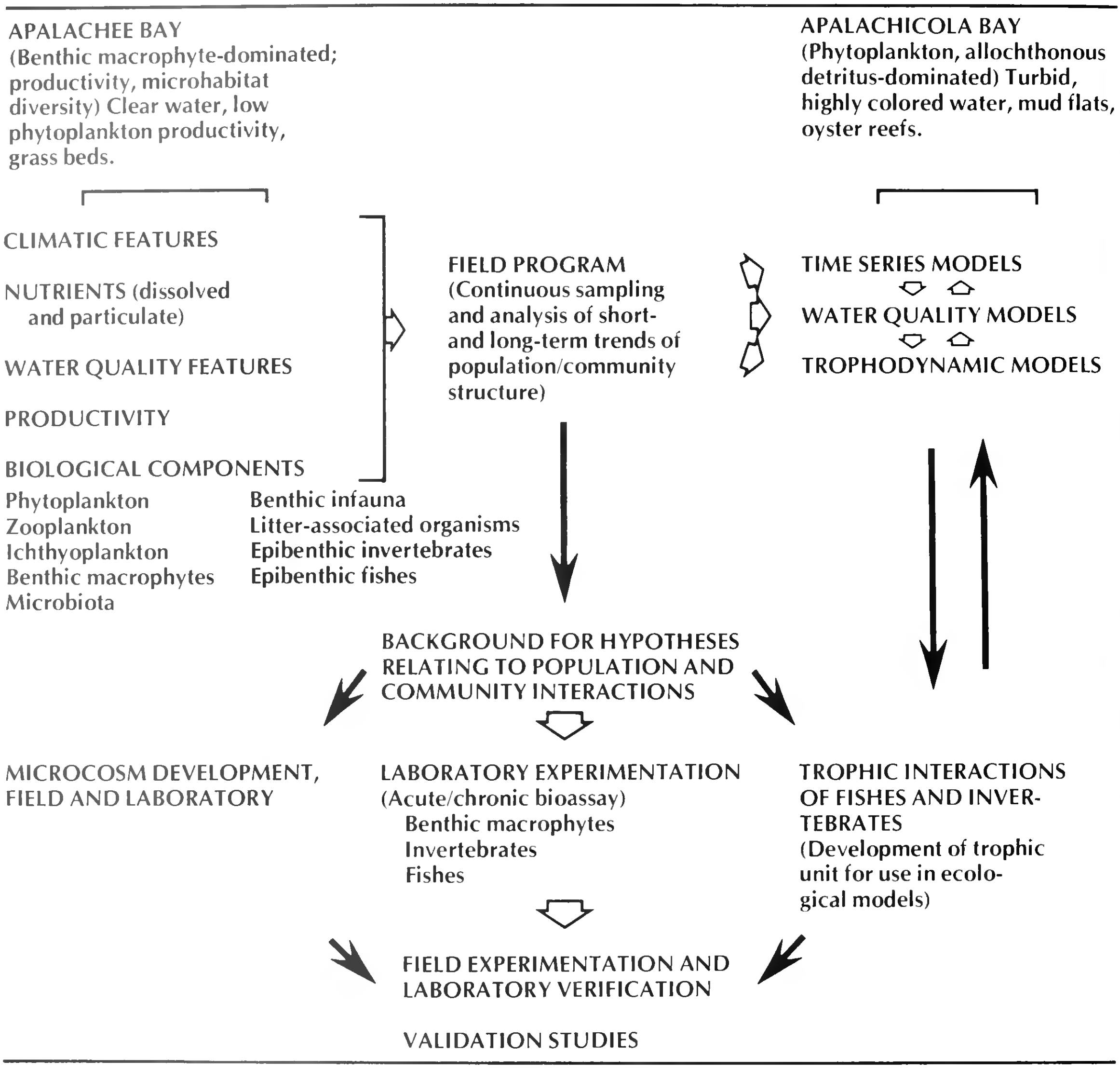
The chief difference between the Apalachicola system and many other similar areas is that, despite some environmental problems, no single form of land use has seriously affected its natural environmental processes. Thus, there is time for solutions to growth problems since the region is still in the initial phases of what seems to be an almost inevitable cycle of economic development. It is within this context that the potential value of scientific research to resource management will be tested.

Research Goals and Problems

The Apalachicola project originated as a routine, baseline assessment of the Apalachicola estuary. The research included monthly assessments of water-quality parameters and biological associations, and was designed as a comparative analysis with Apalachee Bay, an adjacent, though very different, coastal system (Table 1). In 1973, the author was contacted by a group of local fishermen and county representatives who, through their common interests in the seafood industry, were aware of the failing fisheries in populous southern Florida. These people were worried about their future and needed help. Thus began a unique association of fishermen and scientists. For the next eight years, the Franklin County residents provided vital matching funds for the federal grants provided by the Florida Sea Grant program of the National Oceanic and Atmospheric Administration to study the Apalachicola system. Scientists provided continuing guidance and advice for local environmental problems. High school students were taken on scientific field trips. Strong support by the *Apalachicola Times*, a local newspaper, aided in dissemination of scientific information. The proposal by the U.S. Army Corps of Engineers to

Figure 5. Oystermen work the rich waters of Apalachicola Bay. (Photo by author)

Table 1. Comparison of two spatially diverse coastal systems. Research program of Robert J. Livingston, Florida State University, 1970-80.



dam the Apalachicola River galvanized the community and provided the stimulus for the continued cooperative effort to understand and protect the Apalachicola system. The Apalachicola project now includes the work of more than 750 people, and has been in operation for more than nine years. Each piece of information was added to a central data file so that a multidisciplinary core of information is now available to provide an important basis for the Apalachicola research and management effort.

Findings and Applications

Initial studies indicated relatively high levels of phytoplankton productivity and virtually no pollution from organochlorine compounds. Various analyses concerning interactions of estuarine biota and controlling physical factors showed the importance of seasonal and annual fluctuations of Apalachicola River flow on the system. Regular seasonal cycles were superimposed over seven-year peaks of river flooding and local rainfall. Such meteorological cycles were associated with commercial fisheries landings. These studies related the importance of the river to the biological productivity of the bay. River loading of organic detritus and nutrients was analyzed, and subsequent research indicated that river-derived substances are important for the major detrital food webs of the bay system.

Figure 6. Eastern St. George Island where about a third of the oysters of Franklin County are taken. Portions of adjoining lands have already been dredged by developers in anticipation of housing projects. Runoff from such development would threaten more than 25 percent of Florida's oyster crop. Efforts to purchase such lands under Florida's Environmentally Endangered Lands program have been opposed by high state officials. (Photo by author)

Seasonal movements of organic matter were tied to microbial productivity. The microbes, in turn, were consumed by various benthic invertebrates. These organisms served as the basis for the major estuarine populations. Associated studies showed that changes in the drainage system caused by forestry operations could alter such relationships. Estimates of long-term variability of key physical and biological processes have led to a greater understanding of natural and anthropogenic impacts. This, in turn, has led to various new research initiatives in experimental ecology and has provided the scientific basis for the planning and management program in the Apalachicola drainage system.

The long-term data have been used to solve local problems such as pesticide use, aquatic weed control, shoreline development, and other forms of human activity around the bay. The initial studies provided needed information concerning the critical ecological pressure points of the drainage system. Certain macrohabitat features were shown to be critical for specific forms of estuarine productivity. These included the Apalachicola River, the upland wetlands (including the Tate's Hell Swamp), and the barrier islands. These features controlled the hydrological regime, nutrient structure, and physicochemical environment (salinity, water quality) which, together with specific physical conditions — temperature, wind, tidal fluctuations — provided the appropriate environment for the observed seasonal and annual progressions of key estuarine populations. When such facts were documented through reviewed scientific publications, various management applications became possible. Through contact with public officials, state and federal administrators, and leaders of private industry, the university researchers were thus able to channel scientific information into public use. In this way, the Apalachicola research effort was applied to local and regional problems so that alternatives were available to decision makers.

Acquisition of Ecologically Sensitive Lands

As a multidisciplinary research program was developed, the purchase of ecologically sensitive land was emphasized as an effective way to overcome some of the problems inherent in the system. Based on studies linking upland nutrients and organic matter to the aquatic food webs of receiving systems, an ecological connection was made between the hardwood forests of the lower Apalachicola flood plain and the productivity of the Apalachicola River-Bay system. These data were used to justify the purchase of 28,044 acres of the lower Apalachicola flood plain for $7,615,250 as part of Florida's environmentally endangered land program. In 1977, the Florida government authorized the purchase of little St. George Island for $8,838,000, again in response to data concerning the ecological importance of barrier islands to the system. Portions of the eastern end of St. George Island were added to the existing state park under this program. St. Vincent Island was already a national wildlife refuge. Dog Island and other ecologically sensitive parts of St. George Island are still the subject of negotiations for public purchase (Figure 6).

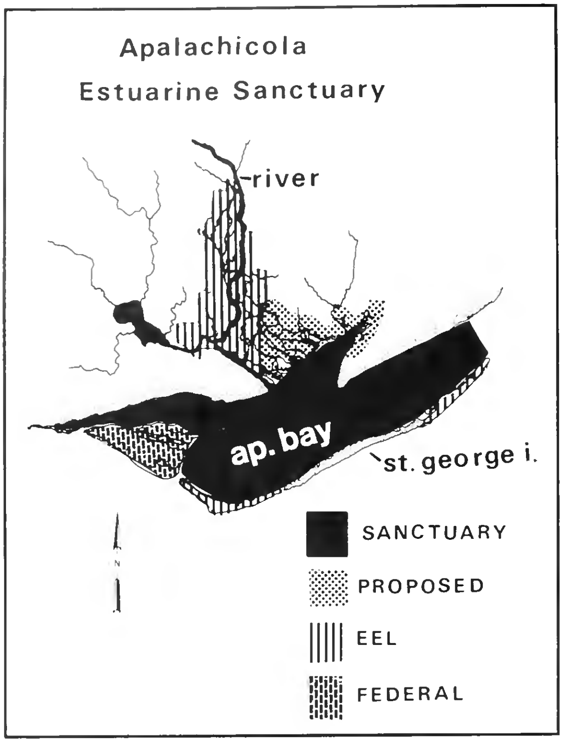


Figure 7. The Apalachicola River and Bay Estuarine Sanctuary, showing patterns of public land ownership in the area. The Environmentally Endangered Lands purchase (EEL) should protect the bottomland hardwood forests of the lower Apalachicola flood plain. The proposed purchase for the sanctuary would include wetlands surrounding East Bay, an important nursery area. While St. Vincent Island and portions of St. George Island are under state and federal control, the critical midsection of St. George remains in private hands and is the source of continuing controversy between developers and the Franklin County Board of Commissioners.

With the establishment of the Apalachicola Estuarine sanctuary, additional wetlands (12,467 acres) surrounding the East Bay system will be purchased for $3.8 million. Various state and federal agencies, and the combined efforts of local government officials and scientific input from the sustained research program, were instrumental in this series of land purchases (Figure 7).

The Apalachicola Estuarine Sanctuary

In itself, public acquisition of land is not enough for system-wide management of an important resource. In the winter of 1975, Robert Howell, the Clerk of the Franklin County Circuit Court, and the author addressed representatives from state and federal agencies in Washington, D.C., under the auspices of John Clark and the Conservation Foundation (see page 22). From this meeting, a series of reviews led to the establishment in September, 1979, of the Apalachicola River and Bay Estuarine Sanctuary. This estuarine sanctuary, set aside by law as a natural field laboratory "for long-term scientific and educational purposes," is the largest (192,758 acres) and most ambitious of its kind in the country. The scientific data base from this program led various groups — including state and federal agencies, the Apalachee Regional Planning Council, the Conservation Foundation, Florida State University, and the Florida Sea Grant program — to develop a comprehensive management plan for Franklin County and the Apalachicola Valley. If successful, this combined effort could serve as the basis for the estuarine sanctuary and assure the continued productivity of the Apalachicola system.

Problems with the Apalachicola Experiment

In the winter and spring of 1980, the Florida Department of Natural Resources (under direction from the Food and Drug Administration), closed most of the Apalachicola oyster beds because of high coliform bacteria counts in the water. Such action followed reports of sickness from eating oysters. Ironically, most of the contaminated oysters came from other areas, but because of widespread publicity, the damage was done. Regulatory agencies found that it was easier to shut down an industry than to protect or manage it. Consequently, even though the origin of the bacteria remains unknown, every time the river floods, the industry will be shut down. In addition, the Franklin County Board of Commissioners, so active in protecting Apalachicola Bay, is being sued by various developers who wish to build in the area. Legal questions have been raised concerning how far a community can go to protect a natural industry.

Despite the efforts of so many people over the last decade, the estuarine sanctuary has been in a continuous state of confusion, threatened on all sides by a lack of funds, bureaucratic ineptitude on the part of state agencies, and interstate politics. Shipping and industrial interests in Georgia continue to apply pressure for the massive alteration of the Apalachicola River. There is an increasing awareness by all parties that municipal water use by areas such as Atlanta will place increasing pressure on free-flowing water in the tri-river system. Thus, despite various successful applications of science and management, there are serious threats to the natural system that could ultimately bring an end to the Apalachicola experiment.

The Future

The long-term research effort has provided a platform for the overall multidisciplinary effort, which includes engineering studies, physical-nutrient modeling, economic evaluations, and comprehensive planning. Such results have led to an experimental ecology program, and will now serve as the basis for the development of a comprehensive management program and local educational initiatives. Such a sustained effort is the bridge to public use of research information through education and the news media. Concentration on both macro- and microscale problems has allowed a broad application of the results. In addition, long-term work allows the most effective measure of an environment's stability and response to stress. Gradual environmental deterioration, which is the fate of so many natural systems, is usually undetectable unless a long-term data base is available.

The Apalachicola experiment is an attempt to develop an area, while retaining an important, sensitive natural resource. The Franklin County fishermen, who financed much of the research, are now helping to fund the final phase — analysis of the data and development of a local educational program to teach the children of Franklin County about their bay. This final step is often overlooked, but education is the only real way to sustain the momentum of current management programs. The scientist has an obligation not only to interact with the public but also to make sure that important information gets into our educational processes, because herein lies the future.

There are many explanations for the dwindling coastal resources in this country. It is an unfortunate truth that people tend to accept environmental deterioration if it occurs over a long enough period of time. What appears unacceptable in the short run remains inevitable as urbanization of our coasts continues. There is something very wrong with a government that cannot or will not protect those who are dependent on natural productivity. It is possible that our society really does not care about such resources as long as the perception remains that we have unlimited natural abundance. Regardless of the cause, if the Apalachicola experiment fails and an endangered culture becomes extinct, no place in this country will be safe from the progress that erodes. The Apalachicola experiment is a clear test of the application of scientific principles to resource management.

Robert J. Livingston is an Associate Professor in the Department of Biological Science, the Florida State University, Tallahassee.

Selected References

Laughlin, R. A., and R. J. Livingston. 1980. Spatial/temporal variability in the distribution of the blue crab *(Callinectes sapidus)* in a north Florida estuary: Abiotic factors, trophic relationships, and cannibalism. *Fishery Bulletin* (In press).

Livingston, R. J. 1977. The Apalachicola dilemma: Wetlands development and management initiatives. National Wetlands Protection Symposium, Environmental Law Institute and the Fish and Wildlife Service, U.S. Department of the Interior, pp. 163-177.

———. 1978. Effects of forestry operations (clearing, draining, etc.) on water quality and biota of the Apalachicola Bay system. Sea Grant, NOAA (Final Report).

———. 1979. Multiple factor interactions and stress in coastal systems. A review of experimental approaches and field implications. In *Marine pollution: Functional responses,* ed. F. John Vernberg. New York: Academic Press.

Livingston, R. J., and J. Duncan. 1979. Short- and long-term effects of forestry operations on water quality and epibenthic assemblages of a north Florida estuary. In *Ecological processes in coastal and marine systems,* ed. R. J. Livingston. New York: Plenum Press.

Livingston, R. J., R. L. Iverson, R. H. Estabrook, V. E. Keys, and J. Taylor, Jr. 1974. Major features of the Apalachicola Bay system: Physiography, biota, and resource management. *Florida Scientist* 37: 245-71.

Livingston, R. J., R. L. Iverson, and D. C. White. 1976. Energy relationships and the productivity of Apalachicola Bay. Florida Sea Grant Program, NOAA (Final Report).

Livingston, R. J., and O. Loucks. 1979. Productivity, trophic interactions, and food web relationships in wetlands and associated systems. Proceedings of the National Symposium on Wetlands, American Water Resources Association.

Meeter, D. A., R. J. Livingston, and G. Woodsum. 1979. Short and long-term hydrological cycles of the Apalachicola drainage system with application to Gulf coastal populations. In *Ecological processes in coastal and marine systems,* ed. R. J. Livingston. New York: Plenum Press.

Prospects for Coastal Resource Conservation in the 1980s

by John Clark and Scott McCreary

Ten years have passed since Congress first proposed a National Estuarine and Coastal Management Act. Although this act failed, a second effort in 1972 produced the Coastal Zone Management Act (CZMA), which cleared Congress on October 12 and was signed into law a few days later. Although the CZM program failed to focus on estuaries and general resource conservation, it did provide federal assistance to the states so they could better deal with burgeoning coastal development pressures. Nineteen states entered the program and, with a great variety of approaches and degrees of success, are now regulating coastal development, coordinating governmental activities, providing technical assistance to cities and counties, or operating sanctuaries.

Those who were involved in the formulative period of the 1960s and the legislative period of the 1970s are now considering the prospects for the 1980s. How well has the CZM program saved the coast and protected its rich resources? How have the hopes of the 1960s been matched by the actions of coastal bureaucracies in the 1970s? What refinements can be expected in the 1980s?

In evaluating the CZM program, it is important to consider the progress made in creating programs that manage unit resources systems, particularly estuarine ecosystems. Our use of "unit resource management" refers to mechanisms that effectively couple the land side together with the water side, thereby managing a unified zone of watershed, shoreline, and waterbody. This has turned out to be a tough order for Coastal Zone Management because the vast land areas of the watershed that discharge directly to estuaries are mostly privately owned and are regulated by land-use powers of local governments, not states. But devastating pollution of estuaries from watershed runoff and loss of vital river inflow from upstream diversions are recurring problems that should logically fall under the heading of coastal protection. Land runoff is only one problem for managers of the nation's remaining productive estuaries. Other real threats lie outside the scope of traditional land-use planning: elimination or degradation of adjacent wetlands or submerged grass beds, obstruction of inlets and internal water flows, discharge of industrial waste or sewage, and dredge destruction of critical shellfish beds and other bottom habitats. Both the complexity and

Outer Banks near Cape Hatteras, North Carolina. (Photo by Bruce Roberts, PR)

vulnerability of estuarine ecosystems are depicted in Figure 1. Disruption of any one of the major driving forces of the ecosystem can quickly reduce its productivity.

In reviewing CZM programs and postulating future directions, we considered four approaches used by the states to launch their CZM programs. These included preparation of a coastal atlas coupled with voluntary guidelines, coastal permitting, land-use planning, and special-area protection. By briefly examining each style of CZM, we see how states approached pieces of the unit resource management puzzle. Programs divided up the coastal zone:

- *in space, by the size of the zone and the amount of "wet side" and "dry side" included.*
- *in time, by only considering new projects as opposed to existing problems in the coastal zone.*
- *by the level of analysis (single permits as opposed to anticipating cumulative impacts*

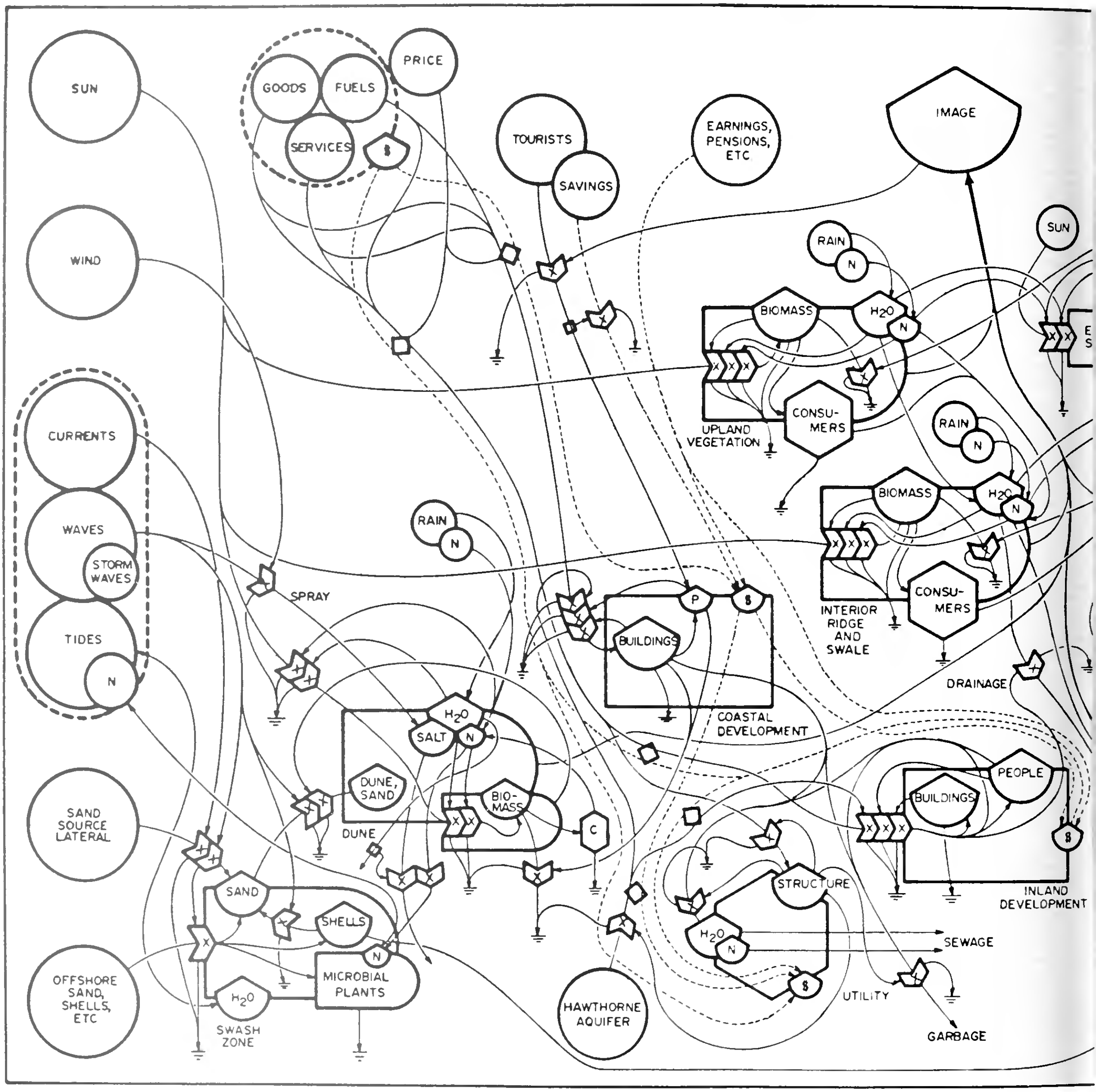
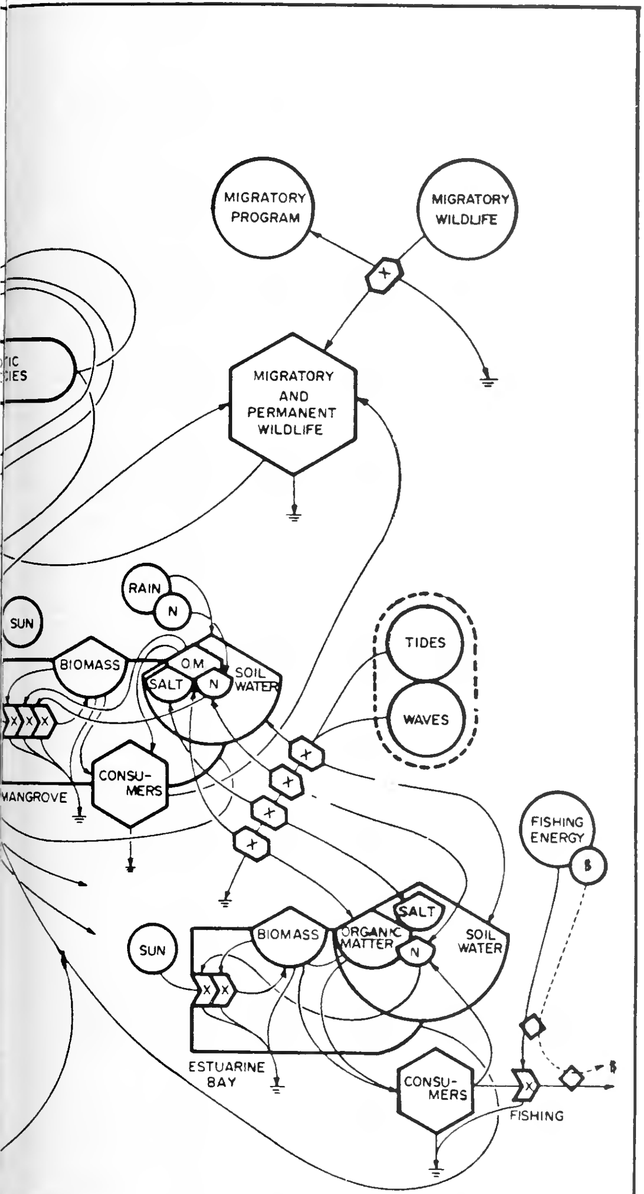


Figure 1. Coastal managers are faced with the problem of managing one of the most complex ecologic-social-economic systems, as demonstrated by the energy diagram of an estuarine ecosystem constructed by Mark Brown at the University of Florida.

by preparing special land-use plans for the coastal zone).

- *by jurisdiction (the levels of government involved and their degree of responsibility).*

In addition, we took a closer look at three ecosystems for which unit resource management has met with varying degrees of success — the White Oak Estuary in North Carolina, Elkhorn Slough in California, and Apalachicola Bay in Florida. Each holds lessons for other areas — both through past successes and failures — and each indicates cause for hope in the pursuit of coastal zone management that protects whole ecosystems. Our conclusions reflect the precedents we see taking hold, as well as the influence of new trends impinging on CZM.



Different States Try Different Approaches

Two states, Florida and Texas, produced elaborate coastal atlases while developing their programs. Derived from "environmental suitability" methodologies developed shortly after the passage of the National Environmental Protection Act, the atlases are based on the premise expressed in the Texas document: "Through inventory and evaluation of coastal zone resources, environments, and land and water uses, programs can be established that will permit use of natural resources and maintenance of environmental quality by adjusting use to resource capability." In each case, a large array of data on soils, geology, vegetation type, and valuable species habitats is presented, along with overlays showing combinations of resources. A weighting and scaling procedure allows the user to assign levels of vulnerability or sensitivity, and a set of table or matrices helps the user predict environmental consequences of projects located in the sensitivity zones. The atlases were exemplary in explaining the coastal zone through an understanding of natural systems, but the data were largely unconnected to either a set of adopted policies or a procedure for translating goals into action.

Coastal permitting, including case-by-case review of development proposals, has been a standard approach for resource planning. California and New Jersey are among the states that have adopted this strategy as part of their coastal programs. In California, permitting for the 100-foot margin around San Francisco Bay dates back to 1965 when the Bay Conservation and Development Commission began to approve or deny projects that would fill the bay bottom or block public access. In 1972, a citizen initiative — Proposition 20 — set up a statewide program of permit review for an unusually broad coastal zone varying in width from 1,000 yards to 5 miles, depending on the configuration of the coast. Between February 1, 1973, and the end of 1976, the state administered a permit system that for scope of coverage and strictness of standards is without precedent in the nation's short history of direct state involvement in land-use control. The regional commissions evaluated some 24,825 applications.

New Jersey opted for state permit control over key decisions on coastal development, using the Coastal Area Facility Review Act (CAFRA), the Wetlands Act, and other waterfront protection statutes. A separate authorization from the Department of Environmental Protection is required to build power plants or housing facilities (CAFRA permit); bridges spanning marsh areas (wetlands permit); and bulkheads, groins, and jetties (waterfront development permit). There can be little doubt that the California and New Jersey programs did a good job of holding the line. But even 25,000 permits do not reflect the "big picture" — especially where the coastal zone is usually less than 1 mile wide.

Land-use planning and zoning to regulate the "dry side" of the coastal zone, or some portion of it, are at the center of many CZM programs. North Carolina and California have used this approach, each delegating considerable responsibility to local jurisdictions. North Carolina operates a "two-tier" regulatory program. The first tier consists of nearshore and estuarine waters, saltwater wetlands, beaches, and primary dunes, which collectively are designated as the Area of Environmental Concern. The second tier is the remainder of the area in all coastal counties. Local governments are responsible for drawing up land-use plans for both tiers according to state guidelines. In the first tier only, the state exercises ultimate authority (by permit).

California's requirement that all 68 coastal cities and counties draw up a Local Coastal Program (LCP) is the basis for the most ambitious state coastal management program with land-use planning at its heart. Consisting of a land-use plan and zoning regulations, these LCPs reflect the state policies on public access, water and marine resources, land environments, new development, ports, and energy facilities. Although the State Coastal Commission has been responsible for drafting guidelines and reviewing draft LCPs for consistency with state policies, local governments have the opportunity of making choices about which goals to emphasize. Some cities and counties embraced the opportunity and prepared first-class plans. Others resisted. Given the scope of the planning effort, and the hostile reaction of many jurisdictions to the recent history of state regulation of the coast, it is not surprising to find the Commission forecasting that some 33 land-use plans and 73 zoning regulations would lag behind the target date for completion by December, 1980. Even where sound LCPs have been drawn, there is real doubt about the ability of local governments to administer the plans. Two major problems are a lack of expertise in natural resource-based planning and considerable uncertainty about how far to go with regulation.

White Oak Estuary

The gaps left by a well-designed coastal regulation program are further illustrated by the plight of the White Oak Estuary in North Carolina, a state that operates both a permit process and a procedure for local preparation of land-use plans. One of 14 rivers flowing to meet the Atlantic within the borders of North Carolina, the White Oak broadens from a narrow, twisting channel to form a well-mixed estuary at sea level near the City of Swansboro (Figure 2). Turbidity reaches its maximum near the freshwater/saltwater interface. High rates of sedimentation are caused by inward transport of sediments from the ocean, flocculation, or river-derived sediments, and the convergence of river and tidal currents.

Intense local concern has been generated by the rapid shoaling of the estuary, a major impediment to boating and a real threat to the viability of once-productive oyster beds. People near Swansboro have implicated two major construction projects: dredging of the Intracoastal Waterway (and accompanying soil disposal) perpendicular to the natural flow of the river, and emplacement of a dirt-fill causeway extending one mile into the White Oak. Compounding these changes in natural flow have been mosquito-control projects, gravel mining, and agriculture in the watershed.

Local interests in Swansboro have had access to the coastal agency permit procedures, but these are designed to govern only new development. Both counties bordering the river are eligible to prepare coastal land-use plans under state guidelines, but controlling land use will not correct the problem. And when approached for assistance, the U.S. Army Corps of Engineers explained that they could not even study White Oak without congressional approval. This year the first real progress was made in getting politicians and federal agencies to take notice. Backed by the local weekly newspaper sporting a banner headline "Study the White Oak: Week 15," the Conservation Foundation convened local officials, fishing interests, and conservation groups. Managed by a professional mediator, the meeting resulted in consensus on three points: forming of a White Oak advisory council, applying for a grant to study the basic causes of the river's problems, and retaining nearshore process specialist Miles Hayes.

The Office of Coastal Zone Management (OCZM) initially balked at the proposal, seeing it as yet another data-gathering effort unrelated to management. With support from the state and two congressional representatives, the study concept is moving toward federal approval. Depending on the outcome of the investigation, management solutions could include corrective dredging of flow ways, redesign of causeways, and pollution control in the watershed.

Statewide mapping and inventory by themselves rarely succeed in accomplishing conservation goals. State permit programs are not sensitive to the needs of particular local resource systems, do not cope with the accumulating impacts of continuing development, and tend to deal with fragments rather than whole systems. Land-use planning is notably weak in generating tough management to follow through. Although these are necessary components of a resource management program, we believe that another component — special-area management — holds the strongest promise for conservation of estuaries and other unit resource systems. We believe, therefore, that the CZM emphasis in the 1980s will shift toward unit resource management with an increasing role for local governments.

Special-Area Management

Management of unit resources, or special areas, is necessary because statewide approaches are too

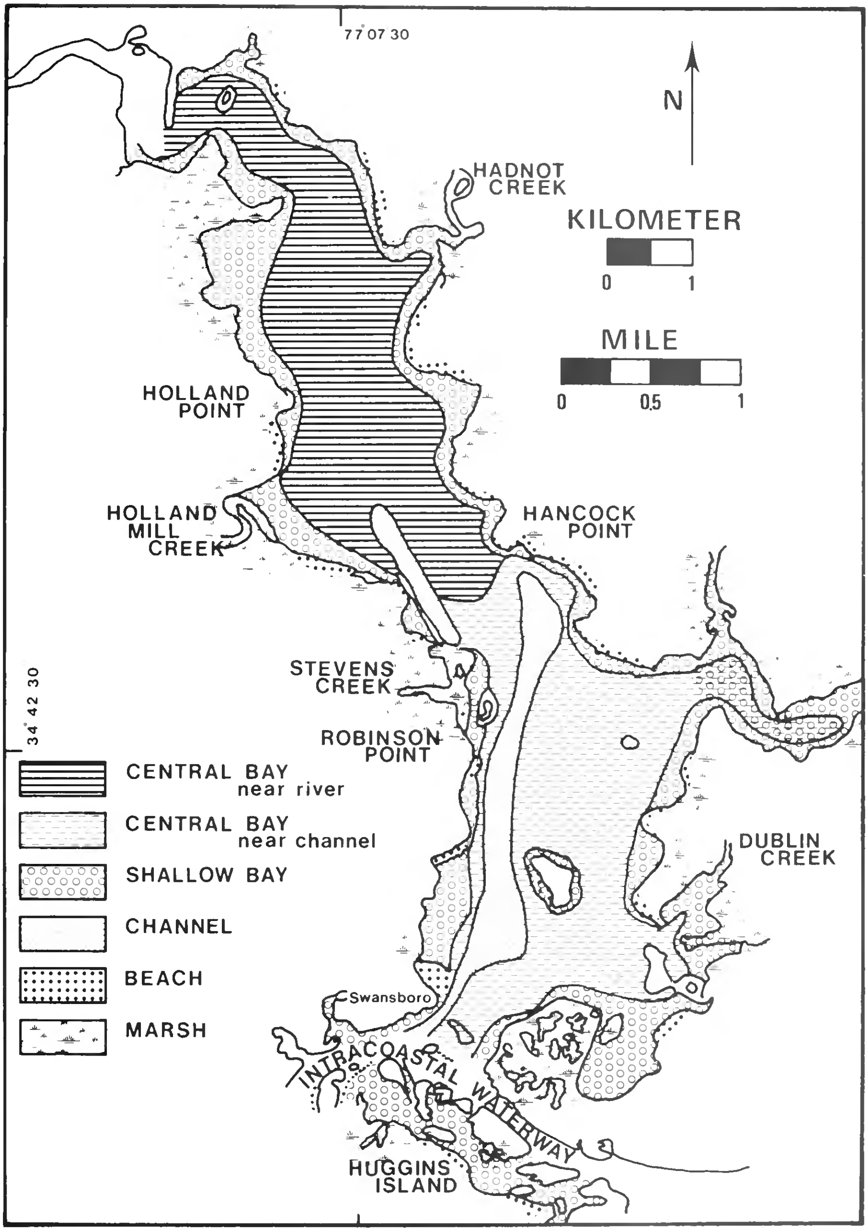


Figure 2. Sedimentary environments for the White Oak River Estuary. After an environmental mediation exercise, the first steps toward unit resource management are being taken for the White Oak River Estuary. A preliminary study will examine the causes of rapid shoaling that has wiped out productive oyster beds and impeded navigation. Management solutions may include corrective dredging of flow ways, redesign of the causeway, and better control of pollution and sediment in the watershed.

Source: Howard A. Bernstein, Modern Sediments of White Oak River Estuary, North Carolina, *Chapel Hill, N.C.: Thesis, Department of Geology, University of North Carolina, 1977.*

generalized and too rigid to meet the specific and unique conservation needs of any particular coastal resource system, such as an estuary. Many states are experimenting with special-area management programs but none has reached the point of embracing whole coastal resource systems short of outright purchase, an expensive and generally unpopular approach.

Florida uses the mechanism of aquatic preserves to conserve estuaries. Each of the 34 designated preserves is treated as a special case. The boundaries typically encompass submerged bottom lands, the water column over the lands, and islands owned by the state. But the preserves are not coupled systems; they are limited to the water side of the coastal zone and thus are separate from management of the adjacent wetlands and upland watersheds that drain into preserve waters.

Hawaii's Natural Area Reserve System, empowered by the state legislature, has carried special-area management a step further by spanning land and water sites. The Ahihi-Kinau Reserve takes in Maui's most recent lava flow, the diverse inshore reef ecosystems in a portion of La Perouse Bay, and unusual terrestrial "mixohaline" ponds (habitats for rare invertebrates). The Hawaii approach stops short of managing the entire Bay and watershed; instead the most unusual portions of the ecosystem are singled out for strong protection.

Many other states have experimented with "critical area" designations whereby private landowners are constrained from certain environmentally damaging activities. The federal government, too, is testing "less-than-purchase" approaches to conserve resource units; for example, the Santa Monica Mountains (California) and the Pineland Reserves (New Jersey) enacted by Congress in 1978 and managed by the National Park Service. These will have spinoffs useful to coastal unit resource management programs. But probably the most relevant experience is the estuarine sanctuary program.

Authorized by Section 315 of the Coastal Zone Management Act, the estuarine sanctuary program provides matching grants to states to acquire, develop, and manage natural estuarine areas as sanctuaries. Responsibility for the details of sanctuary management rests with states. A principal goal is to give scientists and students an opportunity to examine the ecological relationships within these areas over a period of time.

Two major benefits are conferred by the designation of sanctuaries. First, they provide a representative series of natural ecological systems, intended to remain available in perpetuity. Second, they ensure the existence of a natural control or "base case" against which impact of human activities in other areas can be assessed.

Between 1974 and the present, nine estuaries have been elevated to sanctuary status. Paperwork for the most recent addition, Narragansett Bay (Rhode Island) was completed on September 30 of this year. The OCZM anticipates that a minimum of 21 sanctuaries will be necessary to represent the 11 biogeographic provinces and their distinct subcategories. A second goal is to designate 34 sanctuaries, making it possible to have two or three estuaries in each province.

Elkhorn Slough

Although not large and impressive by East Coast standards, nor entirely pristine, Elkhorn Slough Estuarine Sanctuary in Monterey County, California, is an important component of the state's overall CZM efforts (Figure 3). One of the largest remaining estuarine systems in a state once bent on filling, diking, or draining all such ecosystems, Elkhorn Slough includes sand and mud bottoms, open water, 770 acres of "fully tidal" *Salicornia* marsh, and 670 acres consisting of diked marshlands, and a mosaic of salt ponds, dikes, and levees. The slough is used by more than 100 species of migratory birds, and it harbors juveniles of commercially important fish and provides a habitat for the endangered California Clapper Rail and Brown Pelican. The general thrust of the sanctuary proposal was to acquire knowledge of land use in the watershed, which includes principally agricultural and small ranches (ranchettes), and to secure the future of the Slough as a prime research site for Moss Landing Marine Laboratory and the University of California. Land acquisition through the sanctuary program has been designed to complement existing Nature Conservancy holdings and proposed acquisitions by the U.S. Fish and Wildlife Service. The sanctuary should also benefit from a program of land regulation based on watershed characteristics, now being finalized by the county.

The process of setting up the framework for this watershed program illustrates the political complications associated with designing a management program that truly reflects natural ecosystems. The apparent topographic watershed, measuring about 70 square miles, includes the agricultural foothills of North Monterey County, and is included in the coastal zone. But Elkhorn Slough also includes Moss Landing Harbor and three tributaries: Moro Cojo Slough, Tembladero Slough, and Bennett Slough. These, in turn, collect runoff from about 226 square miles of watershed, including portions of Salinas, an island city of 75,000, and San Benito County — a landlocked jurisdiction. Even in California, placing such areas under the sphere of coastal regulation is an untenable proposition.

Elkhorn Slough offers additional insights for watershed-based coastal management. The staff of the Central Coast Regional Commission, seeking administrative simplicity in their permit-review activities, designated watershed areas based simply on their relation to the slough itself. Those slopes draining directly into the slough became "critical," those that discharged into the network of second- and third-order perennial streams became "secondary." A more rigorous analysis, carried out by a Sea Grant sponsored planning team at the University of California, Berkeley, identified more than 35 subwatersheds, each with its own mix of slope, cover type, and soil characteristics. An understanding of these subwatersheds and their hydrologic connection with the slough will provide a more accurate technical basis for resource management and land planning under Monterey County's Local Coastal Program.

Apalachicola Bay

Apalachicola Bay, in Florida, exemplifies an opportunity to provide well-informed management to each component of an estuarine system (see page 14). To appreciate the complexity of this task, we must consider the components of the resource. The coastal basin, Apalachicola Bay, is shallow with an average depth of about 3.5 meters; the bottom varies from coarse sand to fine mud. Oysters occur in concentrated reefs; submerged grass beds occupy more than 20,000 acres of the bay. Crabs, fish, and shrimp move between the bay and the ocean, using the inlets as major pathways; and all three use this bay as a major nursery area, as they do in so many estuaries of the Gulf of Mexico.

The bay receives runoff from the 19,500-square-mile watershed drained by the Apalachicola–Chattahootchee–Flint river system. The terrain embraced by the upper watershed is a mixed forest area, with pine plantations for pulpwood culture, some urban areas (including Atlanta, Georgia), and limited agriculture. The lower portion of the watershed flows through six lightly developed Florida counties.

The Apalachicola River runs free from the Jim Woodruff Dam and navigational locks at the Georgia border. It widens after it is joined by the Chipola River and becomes tidal and increasingly saline. A network of sloughs leads back into the hardwood floodlands that are inundated each year. When they drain, great quantities of leaf detritus are carried downstream to enrich the bay.

The transition area surrounding the coastal basin varies from swamp to marsh to poorly developed dunes formed along low-energy beaches. Tidal amplitude is less than one meter. Flood risk is substantial during hurricanes, when large portions of the roadway are inundated well before landfall.

The water component of the system includes the brackish part of the Apalachicola River and the Bay proper. The salinity gradient, a function of the pulsed river flows that also import nutrients and detritus, together with the vast marshes, grass beds, and oyster bars, account for the enormous productivity of the seafood resource. More than 2.5 million pounds of oysters and 3.5 million pounds of shrimp are harvested annually, providing jobs for

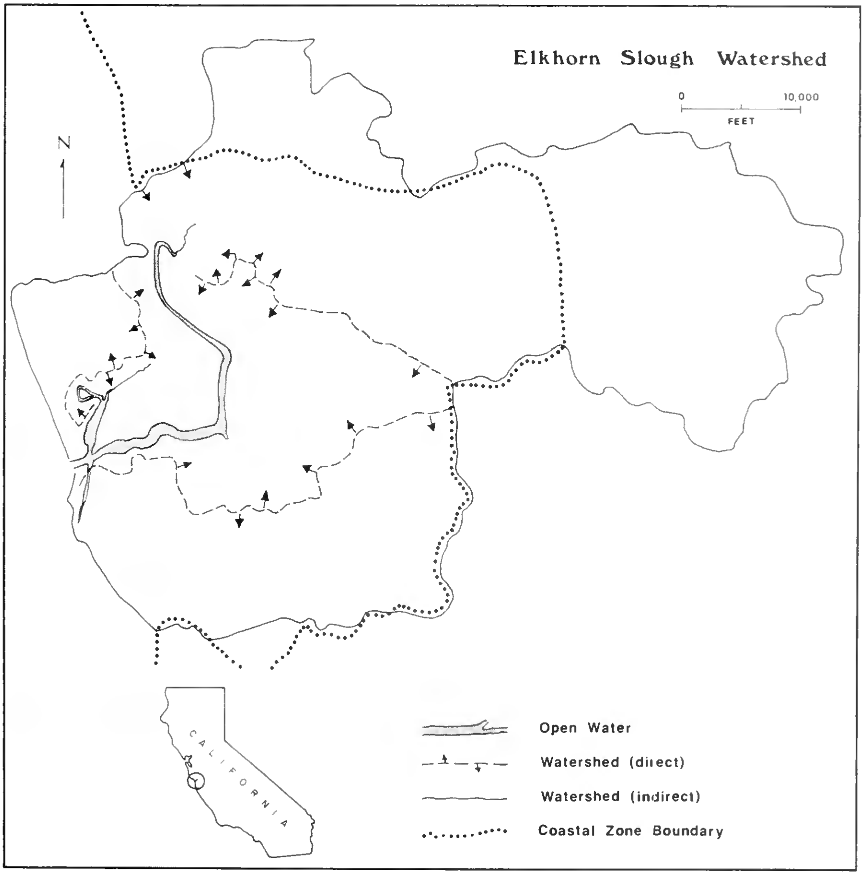


Figure 3. California is moving to protect one of its most important resources: the marshes, mudflats, and open waters of Elkhorn Slough. With the help of the Federal Sanctuaries Program and a "bump" in the state's coastal zone, both the watershed and the slough will be the subject of special management. Runoff from agricultural lands around the perimeter of the slough finds its way directly into the system; rain and irrigation water in the indirect watershed deliver runoff into the estuary via a network of small streams.

about 60 percent of the local work force. Although industrial pollution is not a factor, high coliform counts have plagued the oyster industry. A variety of causes are suspected, including upriver agriculture, inadequate sewage treatment plants, and poorly sited septic tanks.

The ocean component interacts via three inlets (two natural and one man-made) through and around the outer boundary of the barrier islands. Like all barrier islands, those on Apalachicola Bay have adjusted their configuration in response to energy stresses. Since the mid-1850s, 12 significant hurricanes have struck this coast, causing breaching and overwash in several places. As development pressure picks up on the barrier islands, protecting natural storm buffers and guaranteeing safe evacuation become essential.

In October, 1978, the Conservation Foundation convened a workshop of 35 scientists representing a wide spectrum of disciplines to offer a plan for designation of the Apalachicola system as a national estuarine sanctuary. This workshop produced a series of research priorities and recommendations for management of the sanctuary.

In 1980, the Conservation Foundation carried its recommendations forward into the implementation stage. Working in a partnership with Franklin County and the Regional Planning Agency, a shoreline development strategy will address each resource component in the Apalachicola River and Bay ecosystem. A special ordinance has been passed to prevent sand dunes from being leveled on the barrier islands and beaches and to require special building standards in flood-prone areas. Hurricane evacuation is being linked to new growth in that it limits the number of new residential units to 120 annually. A critical shoreline protection zone, 150 feet wide, has been proposed for the perimeter of the Bay, to protect the water quality of Apalachicola and ensure a margin of safety in coastal development. This protective band will subject new houses and businesses alike to stringent controls on septic tanks and removal of vegetation, thereby helping to secure 90 percent of Florida's remaining oyster fishery. All shoreline structures, including docks and bulkheads, will be subject to permit review to make sure they do not damage grass or oyster beds.

A watershed management subcommittee will be convened through the local planning board and the Estuarine Sanctuary Committee to promote discussion between paper companies and seafood interests, intended to improve forestry practices throughout the county. Special attention is being directed at the seafood industry through creation of a Maritime Commercial Zone. Land uses dependent on direct water access will be favored, and realistic standards will be prepared for hurricane safety and water-quality control.

A followup effort is contemplated to link land regulation ordinances with the acquisition and management goals of the sanctuary. A special focus will be techniques of land preservation that acquire development rights at less than the cost of outright land purchase (less-than-fee purchase).

Estuarine sanctuaries can be showcase examples for management of entire coastal resource units. But if the concept is sound, why restrict its application to just 21 or 34 places on the coast? We should insist on pristine conditions, a history of ecological research, and a demonstrated commitment to future investigation for the "best" estuaries, but such requirements effectively exclude most of the nation's 300 or so important estuaries. If an estuarine system is not pristine, that is even more cause for creative management. We believe that each deserves a customized, locally crafted plan that encompasses preservation of water quality and habitat integrity, watershed management, shoreline structures, hazard management, and social concerns — including public access.

The 1980s

The flourishing of resource unit management at the grass roots, exemplified by experience with Elkhorn Slough, Apalachicola Bay, and the White Oak Estuary, will continue in the 1980s. Before the decade is over, we expect to see dozens of examples. Management goals will vary, just as uses and geographic settings vary between a San Francisco Bay and an Apalachicola Bay, but essential features will include:

- *Cooperation and mutual support of local, state, and federal agencies.*
- *Local participation backed by "imported" technical assistance.*
- *Linking of "wet-side" (bay bottoms, water columns), immediate shoreline, and important uplands in planning, regulation, and acquisition.*
- *Management principles that take into consideration the long-term, cumulative impacts of new development and restoration of previously inflicted damage.*

Efforts to guide the use and protection of coupled land and water systems have implications for the organization of state-local relations, the role of applied science in decision making, the types of issues considered in coastal planning, and the style of public participation.

Coastal permitting and land-use programs should continue, with some probable retrenchment as to the types and intensities of uses that fall subject to coastal review. State coastal management offices will develop and expand their capabilities to provide technical assistance, and will direct more of this expertise to implementation rather than survey and reconnaissance work. Special positions may be established for advisors to local governments for issues such as wetlands and watershed management, regulatory techniques, hazard mitigation, and siting of energy facilities.

The role of scientists as technical advisors will expand as coastal management goes beyond land planning and permitting to deal with larger resource units. However, OCZM's reaction to the White Oak Estuary proposal should be regarded as something of a precedent: scientific study must be directly related to management to stand a good chance of CZM funding. The implications for scientists are significant in furthering the cause of unit resource management; they may be asked to step beyond the confidence limits of their data and exercise professional judgment — essentially acting as analysts or planners.

Energy — the most difficult environmental problem of the 1980s — must enter consideration in unit resource management. In many communities, the issues of offshore oil development and energy facility siting already dominate coastal land-use planning and resource protection. Broad public and agency opposition to Lease Sale No. 53 on California's outer continental shelf was couched in terms of both the risks to natural resources and the relation of sale No. 53 yields to regional energy demand. On the Atlantic coast, refineries proposed for Hampton Roads and Pittston have been cross-examined for their possible impacts to critical marine and estuarine resources. But opponents of refineries also question whether additional refining capacity is needed, pointing out that American refineries now operate at just 75 to 80 percent capacity. In the San Francisco Bay area, Pacific Gas and Electric withdrew a proposal to site a power plant on Suisun Marsh, until 1983. Conservation in Bay Area communities had wiped out the projected increase in demand to be served by the new facility.

In the very near term, communities will ask utility companies to look harder at substitute supplies before proposing centralized power plants, refineries, and drilling in sensitive areas. Although coastal protection and energy conservation were once regarded as largely separate issues, we believe that competent coastal resource planning will strengthen the push toward decentralized alternative supplies and a greater reliance on conservation.

We believe that the concept of unit resource management can only work with sustained and genuine participation by the public. And mediation — the practice of convening opposing parties in an environmental dispute with a neutral mediator to reach consensus — will play an increasingly prominent role. Mediation will not only resolve tensions between local developers and conservation interests but should also be used to catalyze interagency agreements on joint studies or management goals. The promise of coastal zone management has traveled a rough road in the 1970s. The 1980s are the years to turn promises into practical realities.

John Clark is a Senior Associate of the Conservation Foundation, Washington, D.C., and Director of its Coastal Resources Program. Scott McCreary is an Associate of the Foundation in its Coastal Resources Program.

Selected References

Armstrong, R. 1980. White Oak River dying. *Tideland News*, Swansboro, North Carolina. February 20, pp. 1-4.

———. 1980. Congressmen support river study. *Tideland News*, Swansboro, North Carolina. March 12, pp. 1-2.

Brown, L.F. et al. 1980. Environmental geologic atlas of the Texas coastal zone, Brownsville-Harlingen area. Bureau of Economic Geology, The University of Texas at Austin.

Browning, B.M. et al. 1972. The natural resources of Elkhorn Slough — Their present and future use. California Department of Fish and Game, Coastal Wetland Series No. 4, Sacramento.

California Coastal Zone Conservation Commission. 1975. *California coastal plan.*

Dickert, T., and J. Sorensen. 1978. *Collaborative land use planning for the coastal zone.* Vol. I. A process for local program development. Berkeley: Institute of Urban and Regional Development, University of California.

Healy, R.G. 1978. The role of the permit system in the California coastal strategy. In *Protecting the golden shore: Lessons from the California coastal commission.* Washington, D.C.: The Conservation Foundation.

Ketchum, B., ed. 1972. *The water's edge: Critical problems of the coastal zone.* Cambridge, Mass.: MIT Press.

Madrone Associates in Association with Jones and Stokes. 1979. Pre-acquisition study: Elkhorn Slough. Prepared for the California Department of Fish and Game.

Odell, R. 1972. *The saving of San Francisco Bay: The role of citizens in environmental planning.* Washington, D.C.: The Conservation Foundation.

United States Department of Commerce, NOAA. 1978a. Final environmental impact statement: State of Hawaii coastal management program.

———. 1978b. Final environmental impact statement: State of North Carolina. Washington State Department of Ecology. 1976. The Washington coastal zone atlas: An overview.

———. 1980. Final environmental impact statement: Elkhorn Slough estuarine sanctuary.

Templates of Change

by Robert Dolan and Bruce Hayden

Coastal inhabitants face two types of storm hazards. The most extreme is typified by Hurricane Allen, the first tropical storm of the 1980 season. Allen devastated a relatively small coastal area in the vicinity of the storm's landfall near Brownsville, Texas. The second is associated with winter frontal cyclones, frequently called northeasters. The Ash Wednesday storm of 1962, a model of the severest kind of northeaster, caused property damage amounting to more than $500 million (1962 dollars) along the Atlantic coast. Thirty-two lives were lost. Damage was reported from North Carolina to New York.

Much of the property damage and deaths during hurricanes and northeasters occur on the barrier islands that rim the Atlantic and Gulf coasts of North America (Figure 1). The risk of living on barrier islands has changed over time as a result of the historical variations in storm frequencies and because shoreline erosion constantly makes property that is close to the sea more exposed to the perils of high waves and storm surge.

Storm frequencies off the mid-Atlantic coast increased almost fourfold between the turn of the century and the 1960s (Figure 2). This trend is seen from Miami to Maine and, to a lesser degree, along the Gulf coast. Coastal property damage resulting from storms during the years 1921 to 1966 was analyzed by John Mather of the University of Delaware. (We updated this record and have included it in Figure 2.) Mather attributed the trend toward greater frequencies of damaging storms to lower central pressures and increased coastal development. It appears, however, that the increase also may reflect an overall change in the number of storms. Although the increase in storm frequency is out of phase with the reported warming and cooling in the Northern Hemisphere, it is in phase with the changing patterns of westerly winds across the North Atlantic.

The trend in increased storm frequencies parallels that of increased storm damage reports. Our studies indicate that between 1920 and 1975, severe storms became more frequent, whereas the number of modest storms remained unchanged. The average storm duration and the length of the winter storm season both increased. The National Oceanic and Atmospheric Administration (NOAA) reported that sea level along the Atlantic coast rose one foot during the same period.

The storm-related hazard of living on the coast was rather modest at the turn of the century, when the first resorts developed and when few people were permanent residents. Since World War II, there has been a marked increase in the frequency of hazardous events and an explosive growth in resorts, second homes, and permanent residences on barrier islands. Today, beachfront property is poised dangerously close to the sea, in part because of the desire for an ocean view and, in

Storms and Shoreline Hazards

part, because of decades of shoreline erosion. Even if storm frequencies return to the lower levels typical of the earlier decades of this century, the risk will remain high for property owners close to the sea.

Patterns of Storm Damage

Barrier island formation has been debated among coastal geologists for many years. There is, however, indisputable evidence that most of the Atlantic coast barrier islands are migrating toward the mainland, some more rapidly than others. Peat deposits and tree stumps, remnants of old forest stands on the back sides of the islands, are often found on open-ocean beaches, indicating marine transgressions. Overall island recession also can be measured from historical maps and aerial photographs.

Shoreline changes along sedimentary coasts vary with the kind and size of sediment within a coastal segment, the frequency and magnitude of hurricanes and northeasters that modify the sand deposits, and the stability of sea level. These factors also are related to the geological origin of the barrier islands.

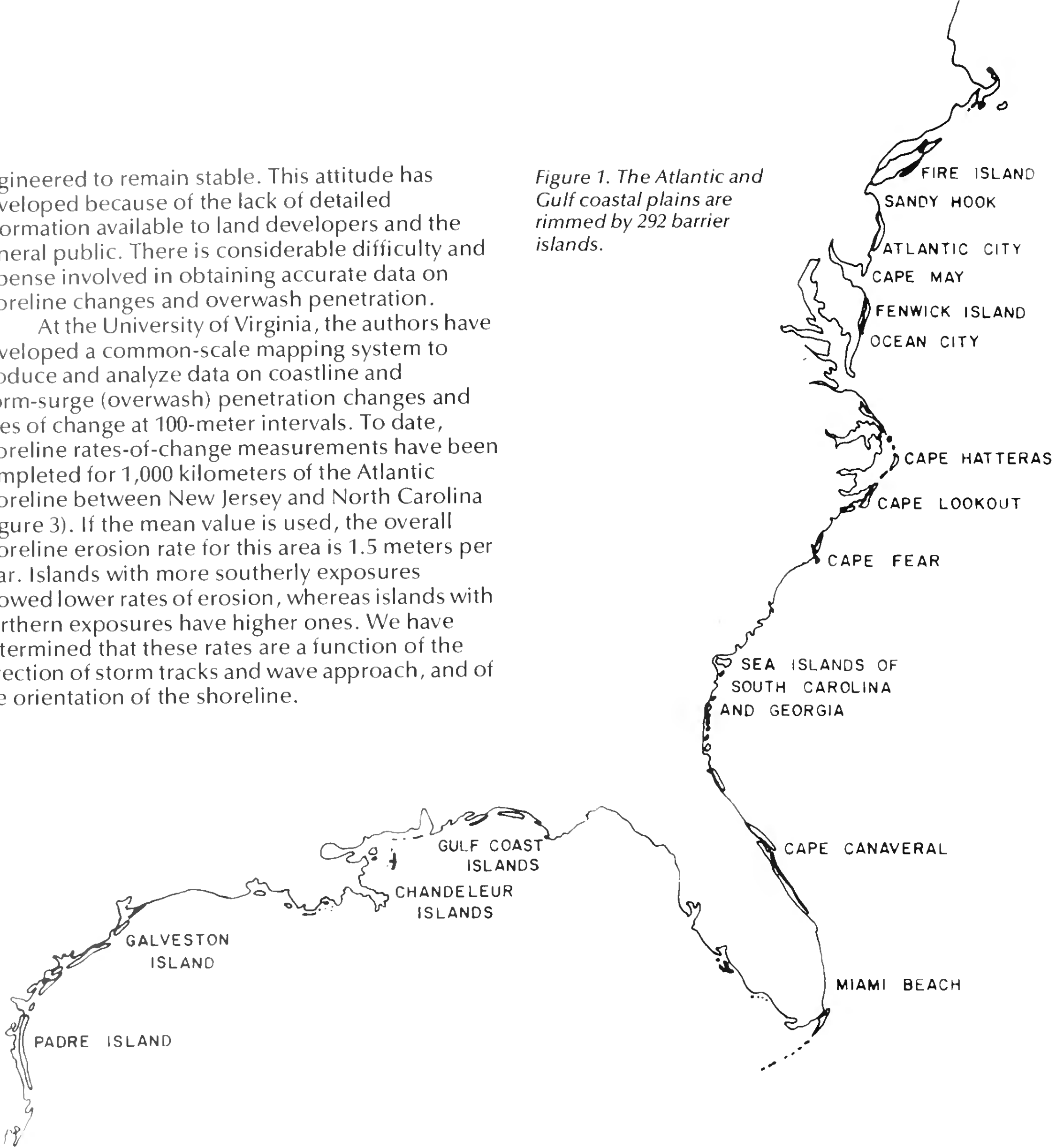
The dominant events of the landward movement of barrier islands are overwash and inlet formation (see page 4). During severe storms, the beach zone and seaward dunes are overtopped by high water levels and waves. This sediment-charged mass of water spills across the beach and flows toward the bays and sounds on the inland margins of the islands. A layer of sediment is removed from the beach and added to the island's interior. This process, repeated over many storms, transforms the shape and position of the island, but the total mass of sediment tends to remain the same.

Even though the long-term trend of barrier-island migration and the effects of periodic storms are now well known — regular warnings and cautions are issued by NOAA, the Department of the Interior, and the U.S. Army Corps of Engineers — coastal-zone planning and development are largely based on the concept that beaches and barrier islands, like other landscapes, can be

At left, NASA's Goes East satellite captures immensity of Hurricane Allen in the Gulf of Mexico. Photo was taken on August 8, 1980. Note satellite photo also captured Hurricane Isis, which was in the Pacific Ocean at the time. (Photo courtesy NASA). Right, hurricane winds attack palm tree along coast. (Photo by William M. Stephens, PR) engineered to remain stable. This attitude has developed because of the lack of detailed information available to land developers and the general public. There is considerable difficulty and expense involved in obtaining accurate data on shoreline changes and overwash penetration.

At the University of Virginia, the authors have developed a common-scale mapping system to produce and analyze data on coastline and storm-surge (overwash) penetration changes and rates of change at 100-meter intervals. To date, shoreline rates-of-change measurements have been completed for 1,000 kilometers of the Atlantic shoreline between New Jersey and North Carolina (Figure 3). If the mean value is used, the overall shoreline erosion rate for this area is 1.5 meters per year. Islands with more southerly exposures showed lower rates of erosion, whereas islands with northern exposures have higher ones. We have determined that these rates are a function of the direction of storm tracks and wave approach, and of the orientation of the shoreline.

Figure 1. The Atlantic and Gulf coastal plains are rimmed by 292 barrier islands.



This data base also can be used to predict future positions of the shoreline and the landward limits of overwash damage zones, based on the assumption that recent history (the last 30 to 35 years) is the key to the future. The landward limit of the shoreline can be predicted on a probabilistic basis using the mean rate-of-change data and variance. At a 50-percent probability level, the change in the position is the product of the mean rate of shoreline change times the defined interval of time. Shoreline positions at other probability levels also may be calculated using appropriate fractions of the variance of the mean rate of change. A similar procedure gives estimates of the change in the position of the landward limit of storm-surge penetration.

Using this approach, the authors have studied the hazards of erosion and the danger of destructive storm-surge penetration for most of the mid-Atlantic barrier islands. We have learned that

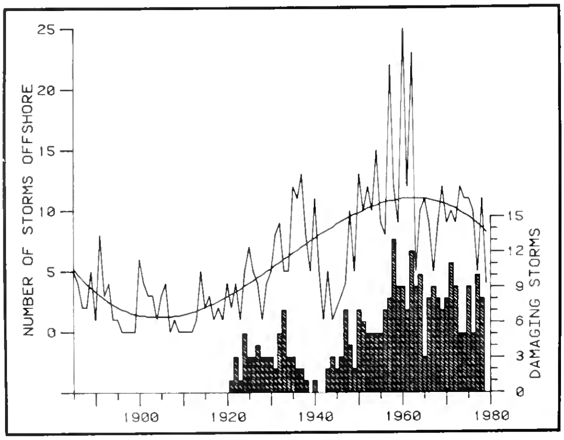


Figure 2. The number of storms passing through a 2½-degree latitude by 5 degree longitude area off the North Carolina coast and the annual number of damaging storms reported for the entire Atlantic coast.

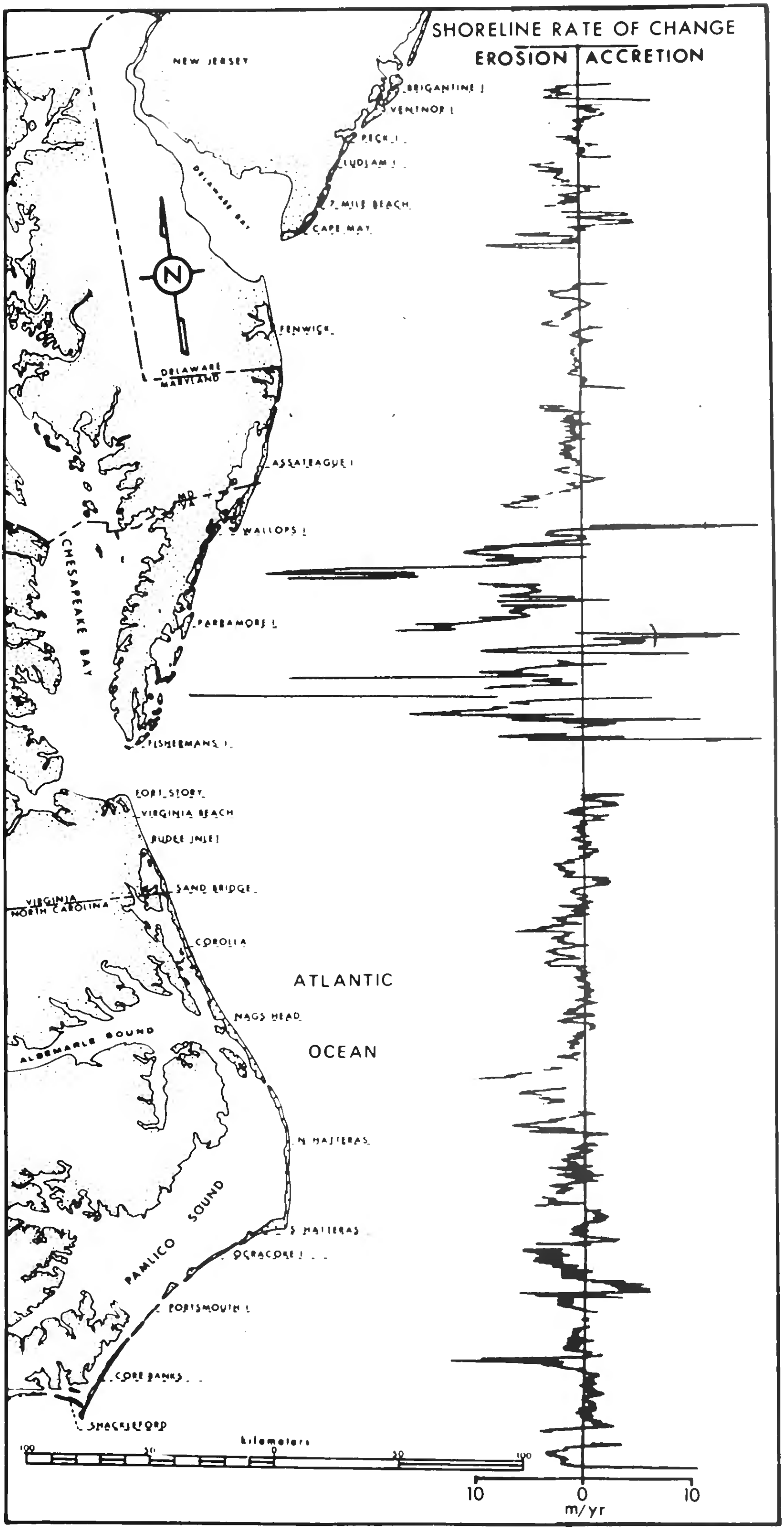


Figure 3. The pattern of shoreline changes at 100-meter intervals along 630 kilometers of the mid-Atlantic coast. Even at this scale, one can see broad patterns that appear to be related to the orientation of the islands relative to the tracks of northeast storms.

storm-surge damage on the barrier islands increases in proportion to the magnitude of shoreline erosion. One hazard is, in part, a function of the other. This has caused problems for the people responsible for estimating the risks of living on a barrier island.

Aerial photographs taken soon after the Ash Wednesday storm show the spatial pattern of storm-surge deposits along the Delaware and North Carolina coasts. All sections of the mid-Atlantic barrier islands showed some degree of overwash resulting from the 1962 storm; however, the distance that sand was transported inland varied markedly. Spectral analysis of these storm patterns and for the 40-year averages of erosion rate suggest that along-the-coast periodicities (that is, regular, recurring patterns) exist for both the long-term average shoreline erosion rates and the inland penetration of overwash during a single storm. Along the North Carolina coast from Cape Henry to Cape Hatteras these rhythmic patterns in erosion have wavelengths of 31, 15.5, 5.0, and 2.5 kilometers. In the vicinity of the Corps of Engineers' Coastal Engineering Research Center at Duck, North Carolina, erosion rates are periodic at 3.5- and 2.3-kilometer wavelengths.

One can conclude that the natural configuration of sedimentary coastlines, as determined by shorezone processes, is periodic and crescentic rather than straight. The larger wavelengths (more than 10 kilometers) are less apparent because their curvature is smaller. Thus, their relative amplitude is lower. In analyzing long sections of the coast, the larger features dominate the variance because their absolute amplitude is greater than the smaller crescentic features. However, it is difficult to recognize the larger crescentic forms while strolling along the beach.

In the 1950s, some homes on the Outer Banks of North Carolina were constructed on concrete slabs. They are still there today, having weathered hundreds of storms, including the great Ash Wednesday northeaster. Other houses nearby have long since disappeared. Is the vulnerability of some places along the coast simply a matter of chance or is there a pattern to the hazards? Our research suggests that even at site level scales (100s of meters) shorezone processes and shorezone landforms assume systematic patterns both along and across the coast. This is a departure from the more common conception that coastal change and coastal hazards are random or happenstance events.

If storm hazard zones along the coast are systematically distributed, then they should be predictable. The problem is that detailed historical information for establishing past patterns is not always available. Our research, however, suggests that sections of sedimentary coasts, which have experienced storm damage and serious erosion in the past, are likely to experience more of the same in the future. We believe there is a natural "template of change" that is governed by the coastal configuration, and the location of headlands, capes, and shoals.

The inhabitants of barrier islands thus face a continuing assessment of environmental hazards with their associated risks. This is a complex process. The probability of error is large because of the century-long trends in rising sea level, storm frequencies, shoreline erosion, and increasing residential densities (Figure 4). In addition to confronting the problems of long-term environmental trends, we must gauge the hazards of individual storms. There is no way yet to predict exactly when or where storms will occur. However, this does not mean that we are limited to general assessments of along-the-coast variations in hazard probabilities. Our research clearly indicates that the impact of large and small storms differs more in intensity than in the geography of their impact. The Ash Wednesday storm caused severe erosion and property destruction in the same locations as previous storms of lesser severity. Adjacent standing and destroyed beachfront homes reflect this variation in hazard intensity. The great storms offshore provide the energy for coastal change, but the application of this energy is determined by the regional morphology of the coast. Our "template of change" can be identified from the historical record. We believe it can be applied in evaluating the risks of living near the sea.

Robert Dolan is Professor of Environmental Sciences at the University of Virginia. Bruce Hayden is Associate Professor of Environmental Sciences at the same university.

Figure 4. The Ash Wednesday storm of 7 March 1962 caused millions of dollars in damage along the Atlantic coast barrier islands. However, the damage zones were not randomly distributed. Some areas were severely damaged, whereas others nearby weathered the storms with little damage. (United Press International photo)

Overwash passes reopened by Hurricane Allen, August 10, 1980, in the area north of the South Padre Island, Texas. Note the numerous breaks in the roadway and extensive sand cover. The island responded dynamically to the storm. Static structures would have suffered damage or destruction. (Photo courtesy of Coastal Hazards Program, National Ocean Survey/NOAA)

Barrier Island Hazard Mapping

by Orrin H. Pilkey and William J. Neal

Barrier island dwellers have special problems. A house built on a barrier is subject not only to the undiminished fury of hurricanes and winter storms, but also to many other hazards. For example, houses have fallen into new inlets formed during storms, or they have been destroyed by inlets that slowly migrated toward the houses. Thousands of homes have disappeared from the beach front solely as the result of a gradual erosion of the beach caused by a continuing sea-level rise. Overwash from even minor storms striking at high tide has toppled houses, and marching sand dunes have buried others in short duration.

The list is endless. Clearly a barrier island is a dangerous place to build a house; however, not all parts of an island are the same. Even someone who has never witnessed a winter storm would recognize that a house with its footings on the beach is in more danger than one built at high elevation in a forest on the back side of an island. The problem is that barrier islands are as complex as they are dynamic, and even though our understanding of them has greatly increased in the last decade, the average property owner has had to rely on the somewhat biased assurances of Chambers of Commerce or realtors and developers concerning island safety.

Several years ago, it became apparent that North Carolina barrier island dwellers had very little understanding of the dangers of the environment in which they lived. Many were from out of state; few had seen the results of a hurricane or northeaster, and none knew that the sea level was rising. We felt that it was particularly ironic that such ignorance existed at a time when scientific understanding of island processes was growing. We produced two books that were published by the North Carolina Science and Technology Research Center, a state agency. The books were written in laymen's terms and discussed quite specifically the safety of individual barrier islands.

The books, entitled *How to Live with an Island* and *From Currituck to Calabash,* were well received, although their impact on local island development has not yet been determined. One developer, for example, told us: "we eventually sell the lot anyway," suggesting that there are both individuals who do not know about coastal hazards and those who will bear the risk.

In 1979, with the support of the Coastal Zone Management Program of the National Oceanographic and Atmospheric Administration (NOAA), we began the long process of producing separate books, patterned after *From Currituck to Calabash,* for each barrier island state from New York through Texas. To carry out this task, we recruited a team of beach experts, including at least one scientist from each state. The final goal is an island safety map for every privately owned barrier island in America.

Island Safety Mapping

No hard and fast rules for determining the safety of an island or portion thereof exist. Each barrier island is different; each responds in its own way to the surrounding natural forces. Some are much less hazardous than others, and on a single island, potential building sites may range from fairly safe to very dangerous. Because the intensity and frequency of natural forces vary greatly from region to region, islands of similar physical makeup that are located in widely separated geographic areas can be quite different in terms of safety mapping for development.

A great deal of information is available in the scientific literature, as well as in federal and state publications, upon which to base island safety mapping. These data, when combined with the intuition, experience, and field observations of an experienced barrier island geologist, suffice to provide a solid basis for mapping.

Among the available data are: 1) periodic aerial photographs of most U.S. shorelines, as far back as the late 1930s; 2) "smooth sheets" available from the National Ocean Survey, showing accurate shoreline positions beginning in the mid-1800s; 3) U.S. Geological Survey topographic maps; 4) island evacuation maps prepared by NOAA's coastal hazards group; 5) flood hazard maps prepared by various agencies, including the Federal Emergency Management Agency; and 6) various federal and state publications, such as Sea Grant, giving island erosion rates, and overwash and inlet history.

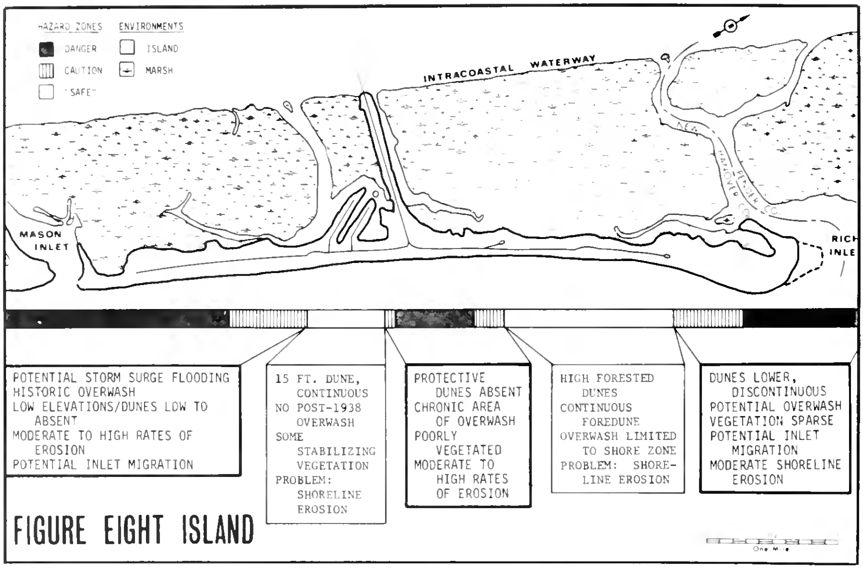
In most cases, a sufficient data base already exists by which island hazard potential can be evaluated. New large-scale basic research programs are not required to construct island hazard maps. Ironically, the major exception is the state of Florida, which boasts the longest and least understood barrier island shoreline in America. Figure 1 shows hazard maps for two North Carolina islands. A simplified classification, pigeonholing all island areas into the categories of "safe," "caution," and "unsafe" was adopted for ease of use by the nonscientist. "Safe" is always put in quotation marks because no barrier island is really a safe place to build a home. These dynamic mounds of sand are natural hazard zones just like Mt. St. Helens or the San Andreas Fault. The question is not if, but when.

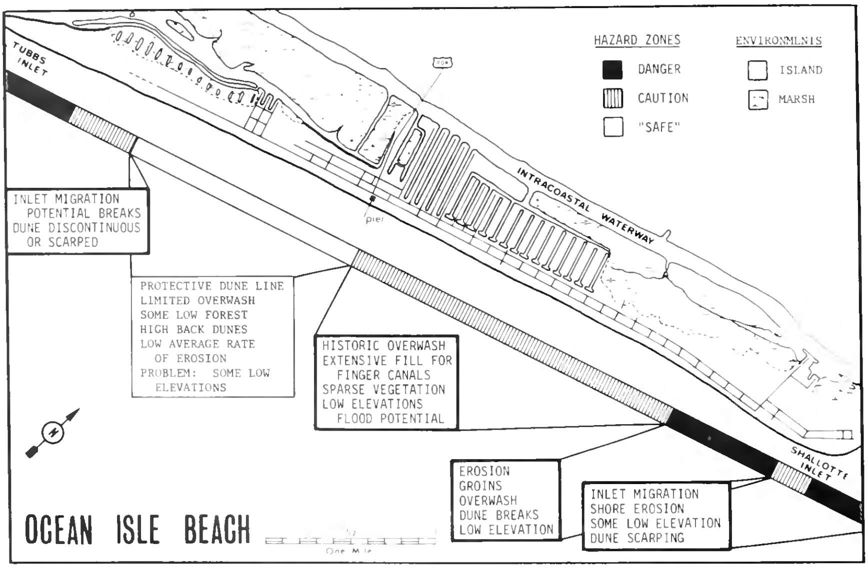
Island classification is based on the sum total of both natural and man-made hazards, evaluated in the context of the island's recent history. In the final analysis, only a third of North Carolina's barrier island front was judged to be "safe."

Understanding how man and nature interact on barrier islands is critical for future research. Geological research in the past has put heavy emphasis on pristine barrier islands, rather than islands that are having development problems. Engineers also must share the blame for the lack of understanding about developed islands. Coastal engineering research has emphasized the immediate effectiveness of shoreline stabilization techniques with only token consideration for larger-scale and longer-range (50 years or more) environmental problems.

Wrightsville Beach in North Carolina is a good example of how man creates conditions hazardous to himself on barrier islands. In the mid-1960s, the United States Army Corps of Engineers filled in a shallow inlet between Wrightsville Beach and Shell Island (Figure 2). This was done by removing the body of sand (called the flood tidal delta) deposited by tidal currents behind the island in the lagoon. Barrier island scientists William Cleary and Paul Hosier found that old tidal deltas on the back sides of islands are "insurance"

A





B

Figure 1. A) Hazard map of Figure 8 Island, North Carolina. B) Hazard map of Ocean Isle Beach, North Carolina. (From Currituck to Calabash*, 1978)*

against future inlet formation during big storms. Inlets form when water piled up into lagoons by a storm suddenly rushes back to sea, cutting through the island from the back side. After an inlet has closed naturally, the tidal delta acts as a shallow obstruction to such backflow, thus interfering with potential reforming of the inlet. Dredging the Wrightsville Beach tidal delta sand for fill increased the water volume behind the island and removed the "insurance"; thus a "safe" area has become one that is prone to the formation of new inlets. On the island front side, closure of the inlet halted the formation of the ebb tidal delta, maintained by the in-and-out action of the inlet's tidal currents, and this seaward body of sand disappeared. Nature then straightened out the island's seaward bulge in a few years, but not before the property lines were drawn and houses built. Several of these houses are now in the surf zone! Shortly after the inlet was filled, a Holiday Inn was built on the exact site of the old channel. Barrier island botanist Paul Godfrey (see page 56) dubbed it the Holiday Innlet, thus assuring the inn's widespread fame among shoreline scientists. In defense of the Corps of Engineers, this project was carried out before we understood much about tidal deltas and their function.

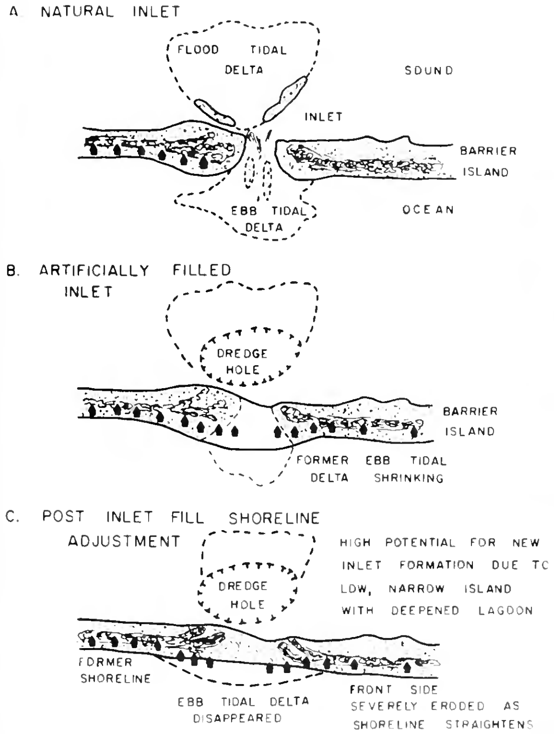


Figure 2. The effect of using a tidal delta for a sand source to fill an inlet. This illustrates the sequence of events that occurred when Moore's Inlet, North Carolina (between Wrightsville Beach and Shell Island), was filled.

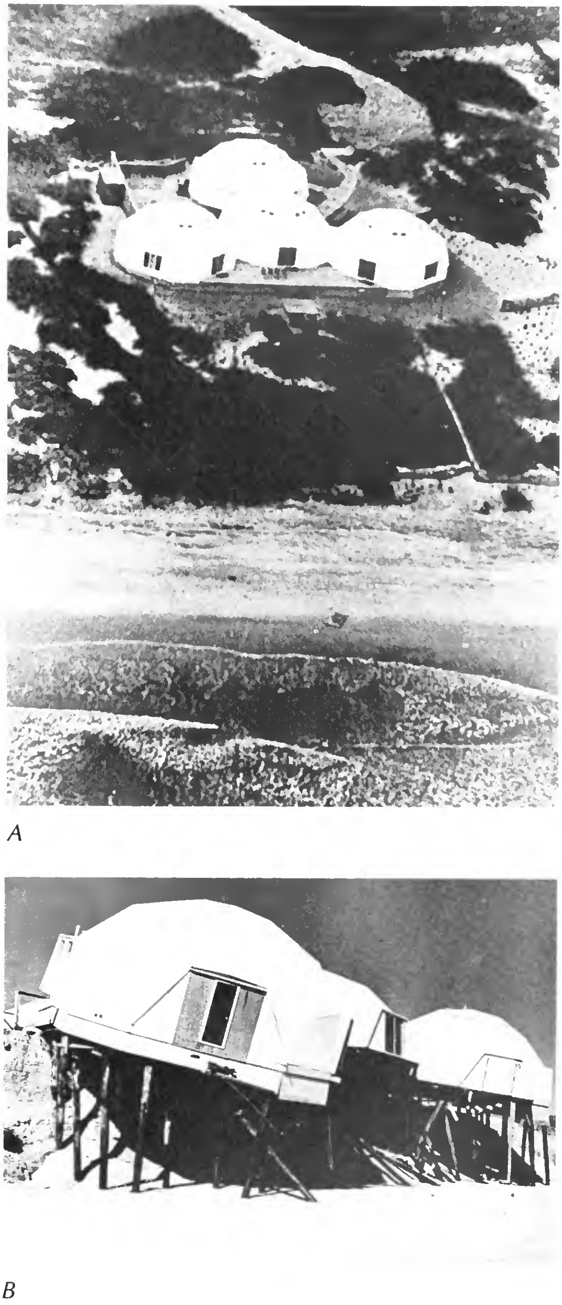


Figure 3. A) Original "dome house" on South Nags Head beach, where a rate of erosion of 1.8 meters per year has prevailed for more than 100 years. B) The result! Note: The cost of moving this house back was borne by the federal taxpayer. The house was insured through the federal flood insurance program, and it was slightly cheaper to move the house than to pay for it when it was in pieces on the beach. Luckily this house was sited on the elongated lots sold during the 1940s and 50s in recognition of the shoreline erosion problem. Today's lots do not allow for future setback of any kind.

Island Safety Criteria

Island safety designation was based on the consideration of a large number of factors, the most important of which are:

Natural Factors

Erosion rate (both front and back side). Most American barrier islands are eroding. Typical rates of landward movement of the open ocean beaches of the U.S. Atlantic coast range between ½ to 2 meters per year. A few islands, for example, some off the Mississippi delta, may be retreating at an average of 20 meters per year. Set-back laws (legislation that allows for future moving of a house threatened by beach erosion) only delay the inevitable (Figure 3). A major factor causing this shoreline retreat is the rising sea level. It is important to understand that an increment of sea-level rise should be expected to produce a much larger horizontal retreat (Figure 4). In a natural island system, part of the frontal eroded sand is carried to the back side of the island. When island development cuts off this sand supply, back side erosion may be accelerated.

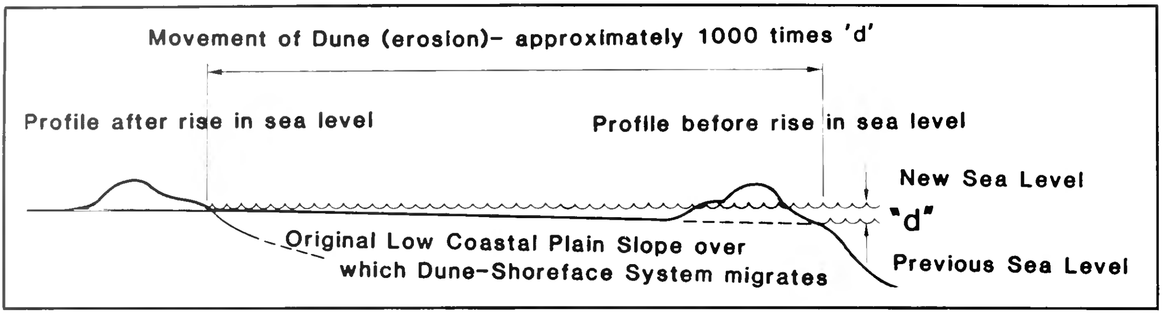


Figure 4. The relationship between sea-level rise and horizontal retreat of the shoreline.

Elevation and Topography. Obviously, the higher its elevation the less likely a building site will be flooded during a storm. Also important is island width (high elevations on the back side are more desirable than on the front side) and size and frequency of breaks in the dune line, which act as passageways for storm surge. Fifteen feet is a good minimum elevation figure for the prudent homeowner. One should consult NOAA island evacuation maps for information on storm surge levels for a given area.

Storm Response. Storm response was evaluated by looking at aerial photos taken after storms. Islands that are overwashed frequently are unsafe. Narrow and low sections of islands may be the sites of new inlets after major storms. Figure 5 shows an inlet that developed in such an area on Long Beach Island, New Jersey, during the 1962 Ash Wednesday storm. In this case, the presence of a finger canal and back side development contributed to the problem. The effect of back side development on storm response remains virgin territory for research.

Figure 5. This inlet at Harvey Cedars on Long Beach Island, New Jersey, formed in the 1962 Ash Wednesday storm as a result of a back side development. New inlets on barrier islands usually form as a result of water rushing out of the lagoon. In this case, the outgoing water flowed into a finger canal and thence across the island. (Photo courtesy U.S. Army Corps of Engineers)

Soil Types. On North Carolina's barrier islands, the development of a mature soil profile is probably the single most dependable guide to a safe location. A mature soil profile (a foot or two of white sand overlying orange sand and no shells present anywhere) is a sign of a site that has seldom been disturbed by saltwater for many years. An exception is found on some rapidly eroding beaches south of Cape Fear. Erosion is so rapid that soil profiles are visible in bluffs next to the beach. Beware of the presence of shells. Brown shells often indicate storm overwash. Black and white shells usually indicate artificial land pumped up from the back side in order to fill in a storm inlet or to give building sites more elevation artificially.

Inlet Proximity. Some inlets "breathe" (widen and narrow). Others migrate. In either case, houses can be endangered. Inlet history is studied from aerial photos and charts to predict its future behavior.

Storm Frequency. Different coastal regions have radically differing frequencies of hurricane occurrences. For example, Georgia and New Jersey barriers are struck by hurricanes far less frequently than North Carolina's Outer Banks.

Vegetation. Heavy maritime forests are much safer in a storm than a lightly vegetated dune flat.

Man-Made Hazards

Road Construction. Roads should go over, not through dunes (see page 56). Roads cut straight and level through dunes from the main road to the beach will act as overwash passes in the next storm. Such roads built to serve the development will eventually cause its destruction.

Sand Removal. Removing sand, particularly from the front side of barriers (to better the sea view) will greatly increase the danger to development. Dune sand is important during a storm. Basically, the storm waves spend time chewing up the dunes before they chew on houses. Thus, the more sand there is, the longer the reprieve for houses.

Land Area Alteration. Frequently "new" land has been made on the back side of islands by marsh filling. Such land may provide poor footing for houses and poor septic tank drainage. In other cases, removing natural sand bodies behind islands increases the likelihood of inlet formation (Figure 2).

Finger Canals. These are possible sources of pollution, bad odors, and may become new inlets during a major storm.

Vegetation Removal. Developers sometimes remove the protective cover of vegetation. Removing forests may enhance the probability of high wind damage to structures. Loss of ground cover may make the sand migrate. The homeowner may have to use a bulldozer for a lawnmower.

Shoreline Engineering. Eroding shorelines that have "caught up" with the first row of houses are often "stabilized" — the erosion is halted with sea walls and groins. Although stabilization offers short-term protection to beach houses, ultimately it destroys the beach and does not offer effective protection during major storms. Shoreline engineering is less of a natural hazard than it is an economic and aesthetic problem. Stabilization is costly to local taxpayers, and, since it essentially destroys the beach, it destroys the *raison d'être* for most beach dwellings. Figure 6 is an illustration of a very common problem. The Corps of Engineers proposes to put in jetties (at a cost of $70 million) to stabilize Oregon Inlet on North Carolina's Outer Banks. The jetties potentially will increase erosion rates for miles in both directions. Figure 6 also shows the 1962 inlet configuration after the Ash Wednesday storm. The jetties will prevent such future storm blow out and may cause a new storm inlet to form elsewhere, possibly through the nearby town of Nags Head.

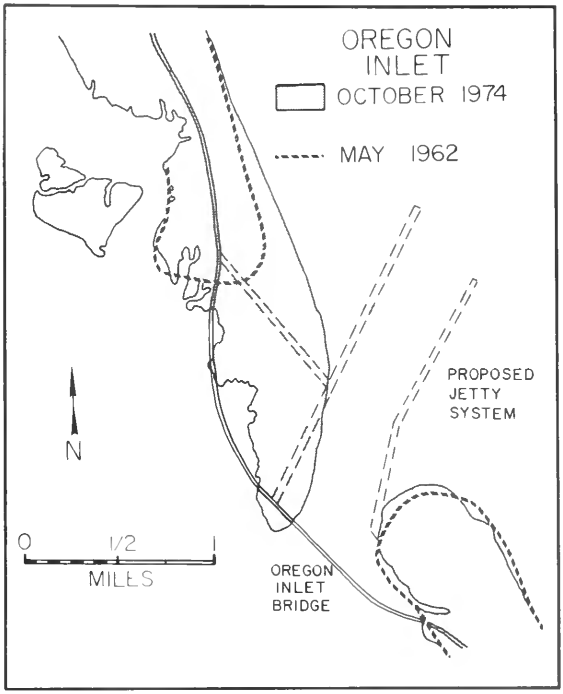


Figure 6. Oregon Inlet on the North Carolina Outer Banks. This inlet formed in the 1940s and has migrated more than 2 miles since that time. The May 1962 inlet, shown by the dashed line, formed as a result of the Ash Wednesday storm and is 2 miles wide compared to the normal width of one-half mile. The proposed $70 million in jetties to be built by the Corps of Engineers may prevent such future blowouts and thereby could cause a new inlet to form elsewhere, possibly through the nearby town of Nags Head. The new inlet, of course, will necessitate a new bridge. On very active islands such as North Carolina's Outer Banks, ferries should be used instead of bridges to connect islands. (Data furnished by the NOAA coastal hazards group)

Beach Replenishment. A beach that has been or is being replenished is a sure sign that erosion has advanced to the point that shorefront buildings are threatened. The long-range prognosis in terms of probable storm damage and extensive tax assessments for beach repair is bad. Initial cost to replenish 15 miles of Miami Beach in 1979-80 was $65 million. In some communities a cheap and temporary job of replenishment is done by bulldozing sand from the lower to the upper beach. This actually increases the rate of erosion. Ocean City, Maryland, purchased a whole fleet of war surplus bulldozers for this purpose.

Politics. A carelessly run or nonexistent program in building code enforcement will result in poorly built buildings. Such buildings act as battering rams in storms and take down well-built buildings. Many communities in North Carolina have allowed people to remove frontal dunes, thus clearly endangering residents. Strict enforcement of all laws related to natural and man-made island hazards is necessary. A solid, well-publicized, storm evacuation plan is needed as well.

Island Egress. You must be able to get off an island before a storm. Roads and bridge abutments should be at least 6 feet in elevation. The coastal hazards group of NOAA has concluded that a number of New Jersey and Florida islands could not be completely evacuated even with 24 hours notice. Depend on it; if your bridge has a movable span to let boat traffic through, it will be stuck at your moment of need.

At this point we are reminded of a gentleman we met on the ferry to Ocracoke Island, North Carolina. He was a vacationing Georgian who bragged to us that he and his eight-year-old son were the last individuals to get onto Sea Island, Georgia, before Hurricane David hit. We were speechless.

Utilities. Water/sewer/electricity sources crossing areas of high potential for inlet formation are obvious hazards to comfort and property value. They also are hazards to the island because protecting such utilities often in the long run leads to sea walls that cost money and destroy beaches.

The Impact of Island Safety Maps

There is legitimate reason to question the usefulness of island safety mapping, since our North Carolina experience tells us the islands will develop no matter what we say.

For example, Lea Island, North Carolina, is so low and dangerous and so frequently flooded by storms that we assumed no one in his right mind would build there, and we debated whether to even include the island in our mapping. Most of the island's land area is the result of the migration of an inlet in 1940. A future storm will likely "take back" the new island.

After some discussion, we included the island in our book, classifying it as totally unsafe. A year or so after publication of *From Currituck to Calabash* we received an advertisement for shore-to-sound lots on Lea Island.

Island mapping has proved valuable in the political arena in subtle ways. The maps have received a lot of publicity and have greatly increased public awareness of island problems. Serious questions are now asked in the North Carolina state legislature concerning the wisdom of spending tax money to save threatened houses.

The increasingly widespread understanding of the reality of the slow-acting sea-level rise and catastrophic hurricanes and northeasters has provided a basis for a relatively strong statewide coastal zone management program. The highly publicized maps make it difficult for individuals to say, "How was I supposed to know this was a dangerous site?" Last, but not least, the maps give the environmentally concerned and conscientious citizen the opportunity to avoid building or buying a home in a dangerous location.

A Do-It-Yourself Guide

Common sense will go a long way in helping the barrier island dweller evaluate his lot or hoped-for lot. Some of the important factors are listed in Table 1, but it is only a generalized summary. Every island is different, so a single checklist for all islands must be used with caution and good sense.

The concerned island visitor first should find the available appropriate literature for the area. The Sea Grant program in each state usually has useful documents on island safety. Also much can be learned from talking with island dwellers and even from visiting the local courthouse. A list of questions might include:

What happened during the last hurricane?
What is that foundation over there without a house on it?
What happens to the beach during winter storms?
What is this area like after heavy rains?
Is there active enforcement of building codes?
What is the community's attitude toward sand removal in mid-island areas?
What is the history of sand removal/emplacement in your neighborhood?
What is the community's attitude toward dune protection? Is the attitude enforced?
Is there planning or zoning?

There is a problem, however, that we have discovered after numerous conversations with island dwellers. No one would really expect a realtor or developer to voluntarily bring forth the fact that all the houses in the neighborhood were destroyed during the last hurricane; however,

Table 1. A Do-It-Yourself Guide to evaluation of island safety.

Island Attributes	Hazard Potential		
	High	Moderate	Low
Island elevation	<5 Feet	<15 Feet	>15 Feet
Presence of sand dune line and beach	No dunes	Dunes low, discontinuous	High, multiple dunes
Island width	Narrow	Intermediate	Wide
Island backed by salt marsh	None, open sound	Some marsh, narrow sound	Wide marsh
Position relative to existing inlet	Near	Moderate	Far
Shoreline erosion rate	High (>3 ft/yr)	Low (<3 ft/yr)	None or accretion
General storm response	Dunes destroyed, new inlets	Moderate changes	Few changes
Historic overwash	Yes	None recent	None
Vegetation	None or sparse	Shrub cover	Maritime forest
Footing material (subsidence potential)	Compactible layers (peat, clay, etc.)	Mainly noncompactable layers (sand w/ few thin clayey sands)	Noncompactable layers (thick sand)
Drainage (visit island in rainy season)	Poor	Good	Excellent
Water supply (talk to neighbors)	Inadequate or contaminated	Potentially inadequate or contaminated	Abundant, high quality
Septic suitability (talk to Health Dept.)	Improper sediment, intersects water table	Proper soil and elevation for light developments	Proper soil and elevation above water table
Soil type	Very shelly	Few shells	Good soil profile
Finger canals	Present	Few, short in length, Unpolluted	Absent

many well-meaning citizens also may inadvertently offer poor counsel. One older gentleman informed a reporter, in all sincerity, that he had observed no important changes during his lifetime on the island, but we knew from newspaper accounts and aerial photos that a whole row of houses had gone into the sea. Experiences like this repeated many times have made us depend much more on our charts and aerial photos than on our neighbors.

Certain telltale signs are abundant on many barrier islands, which the observer can find by driving or hiking the length of the island. Scarps (small cliffs) in dunes suggest active erosion. Fallen trees on the beach, stumps (Figure 7), and outcrops of mud all point to the same active process. So-called protective structures on the beach, such as sea walls and groins, indicate shoreline erosion problems in an advanced stage. Foundations of houses minus houses, pilings without houses, roads ending abruptly on a beach, all indicate the obvious.

The Ideal Island

Our concept of the ideally developed island is one that is both aesthetic and safe (Figure 8). Most

Figure 7. Stumps exposed on Caswell Beach, North Carolina, 1977. The trees once grew in a maritime forest on the back side.

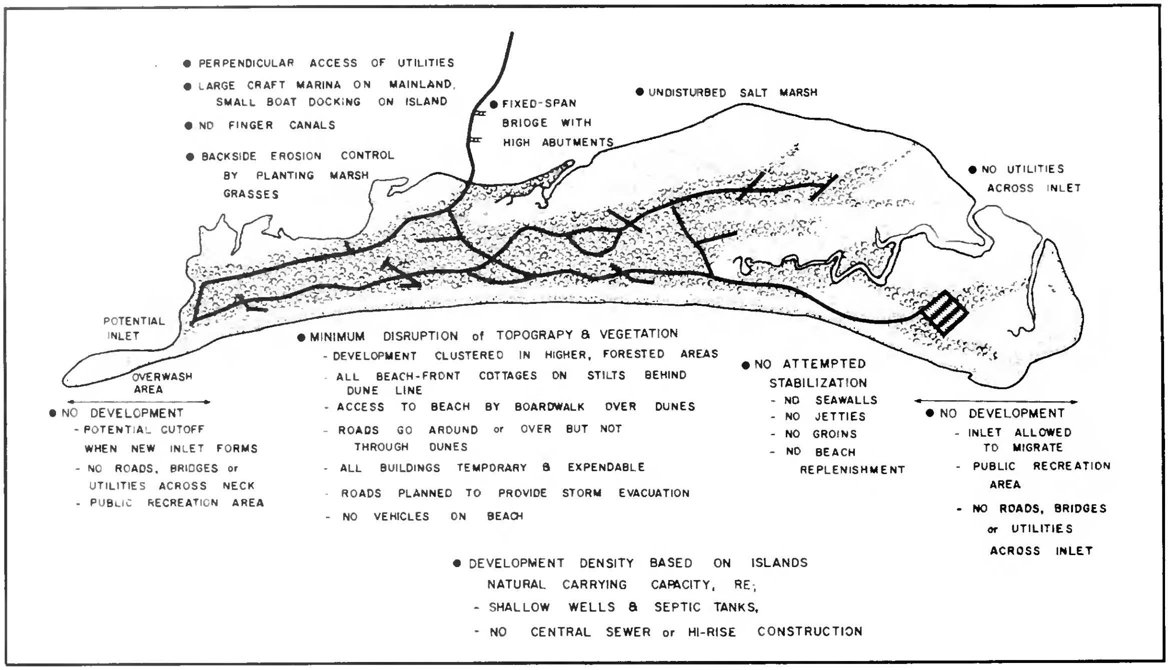


Figure 8. The ideal island.

important of all, dynamic island processes will go on relatively unhindered. The island ultimately will be in the hands of the present inhabitants' great, great grandchildren, and will still be in a beautiful state, but not necessarily with the same buildings.

The principal idea behind this development is to build so as to totally avoid stabilization. The evidence that stabilization or halting of island processes has disastrous effects can be seen along miles and miles of New Jersey and South Florida shores. Care also must be taken to avoid making development moves that will result in calls for stabilization 50 years hence. For example, power lines built through an inlet-prone area will someday be broken. Will the island dwellers insist on confronting nature in order to replace the power lines? Better to have perpendicular access of utilities. No utilities should come from adjacent islands.

The ideal island will have contingency planning allowing for inlets to break up the island in a hurricane. The inlets will not be repaired nor will they be bridged. Rather, ferry systems should be installed.

Most important of all, beachfront homeowners will know that they will not be allowed to protect their houses from the rising sea level. Instead they must be prepared either to be good sports as their houses fall in or to migrate as the island migrates.

Although the ideal may not exist, examples of good development do. Pine Knoll Shores on Bogue Bank, North Carolina, and Kiawah Island, South Carolina, are cases in point. Unfortunately, these areas tend to be expensive and exclusive. How will their residents respond to long-term changes, such as the relentless sea-level rise or major hurricane impact? Will they choose to roll with the island or will they attempt to stabilize it? Tune in tommorow.

Orrin H. Pilkey is a Professor of Geology at Duke University, Durham, North Carolina, and at Duke University Marine Laboratory, Beaufort, North Carolina. William J. Neal is Professor of Geology at Grand Valley State Colleges, Allendale, Michigan. He is presently Visiting Scientist, Department of Geology, Duke University.

Acknowledgments

We wish to thank many colleagues for long and valued philosophical discussions concerning the American shoreline "problem." Mark Evans drafted the figures and offered useful suggestions concerning the manuscript.

Selected References

Kaufman, W., and O. Pilkey. 1979. *The beaches are moving.* Garden City, N.Y.: Anchor Press/Doubleday.

Pilkey, O. H., O. H. Pilkey, and R. Turner. 1975. *How to live with an island.* North Carolina Science and Technology Research Center.

Pilkey, O.H., W. J. Neal, and O. H. Pilkey. 1978. *From Currituck to Calabash.* North Carolina Science and Technology Research Center.

Federal Policies

Barrier Island Development

House trailers are notoriously fragile before high winds, even when anchored in hurricane cradles. Blowing from the east (left) as it made landfall, Hurricane Frederic peeled this trailer open like a sardine can.

Midnight, September 13, 1979. The eye of Hurricane Frederic passed over Dauphin Island, Alabama, and swirled inland. Two or three miles east of the mouth of Mobile Bay, 94 of the 100 houses in one area were totally destroyed by winds exceeding 120 miles per hour and a storm surge that swept water more than 2 meters deep across the entire peninsula. Along the 38-kilometer reach from Fort Morgan to Gulf Shores, Alabama, two-thirds of the houses in the first 100 meters landward were totally destroyed. Agricultural damages inland were estimated to be in the millions of dollars. In Mobile, there were heavy wind damages to houses and trees; large parts of the city were without electricity for days. Estimates of total property damage in a three-state area — Alabama, Mississippi, and Florida — were as high as $2 billion, making Frederic one of the costliest storms ever to hit the United States.

In the wake of Frederic, the three states were officially termed by the President to be disaster areas, which activated the federal relief and recovery process. Federal expenditures related to the presidential declaration now total an estimated $456 million, not including expenditures by the Federal Highway Administration, Environmental Protection Agency, and the Department of Housing and Urban Development.

Efforts to restore Dauphin Island to normal have generated conflict. Frederic heavily damaged houses and commercial structures on the island, as well as the causeway and bridge to the island. Unless a challenge is sustained on appeal,* at least $38 million will be spent by the Federal Highway Administration to fund a new bridge and causeway. Another $3.5 to $5 million may be spent by the Environmental Protection Agency to fund a secondary wastewater treatment plant for the island. The construction of the bridge and plant would not only allow the island to return to its predisaster development levels, but would also permit development of the remaining undeveloped lots on the island.

Nineteen hurricanes have affected Alabama in this century; six caused severe damage on the coast, and three breached Dauphin Island. It seems inevitable that any new houses in the area will experience a major storm. Thus, federal highway and pollution control funds could be instrumental in setting the stage for a disaster on Dauphin Island greater than that wrought by Hurricane Frederic.

The federal role is perhaps most visible after disaster has occurred. This is when storm damages are most evident, widespread devastation is felt throughout the community, and the need for help is politically irresistible. The role played by the government in the guise of community and economic development is most pervasive at this moment. On barrier islands, it includes direct subsidies for access to the islands by way of bridges, causeways, and roads; for urban infrastructure, including water supply, water treatment, wastewater treatment facilities; and for shore protection to reduce erosion by sea walls, groins, jetties; and beach nourishment. Federal tax incentives, guaranteed loans, and other forms of financial assistance add to the measures that promote barrier island development. Finally, federal regulations set minimum standards for development. These may delay development, but generally do not prevent it.

The Barrier Islands

Development of barrier islands is a gamble with time and nature. They are the first line of storm defense for a thousand miles of Atlantic and Gulf coastlines. When we use the term barrier islands, we mean a succession of islands, barrier spits, and bay barriers on those two coasts which are characteristically narrow, elongated land forms, generally parallel to the mainland coast, formed by interactions of waves, currents, tides, winds, and sediments.

The National Park Service has identified nearly 250 barrier-island units along the two coasts, consisting of single islands or clusters of barrier structures. Normally there is open water separating barriers from the mainland. Barriers generally consist of sands or other kinds of unconsolidated sediments; geologically, they are recent structures. On their seaward side, the barriers are most often fronted by a beach; on the mainland side, by highly variable zones of wetlands (Figure 1).

The dynamics of barrier islands make them truly hostile environments for man to build on. They change position, occasionally very rapidly, in response to storms, changes in water level, and changes in current patterns. The barriers are generally receding toward the mainland, responding to the progressive rise of sea level (see page 4). Among the hazards are the migration of old inlets, formation of new inlets during storms, and storm overwash that can undermine foundations by liquefying soil. The combination of rising water level, coastal storm surges, wave action, battering by debris, scouring, and high winds makes development very hazardous on many parts of the islands. The biblical admonition about the foolish man who built his home on sand is no less apt today than it was 2,000 years ago.

Despite the dynamics of barrier islands along the Atlantic and Gulf coasts, development in these areas is growing at a rate greater than 6,000 acres per year. That rate, if applied to the remaining undeveloped islands identified by the National Park Service, could consume the developable upland portions of those islands by the year 1995, just 15 years from now. In 1950, some 90,000 acres were developed; the Department of the Interior reported that 228,680 acres were developed by 1973-1974, and an estimated 280,000 acres by 1980.

Barrier islands make up more than 1,400,000 acres of upland, wetlands, and interior waters. Of those, about 885,000 acres are in the public domain, owned by federal, state, and local governments, and protected from development. More than two-thirds of the undeveloped, unprotected islands are wetlands and interior waters (about 182,700 acres). Of the 93,000 acres of uplands on these undeveloped islands that are potentially developable, about 55,400 acres are contiguous to partially or totally developed areas, and about 37,900 acres are on 54 totally undeveloped barrier structures.

The distribution of these undeveloped, unprotected islands is shown in Table 1. More than 95 percent of the barrier island acreage is found from Virginia south along the Atlantic coast, and along the Gulf coast. Texas alone has more than 40 percent of the acreage; 75 percent of the acreage is found in Texas, Florida, Georgia, and South Carolina.

Federal Policy on the Barrier Islands

What action to take on the remaining undeveloped, unprotected barrier islands of the United States

---

*Sierra Club and Natural Resources Defense Council v. Hassel, Civil Action No. 80-0170-P, USDC (SD, Alabama), 1980.

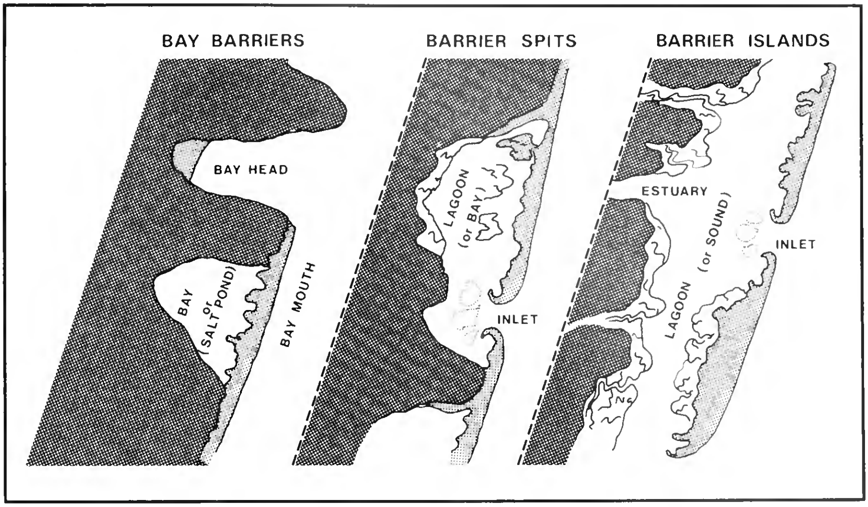


Figure 1. Examples of barrier structures.

Table 1. Undeveloped, unprotected barrier islands of the Atlantic and Gulf of Mexico coasts (September 1980).

State	Contiguous Units[1] Uplands (Acres)	Contiguous Units[1] Wetlands[2] (Acres)	Totally Undeveloped Uplands (Acres)	Totally Undeveloped Wetlands[2] (Acres)	State Total	No. Units Totally Undeveloped / Total Contiguous and Totally Undeveloped Units
Maine	702	136	0	0	838	0/3
Massachusetts	3,226	1,447	1,276	1,027	6,976	5/24
Rhode Island	777	432	70	0	1,279	1/9
Connecticut	72	203	22	29	326	1/5
New York	1,327	535	0	0	1,862	0/10
New Jersey	60	290	0	0	350	0/1
Delaware	156	200	0	0	356	0/1
Virginia	0	0	1,786	6,587	8,373	3/3
North Carolina	2,608	5,065	1,939	12,235	21,847	6/16
South Carolina	6,288	8,915	4,293	21,064	40,560	11/18
Georgia	0	0	5,706	23,084	28,790	2/2
Florida	14,176	8,174	1,040	3,176	26,566	6/18
Alabama	465	1,162	0	0	1,627	0/1
Mississippi	0	0	1,970	1,325	3,295	3/3
Louisiana	860	4,972	4,151	11,744	21,727	10/10
Texas	24,797	51,770	15,459	20,088	112,114	3/8
September 1980 Totals	55,514	83,301	37,712	100,359	276,886	52/132

[1] "Contiguous Units" are those undeveloped, unprotected barrier structures contiguous to partially or totally developed areas.

[2] Wetland acreages include interior waters.

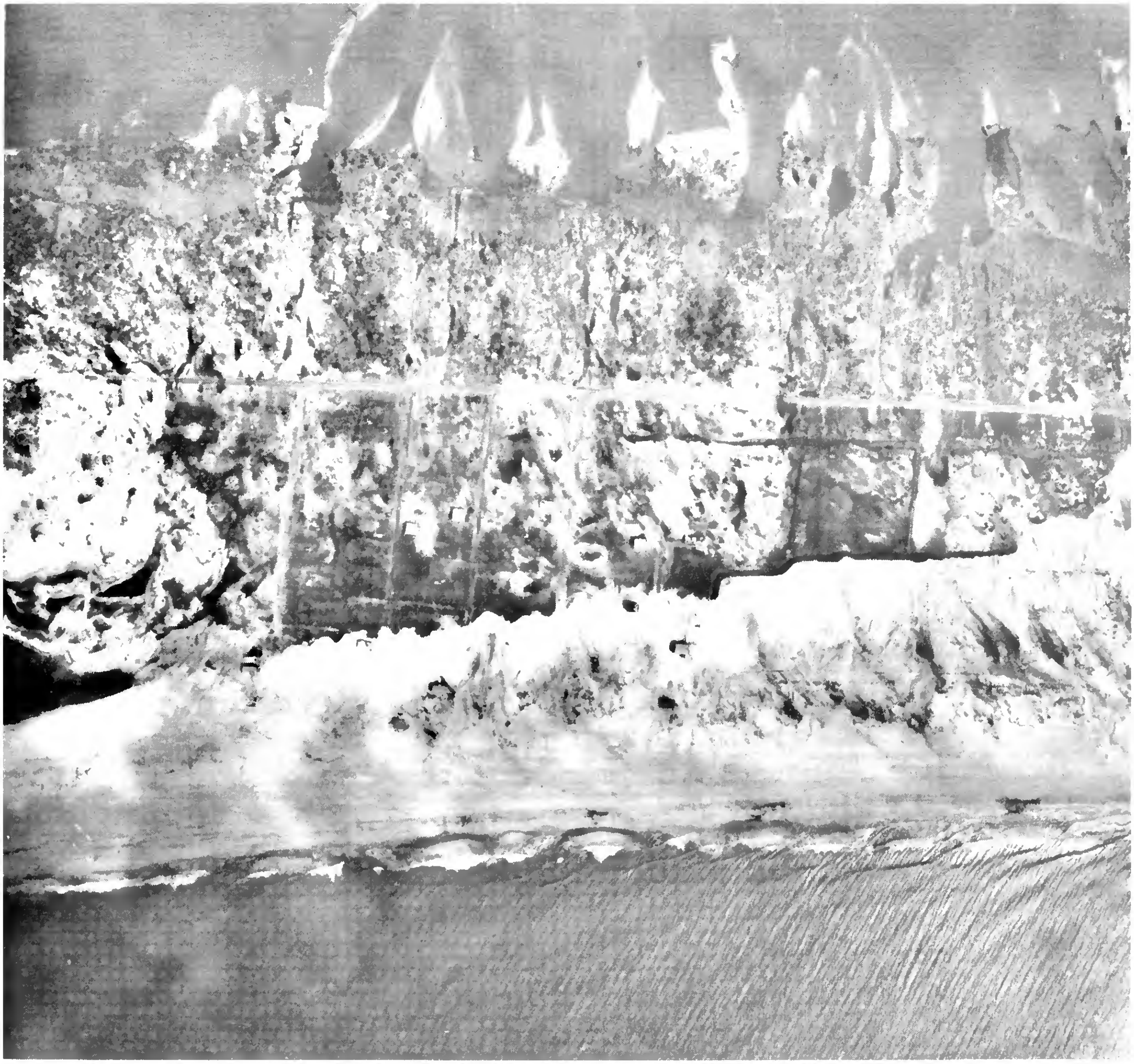
Sources: Author, using:

1. (1) Summary of the undeveloped and unprotected natural areas on barrier islands along the Atlantic and Gulf coasts — U.S. Department of the Interior, National Park Service. (Washington, D.C., April 1980)
2. (2) Table 1. Barrier structures and parts of structures listed in April 1980 National Park Service inventory that have been determined to be protected by existing owners and deleted. (Revised to Sept. 9, 1980)
3. (3) Table 2. Other barrier structures or parts of barrier structures deleted from April 1980 National Park Service inventory. (Revised to Sept. 9, 1980)
4. (4) Table 3. Barrier structures determined to qualify for addition to the inventory of undeveloped and unprotected barrier structures. (Revised to Sept. 9, 1980)

Before and after Hurricane Frederic: Subdivisions just east of Ft. Morgan, Alabama, show the full fury of winds, waves, and storm surge. Storm surge at least 2 meters deep covered the entire width of the peninsula. Sustained winds of 135 miles per hour swept the area at the height of the storm. Of 100 houses pictured within 500 meters of the Gulf of Mexico (bottom of

raises profound questions about federal policy toward these lands, and, by extension, other lands that are environmentally sensitive or subject to repeated natural hazards. Current federal policy is ambivalent. It is weighted through subsidies, tax incentives, and financial assistance toward development, and offset somewhat by the National Flood Insurance Program, which regulates minimum building standards (predominantly elevation above the 100-year flood level). This is modest indeed when compared to the forces of private development combined with federal, state, and local financing, regulation, and general encouragement of barrier island development.

Begun in 1977, a major review of federal policies on barrier islands was undertaken by the Department of the Interior. Its environmental impact statement and report, entitled in draft "Alternative Policies for Protecting Barrier Islands along the Atlantic and Gulf Coasts of the United States," is a major statement and evaluation of federal policy toward barrier islands. It presents three options: 1) *status quo* — relying on current authorities and programs, 2) *moderate* — using more effective and strengthened enforcement of existing policies, and 3) *high* — seeking new laws or amending existing authority to strengthen federal programs to protect barrier islands.



pictures), 94 were totally destroyed, and the remainder sustained greater than 50 percent damages. (Before photo courtesy of Reynolds, Smith, and Hill, Orlando, Florida. After photo by Florida Department of Transportation)

At the same time, other efforts were undertaken in Congress. Bills pending before the House and Senate in the 96th Congress seek to effect the third option. Both HR 5981, introduced by Rep. Phillip Burton (Democrat, California), and S 2686, introduced by Sen. Dale Bumpers (Democrat, Arkansas), would remove federal subsidies for bridges, roads, airports, boat-landing facilities, and erosion-control structures on the remaining undeveloped, unprotected barrier islands. Also, HR 5981 would provide new acquisition authority for the Secretary of the Interior to bring unprotected barrier-island units into the National Park System if owners would voluntarily sell their properties. If enacted, removal of federal subsidies would be a powerful new precedent.

Strategies for the Barrier Islands

There are basically only two strategies for dealing with the barrier islands: corrective and preventive. A corrective strategy would focus on existing problems, essentially the 280,000 acres of barrier islands that are already developed. No effort is being made in any of the current alternatives to "correct" existing development on the barrier islands. Pending legislation addresses only undeveloped, unprotected barrier islands.

A preventive strategy is most germane to federal policy for the undeveloped, unprotected islands. Its principal tools are regulation, acquisition, and governmental nonparticipation in development. All three elements are contained in proposals now being considered: 1) use of existing or strengthened federal regulations to guide development on the barrier islands, 2) removal of federal subsidies for infrastructure and access to barrier islands, and 3) public acquisition of undeveloped, unprotected barrier islands.

Very basic questions regarding federal goals for development of barrier islands must be addressed in the new federal policy, and strategies must be tailored to the goals:

> *If a goal is to establish minimum criteria for development, but to permit development of the islands to continue, the policy will emphasize a strengthening of federal regulatory authority.*
>
> *If a goal is to remove federal participation in development on the islands, but not to prevent further development, removal of the federal subsidies for bridges, roads, airports, boat landing facilities, and shore protection structures would be an important new policy to adopt.*

Note, however, that neither strengthened regulations nor removal of federal subsidies will prevent new development.

Federal Regulations

Regulations generally set minimum requirements for development, but do not prevent development. Effects include: some minimal delay in development until the regulations can be complied with, and a reduction in flood and wind losses until the design limits of the regulations are exceeded, in which case there may be catastrophic loss. For example, a house built in the coastal high-hazard area and elevated to the wave-crest level associated with a 100-year (1-percent chance) storm, should be protected against waves up to that height. But when there is more than a 50-year life expectancy for a coastal home, there is a 1-in-3 possibility of it being struck by a 125-year (0.8-percent chance) storm, and a 1-in-4 possibility of it being struck by a 200-year (0.5-percent chance) storm. Moreover, damage to roads, water supplies and water mains, sewers, utilities, and shore protection devices associated with the home could be sustained in much lesser storms.

Federal Subsidies

Removal of federal subsidies would at least move the federal government out of the development business on the barrier islands, and would shift the entire burden of any new development to the developer, his private financial resources, and ultimately to the consumer. This could have the effect of delaying some development, perhaps for considerable periods of time. It would also make the development that does occur considerably more expensive than if federal subsidies were available. For instance, I estimate that if the Dauphin Island bridge is funded by the Federal Highway Administration, the subsidy will amount to more than $50,000 for each of the 650 structures on the island before the storm, and more than $20,000 per structure if all the lots mapped on the island were developed. Shifting that burden to the private sector could profoundly affect economic justification of a given development. Hence, removal of federal subsidies from barrier island development would be an important new federal policy inhibiting, if not preventing, development.

Public Acquisition

A third alternative stems from the premise that development of the undeveloped, unprotected islands should not simply be delayed, but should be prevented. The principal tool for preventing development is public acquisition, either voluntarily or by eminent domain. Congressman Burton's proposal in HR 5981 would authorize acquisition only through voluntary sales, that is, the federal government could acquire a barrier island only if the owner of the island would voluntarily sell it.

Public acquisition is resisted in many quarters for a variety of reasons. To some it is too costly, an issue that was addressed in the hearings on HR 5981 and S 2686 during spring 1980.

Federal Programs versus Public Acquisition

Two colleagues, John R. Sheaffer and Louis Rozaklis, and I prepared testimony that compared the estimated costs of current federal programs if applied to development of the undeveloped, unprotected islands and the estimated costs to acquire them.* Table 2 summarizes the high estimates used by Sheaffer and Rozaklis in their testimony in the House of Representatives and the low estimates that I presented in the Senate.

The high estimates in Table 2 are based on the National Park Service's April 1980 inventory, showing 480,000 acres of undeveloped, unprotected barrier structures, consisting of uplands, wetlands, and interior waters. The estimates assume the development of the upland portions of the islands, and the dredging and filling of as much as 60,000 acres of wetlands for development purposes. The low estimates assume development of 160,000 acres of uplands only, and omit wetlands and interior waters from the calculations.

---

*Copies of the testimony are available upon request to the author.

Table 2. Estimated present worth of current federal programs approach.

Programs	*Low* *Federal Costs*	*Low* *Percent*	*High* *Federal Costs*	*High* *Percent*
	($ Billion)			
Sewers and wastewater treatment	$1.20	29	$ 3.61	32
Water supply	$0.68	16	$ 2.00	18
Roads, bridges, causeways	$1.11	27	$ 2.77	25
Disaster relief	$0.42	10	$ 1.31	12
Flood insurance	$0.25	06	$ 0.79	07
Shore protection, maintenance, flood control	$0.47	11	$ 0.72	06
Total	$4.13	100	$11.20	100

Source: High estimates — "Barrier Islands Purchase: A Cost-Effective Approach to Management." Testimony of John R. Sheaffer and Louis Rozaklis before the House Committee on Interior and Insular Affairs, Subcommittee on National Parks and Insular Affairs, on HR 5981, March 27, 1980.

Low estimates — Statement of John R. Sheaffer, H. Crane Miller, and Louis Rozaklis, Sheaffer & Roland, Inc., before the Committee on Energy and Natural Resources, United States Senate, concerning S. 2686, June 12, 1980.

In summary, our analysis showed that public purchase of the undeveloped, unprotected barrier islands would be the most cost-effective approach to manage these unique and fragile ecosystems. The cost to the federal government of subsidizing their development would be five times or more the cost of purchasing the islands, in both the high and the low development estimates.

Low development estimates of current federal program costs were $4.1 billion; high estimates were $11.2 billion. Low estimates for public acquisition were $0.8 billion; high estimates were $2.0 billion (Table 3).

Costs to acquire the undeveloped, unprotected barrier islands were based on $5,000 per acre for developable uplands, and $4,000 per acre for wetlands. The price per acre for uplands was derived from National Park Service acquisition of land for four southern National Seashores from 1974 to 1979, which averaged $4,890 per acre (adjusted upward slightly to reflect 1980 values). No comparable average figure was found for wetlands; nevertheless, an average cost of $4,000 per acre is considered to be very conservative on the high side.

Since those analyses were prepared, the National Park Service revised its April 1980 inventory of barrier islands, removing nearly 200,000 acres from the undeveloped, unprotected category. In its August 1980 revision, the Park Service deleted about 150,000 acres from the inventory on grounds that the lands did "not fully satisfy definition of a barrier structure." Most of the acreage deleted was in Texas (108,000 acres) and Louisiana (39,000 acres). An estimated 45,000 acres were transferred into the category of protected islands (Class II) when it was determined that they were, in fact, public recreational beaches, wildlife protection areas, public parks, wildlife refuges, or military areas. Finally, about 4,300 acres were reclassified as developed (Class I), and removed from the undeveloped category.

Table 3. Summary comparison of estimated present worth of public purchase versus estimated present worth of current federal programs.

	($ Billion) *Low*	*High*
Present worth — public purchase	$0.80	$2.02
Present worth — current programs	$4.13	$11.20
Ratio of current programs to public purchase	5.2:1	5.5:1

Source: See Table 2. Both Table 2 and Table 3 are keyed to acreages in the April 1980 inventory of undeveloped, unprotected barrier islands, National Park Service.

The August 1980 inventory removed nearly 43 percent of the acreage from the undeveloped, unprotected category of barrier islands (Table 1). Since our current federal programs and public acquisition costs were keyed to acreage, I have derived more estimates based on the latest inventory, applying the same methodology used in our analyses for the congressional testimony (Table 4). Although the dollar figures are lower, the ratios of current program subsidies to the cost of public acquisition are comparable.

Table 4. Comparison of estimated present worth of current federal programs to estimated present worth of public acquisition.

	($ Billion)			
	Low		*High*	
Programs	*Federal Costs*	*Percent*	*Federal Costs*	*Percent*
Sewers and wastewater treatment	$0.70	29	$2.03	34
Water supply	$0.40	16	$1.13	19
Roads, bridges, causeways	$0.86	35	$1.50	25
Disaster relief	$0.25	10	$0.73	12
Flood insurance	$0.15	06	$0.45	07
Shore protection	$0.10	04	$0.21	03
Total	$2.46	100	$6.05	100
Estimated costs of public acquisition	$0.46		$1.16	
Ratio of current programs to public acquisition	5.3:1		5.2:1	

Source: Author. Estimates keyed to August 1980 inventory of undeveloped, unprotected barrier islands, National Park Service.

Along a 20-mile reach from Ft. Morgan to Gulf Shores, Alabama, Hurricane Frederic swept hundreds of houses cleanly off their piling foundations. Pilings left behind were often the only evidence remaining that a house had once been on the site. Sand dunes that once fronted the Gulf were flattened and spread hundreds of meters inland.

Based on the April 1980 barrier-island inventory, current program costs to the federal government were estimated to be 5.5 to 5.2 times the acquisition costs for the high and low estimates, respectively (Table 3). As adjusted to the August 1980 inventory, the current program costs were 5.2 and 5.3 times the acquisition costs for the high and low estimates.

Implications for Federal Policy

Tables 2, 3, and 4 suggest the potential magnitude of federal participation, encouragement, and subsidy of development on the undeveloped, unprotected barriers. The tables should not be read as absolute dollar amounts, but rather for their relative magnitude if the federal government were to continue a *status quo* approach with current programs. Nor should they be read as commitments to the levels of development or levels of federal funding assumed in the analyses. They simply estimate what could result if current programs were funded and applied to develop the remaining islands. In contrast, in terms of both low cost and effectiveness in protecting the islands, public acquisition appears most favorable. There are several implications for federal policy on the barrier islands that can be drawn from these analyses.

Strengthened Regulations

If the federal government adopts a strengthened regulatory posture, there would only be a minimal reduction in federal subsidies, principally the subsidies attributable to flood insurance and disaster relief. This acknowledges that federal expenditures for access to, infrastructure on, and shore protection for the islands would continue as at present, but that strengthened regulations (that is, elevating houses in the coastal high-hazard area to the wave-crest level, flood-proofing public facilities such as wastewater treatment plants, and elevating bridges and engineering them better) would reduce certain flood losses and disaster-relief expenditures. The result is essentially a *status quo* approach, and based on the estimates presented in the tables would cost the government about four to five times as much as it would cost to acquire the remaining barrier islands.

Removal of Federal Subsidies

If Congress enacted legislation removing federal subsidies and did not succumb to subsequent special-interest development pressures, there would be a significant reduction in federal expenditures for a number of years. Removal of the federal subsidies would shift the entire burden of development (including access, infrastructure, and shore protection) to the private sector. As suggested by my example of the Dauphin Island bridge, the additional costs of development thus borne by individual homeowners and commercial interests could be significant, if not prohibitive. In such a case, economics would tend to dictate high-density development — such as high-rise condominiums, or very expensive, exclusive development — in order to compensate for the removal of federal subsidies.

In time, the demand for coastal property can be expected to make high-priced development economically feasible for the developer. Demand for property with an ocean view can be expected to increase; and the supply of land available will decrease to the point that it is then economical to construct high-priced structures in any given location. Under pending proposals, disaster relief would still be available to communities following a major storm. High federal costs would be incurred for debris removal, damage to roads, sewers, shore protection facilities, and other public property. As development densities increase, a major hurricane disaster would cause damages comparable to or greater than those incurred during Hurricane Frederic. I estimate that those damages could approach or exceed the cost of acquiring the lands before they are developed.

Thus, I foresee significant reductions in federal expenditures if federal subsidies are removed, but increased federal disaster assistance as development densities increase. Given the dynamics of the barrier islands and the inevitability of major storms, any federal policy short of acquisition of the remaining undeveloped islands is going to be a very costly proposition.

Pilings leaning before the wind are dramatic, if mute, evidence of the wind and wave forces of Hurricane Frederic. Inadequate piling depths, liquefied sand, poor piling-to-floor connections, and inadequate pile bracing contributed to the failures of these houses during the storm.

Public Acquisition

If Congress is serious about protecting the undeveloped, unprotected barrier islands, a program to acquire them must be authorized and funds appropriated for that purpose. Such a program is the only effective way to avoid major federal disaster-relief costs on the islands, and a sure means of preventing development. It also is the only fair way to compensate individual barrier-island property owners for the taking of their right to develop the islands. I estimate that the present value of the cost of acquiring the upland portions of those islands over the next 20 years is roughly equivalent to the estimated federal disaster-relief costs for Hurricane Frederic — about $460 million. The question for federal policy on the barrier islands is not can we afford to buy them, but, can we afford *not* to buy them?

H. Crane Miller is Vice President and General Counsel of Sheaffer and Roland, Inc., a firm engaged in environmental planning, engineering, and resources management. He has written extensively on coastal management and flood insurance subjects. He also has served as counsel on Oceans and Atmosphere, Committee on Commerce, United States Senate, and as Assistant General Counsel of the Smithsonian Institution.

Ecological Effects of

by Paul J. Godfrey and Melinda M. Godfrey

The last two decades have seen an enormous growth in the use of four-wheel drive vehicles for recreation in a variety of environments. The occasional individual who used to obtain a surplus military jeep has now multiplied into hordes of enthusiastic drivers equipped with a remarkable array of vehicles designed for operation on sand, mud, or any unpaved surface. Coastal beaches are among the more heavily used environments, with Cape Cod, Massachusetts, Fire Island, New York, Assateague Island, Virginia, the Outer Banks of North Carolina, and large parts of the Florida and Texas coasts being most popular. In Cape Cod National Seashore alone, off-road vehicle (ORV) registrations grew from 966 in 1964 to 5,843 in 1978. Figures on actual use are even more revealing: for example, between June and September, 1976, 33,378 ORV passes were made through access points in Cape Cod National Seashore.

Fishing accounts for about half the driving on sand beaches: the ORV is ideal for finding and following schools of feeding fish. It also provides most of the comforts of home — including ice, beverages, and heavy fishing paraphernalia, while also providing shelter from the sun, insects, and thunderstorms (Figure 1).

Touring is another frequent use of ORVs on dunes and beaches: on Cape Cod, commercial tours are very popular with summer visitors, who are taken along marked trails through the scenic dunes. Some ORVs are used in official search and rescue operations, patrolling, utility maintenance, and scientific studies.

Then, as with most pursuits, there are the outlaws: joyriders acting out the suggestions of some ORV advertisers to "see what this hot little buggy can do." "Dune busting" is illegal, but guilty parties are rarely caught. And a certain unknown amount of ORV driving is related to theft, smuggling, and other crimes.

Regardless of why an ORV is on the beach or dunes, a certain physical impact is clearly delivered to the environment by the heavy machine. Concern for the well-being of coastal habitats has grown as land managers, conservationists, scientists, and ORV users themselves have seen more and more vehicles off the road, and the countless tracks left behind. Those worried about beach damage began to demand restrictions and bans, while ORV drivers became ever more organized and vocal about their rights. Decision makers were caught in the middle,

Off-Road Vehicles on Cape Cod

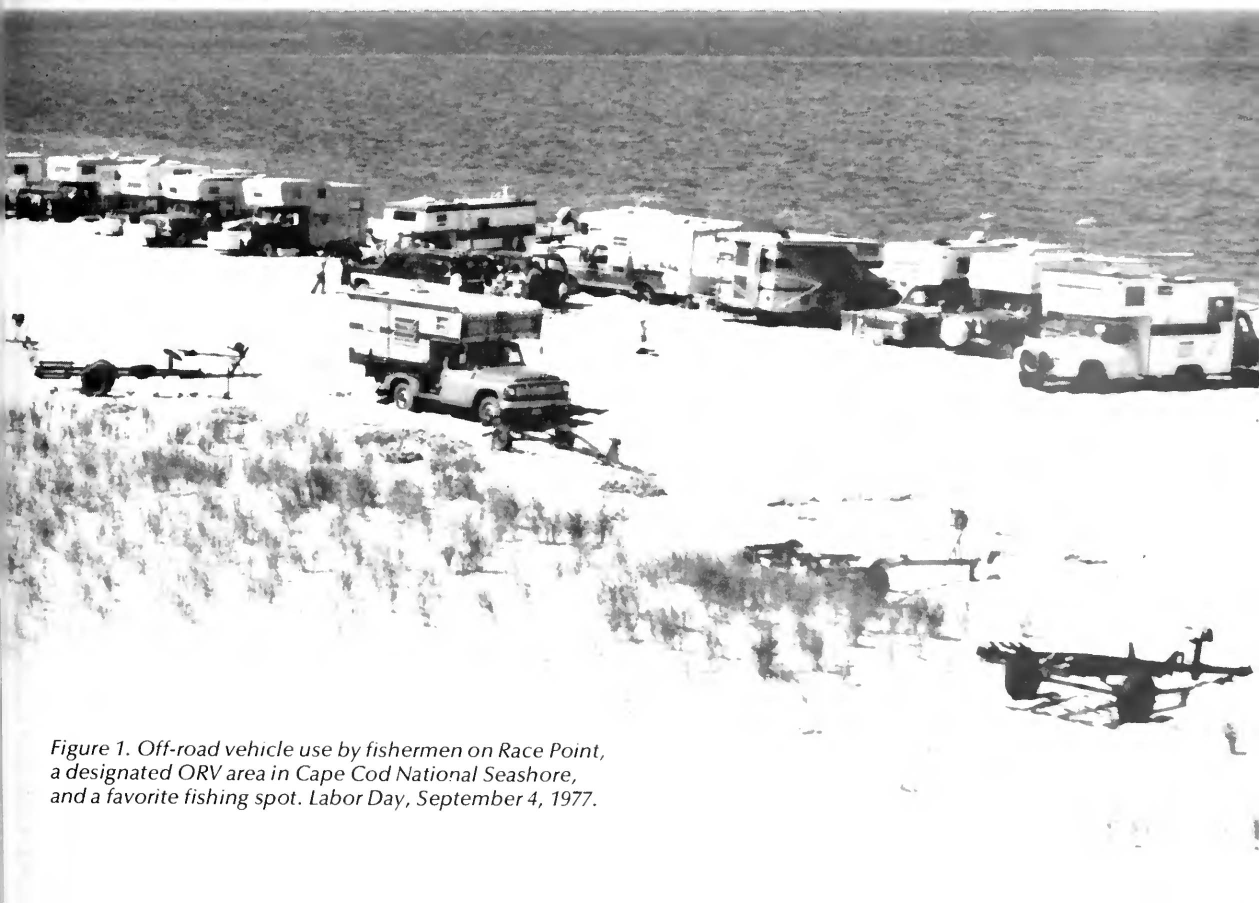
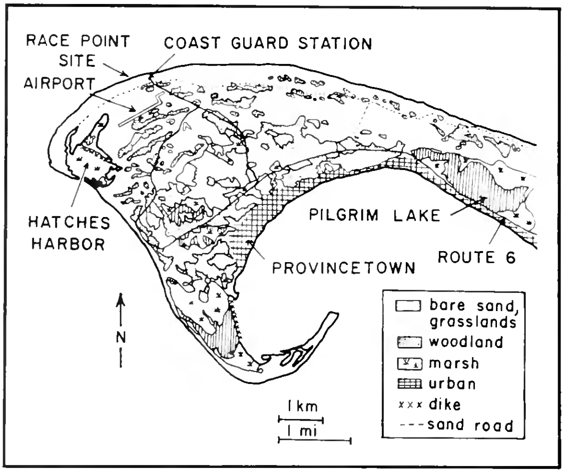


Figure 1. Off-road vehicle use by fishermen on Race Point, a designated ORV area in Cape Cod National Seashore, and a favorite fishing spot. Labor Day, September 4, 1977.

with only anecdotal and observational data to draw on. To begin remedying this situation, National Park Service (NPS) officials requested a scientific evaluation of ORV impacts at Cape Cod National Seashore, and the National Park Service Cooperative Research Unit (NPS CRU) at the University of Massachusetts at Amherst began an experimental study of the problem in 1974.

The NPS CRU study was done in the Province Lands of Cape Cod, where ORV use was heavy, and also where littoral currents and prevailing onshore winds provided optimal physical conditions for dune and beach development. Any damaging effects would be primarily caused by the experiment. These tests involved driving a research ORV over selected habitats (Figure 2), measuring the resulting destruction of biota and alterations of topography, and then closing off the sites and monitoring their recovery through 1978. Habitats included the ocean beach and backshore, uplands including fore, rear, and stable dunes, and intertidal salt marsh and sand flats (Figure 3). The effects of vehicles on shorebirds, primarily nesting least terns, and on sandflat infauna, with emphasis on soft-shelled clams, also were included in the project. More than 30 students and staff assistants, three senior researchers, and two additional faculty advisors from the University of Massachusetts were involved.

Although Cape Cod is representative of the northeastern United States, it differs in various ways from southern coasts. Decisions about ORV impacts in the middle-Atlantic, southeastern, and Gulf states should be based on local data rather than on direct extrapolation from the results of the Cape Cod project. Studies now under way will provide more regional information on ORV effects.



Province Lands, Cape Cod, showing ORV study sites.

The Beach: Foreshore and Backshore

The intertidal ocean beach is a zone of constant change, alternately submerged by the tides and then exposed to air, and continually rearranged by wind, waves, and currents. Nevertheless, it teems with microscopic life: large numbers of bacteria exist by breaking down the organic matter that washes up, making the beach an important site of nutrient recycling. Single-celled algae serve as primary producers, surviving, like the bacteria, on

Figure 2. ORV experimental impact test site on Race Point Beach. Impacts delivered to the test track on the right side totalled 675, and on the left, 270. (Photo by John Brodhead, July 13, 1974)

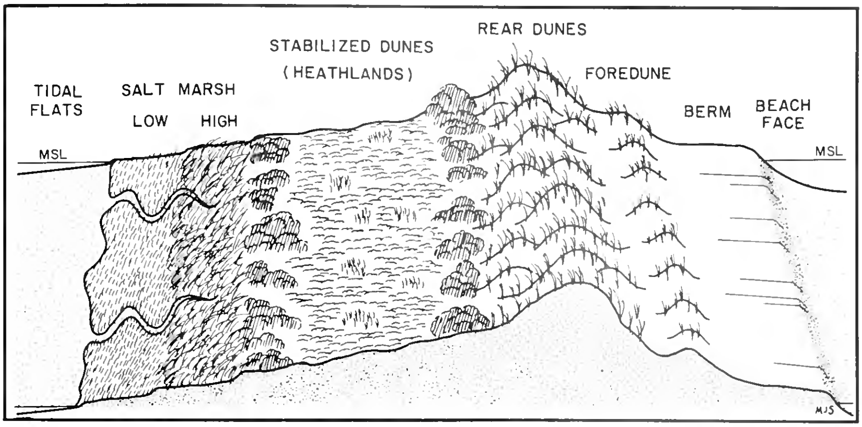


Figure 3. Habitats impacted during the ORV study on Race Point Beach and Hatches Harbor, Cape Cod National Seashore. Highest tides can reach the foredune edge on the ocean side, and cover the high salt marsh on the back side. The region in between represents an upland environment.

and between the grains of sand; and almost every invertebrate phylum has interstitial representatives. Macroscopic animals most commonly found on the Province Lands beaches of Cape Cod, other than birds, are various amphipods, of which *Talorchestia* is an example. Much of the beach life is concentrated in and around organic drift lines (accumulations of debris left by high tides) on the backshore: here bacteria are 1,000 times more numerous than in bare sand nearby. Many amphipods, insects, spiders, and other organisms occupy predatory and scavenging niches in the drift-line community.

Experimental impacts on the beach system were difficult to conduct and results varied greatly, partly because of the frequently changing habitat. Nevertheless, Henry Walker* determined that ORV impacts on the beach foreshore were capable of reducing populations of diatoms by 90 percent. The next tide cycle, however, would rearrange the beach sand, and populations would quickly recover.

James Gilligan's work showed that microbes were highly concentrated under patches of organic detritus on the backshore. When impacted by an ORV, the detritus was broken up and the bacterial populations reduced by one-half, which he attributed to dessication. Further studies on the drift lines by David Reynolds and Robert Zaremba showed that ORV impacts were a serious problem for higher plants. The drift material contains the seeds and fragments of beach plants, mainly *Ammophila breviligulata* (American beach grass), which sprout and grow after being deposited on the backshore by high tides, usually in winter (Figure 4). Wheels passing over the drift lines pulverize and disperse organic matter; the churned up sand dries out, nutrients are lost, and the young dune plants that would be the precursors of new dunes are physically destroyed.

As a result of these studies, we recommend that if vehicles are to be allowed on a beach, they be confined to an "ORV corridor" between the berm* crest and the upper drift lines, except where birds are nesting (Figure 5). This part of the beach is, in general, minimally populated by plants and animals, its topography changes frequently in any case, and it offers safer passage to vehicles than does the beach face. The upper beach drift-line area should be strictly off limits.

Figure 4. Drift lines and sprouting beach grass plants, Ammophila breviligulata, *near Herring Cove Beach in the Province Lands, Cape Cod. ORV traffic in the background has demolished a portion of the drift line and all plants therein. Where traffic does not follow the base of the dune, a sloping profile is visible. A scarped profile can be seen in the background where ORVs do travel at the base of the dune. (October 24, 1980)*

---

*Researchers cited in this article were graduate students at the University of Massachusetts at Amherst when the study was done, except as otherwise noted.

*The sandy strip between dunes or cliffs and the mean high water line.

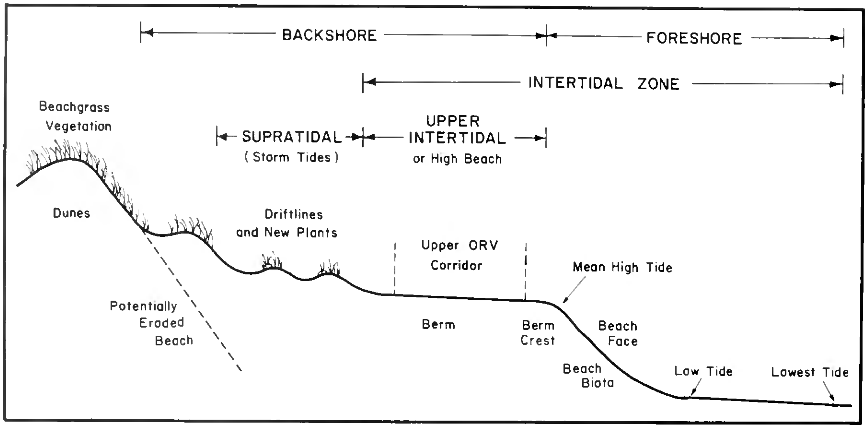


Figure 5. A typical beach showing optimal conditions for the establishment of an "ORV corridor" on the berm. Traffic should stay seaward of the upper drift lines and toward the berm crest – this will provide the safest track, and be least damaging environmentally. Terns nest, and new dunes form, in the drift line region. ORV traffic may be possible at low tide on the beach face, particularly during winter when a "lower ORV corridor" might be established, but this area is often hazardous. A severe storm could potentially erode the beach back to the foredune edge. Under such conditions, ORV traffic should be prohibited.

Birds

The backshore of sand beaches is a favored nesting site for water birds, particularly terns, which are of special concern to conservationists and park managers. Bradford Blodget set out to measure the effects of ORVs on the least tern (*Sterna albifrons*), which nests regularly on the Province Lands beaches. He determined how close a vehicle could approach before the birds left their nests. (Obviously, when birds are off their nests, eggs are exposed to heat or cold, and to predators.) The results of the experiments will not surprise anyone accustomed to using a vehicle as a wildlife observation blind: the terns were far less disturbed by a vehicle than by people or dogs on foot. The "flushing distance" for an ORV was twice that for a person. The management implications are plain: if vehicles stay out of the actual nesting area, they may pass within 5 meters of the sitting birds without causing much alarm, but a person approaching on foot or perhaps someone just getting out of an ORV for a few seconds, will quickly put them to flight.

Least tern on nest, Race Point, Cape Cod National Seashore.

Once the chicks hatch, there are new problems: the precocial nestlings begin running out of the colony, and on the approach of a vehicle they try to hide in tire tracks. It is especially important for drivers to be vigilant during such times.

Efforts have been made to mark tern nesting areas, and to educate the public about protecting them. At the Cape Cod National Seashore, tern colonies have been diligently marked and fenced, monitored, and protected by "tern wardens" and official volunteers, with the cooperation of many ORV drivers. Most Cape Cod drivers have learned to take care near the colonies, but the occasional unthinking individual can still endanger every nest and chick in his path. Continued ORV traffic through traditional colonies has forced common terns on Long Island, New York, to seek new colony sites, often in less suitable habitats, such as marshes and low sandy banks subject to storm flooding (Dr. P. A. and F. G. Buckley).

Little is known about the effects of ORVs on transient flocks of shorebirds that rest and feed near the paths followed by beach drivers: light traffic may be of little significance, but we suspect that constant disturbance may be very detrimental to birds that are already tired and hungry.

Foredune and Rear Dune

On an accreting beach, just landward of the backshore, there is a zone of young, low dunes that has formed from drift lines or by seaward extension of older dunes. These foredunes are a

Figure 6. A scarped foredune edge created by vehicles running too close to the dune on Race Point Beach. Traffic has prevented beach grass plants from expanding out onto the backshore. Demolished drift lines can be seen on the left. (October 24, 1980)

region of active growth of beachgrass, stimulated by the continual addition of wind-blown sand. John Brodhead found that rhizomes of beachgrass could grow seaward more than 2 centimeters per day under good conditions, with an overall advance by the dune of 1 to 2 meters during the growing season. The vertical growth of foredunes on our study plot was 1.2 meters during the four-year monitoring period.

The effect of ORVs on the foredune edge is especially dramatic. Brodhead's tests showed that 50 passes of a vehicle were sufficient to stop the seaward growth of the dune completely. Traffic can produce a scarped rather than a sloping dune front, leaving the unprotected sand open to wind erosion (Figure 6). This zone was quick to recover when disturbance ceased: two years sufficed for its complete rehabilitation. Nevertheless, the dune edge should be protected from continued ORV traffic, to allow seaward advance of the dunes (Figure 7).

ORV impacts delivered to the foredune crest, and the rear dune behind it, totaled 675 passes in the experiments on heavy impact and 270 in tests on moderate impact. The beach grass rhizomes normally grow between the upper dry layer of sand and the lower moist layer (usually 10 to 15 centimeters below the sand surface), and the churned up sand dried out to below this level. *Just one pass is enough to damage the plants physically.* As the tires roll over the dune surface, shear forces extend down into the sand and break rhizomes. Although fragmentation is an advantage to plants undergoing natural erosion, it is not beneficial to plants being hit by tires, for the fragments are churned up to the surface and die. After 70 to 175

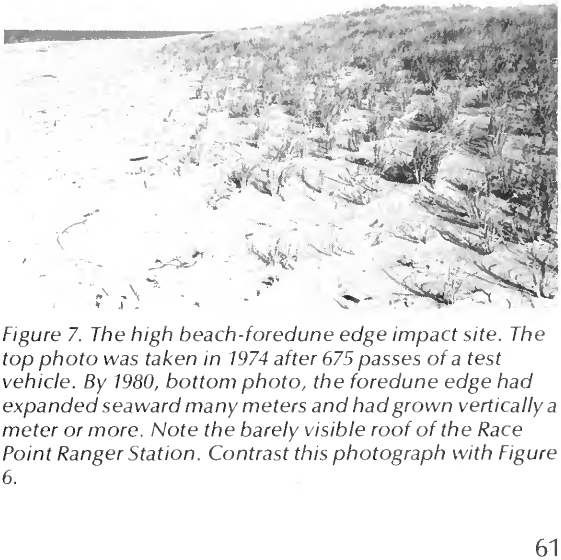


Figure 7. The high beach-foredune edge impact site. The top photo was taken in 1974 after 675 passes of a test vehicle. By 1980, bottom photo, the foredune edge had expanded seaward many meters and had grown vertically a meter or more. Note the barely visible roof of the Race Point Ranger Station. Contrast this photograph with Figure 6.

passes, plant biomass in the dunes was reduced to nearly zero. Maximum damage was done to the vegetation by a relatively low level of traffic, and we determined that no carrying capacity for vehicles can be assigned to dune vegetation. It makes little difference whether 100 or 10,000 ORVs use a dune track; a road has been created in any case. It is therefore better to have a few well-managed and well-patrolled dune tracks than to have many lightly used trails.

When bare tracks are oriented toward prevailing winds, erosion can create a "blow-out" — an ever-increasing dune hollow — that will threaten the stability of the surrounding dune system (Figure 8). When grass shelters a track from prevailing winds, little or no erosion results. But by making sure that such vegetation exists along designated tracks in the dune uplands, we can reduce erosion problems. Wooden ramps on trails that go over dune ridges to the beach can prevent downcutting and loss of the sand.

Figure 8. Major dune damage by ORVs and a resulting "blow-out" in a restricted area of the Province Lands. The dune faces northwest and is now subject to erosion by prevailing winter winds.

After the 1974 experimental impacts were completed, dune vegetation recovered at different rates depending on the site. It made no difference how many impacts had been delivered. The foredune crest recovered after two years, at least from the standpoint of measured biomass, although the tire tracks were still faintly visible. Now, six years later, the site is detectable only to one who knows exactly where it is.

On the rear dune, however, where the supply of fresh sand is reduced to a trickle and grass growth is less vigorous, recovery was slower and the tire tracks can still be seen (Figure 9). Mark Benedict, surveying closed trails throughout the Province Lands, found that tracks through older, stabilized rear dunes were clearly visible for at least eight years. Therefore, careful management of inner dune areas is essential if long-term damage is to be avoided.

Figure 9. Reardune impact site on Race Point Beach. The top photo taken in 1974 shows the effects of 675 passes. In 1978, bottom photo, the track was still plainly visible even though revegetated. The present appearance of the track is very much the same. A new building appeared on the horizon in 1978 – the famous Old Harbor Station, which was moved from Nauset Beach in Orleans.

On retreating barrier beaches (not studied in the Province Lands), the foredune zone may be lacking since it would be the first to go in a storm. Frequently, the dunes are broken down by storm tides and the sand is carried from the beach into and through the dune zone, creating "overwash fans" on which new dune lines form from drift material that is deposited on the sand, just as on an accreting shore. New dunes also can start as rhizomes from surviving grass grow out into this overwashed sand. As these embryonic dunes grow, they impede further overwash and conserve the supply of sand by slowing wind loss as well.

Vehicle traffic through overwash passes prevents the growth of these young dunes that would eventually seal the gap. Similarly, driving on an overwash fan will keep it bare, low, and uncolonized by dune and marsh plants that could trap and slow sand movement. On Nauset Beach, Massachusetts, Robert Zaremba and Stephen

Leatherman* planted beachgrass in overwash passes being used by ORVs. Overwashes during the New England blizzard of 1978 moved sand across the barrier at these sites and at similar but unplanted passes. At the former, the grass held, and there was much less overall change to the barrier than at the latter, where severe overwash occurred and continued.

This is not to say that all overwashing is caused by vehicles, or that overwash is bad; indeed it is the natural means by which a barrier beach survives rising sea level (see *Oceanus*, Vol. 19, No. 5, p. 27). But if we allow vehicles to increase the probability and severity of overwash by interfering with natural dune formation, we clearly create unnatural conditions. We believe that retreating barriers are rather delicately balanced between the forces of the sea and the ability of vegetation to recover from storms and stabilize the barriers. If the impacts of vehicles are added, it might push the resiliency of the system too far. A degraded barrier would be less effective protection for the marshes and lagoon behind, and would leave the mainland more vulnerable in severe storms. Vehicles should therefore be prohibited from eroding barrier beaches wherever possible.

Stabilized Dunes

Once a dune system reaches a stable state in which no new sand is being added and none is being blown away, the beachgrass community is slowly replaced by other species better adapted to the new conditions. In the northeast, these new communities are various types of heathlands and grasslands. Heathlands were once widespread on Cape Cod, having resulted from burning and grazing of inland vegetation types as well as from succession on stable dunes. Bearberry, beach heather, bayberry, huckleberry, blueberry, and other low shrubs may be found here; in time larger shrubs and young pitch pines take over, and the next stage of succession is the typical Cape Cod oak-pine woodland.

Low-growing grasslands and heathlands invite ORV use, and therefore researchers subjected three such communities to 50 vehicle passes and observed their rates of recovery for four years. These communities were heathland dominated by bearberry, *Arctostaphylos uva-ursi*, heathland dominated by false beach heather, *Hudsonia tomentosa*, and grassland dominated by hairgrass and lichens, *Deschampsia flexuosa* and *Cladonia* spp.

In the bearberry heathland, all leaves and twigs were killed by the driving, but the hard, woody, creeping stems were left intact. Soon after the treatment, new leaves and twigs emerged from the stems, and within four years no effect of the vehicle could be measured (Figure 10). We believe, however, that if heavier impact had broken the stems, we would not have seen such full and rapid recovery. Also, it must be remembered that these tests were done on level ground. Where vehicles have been driven on hillside bearberry communities, the tracks have formed gullies and remained visible for many years.

The beach heather vegetation was completely destroyed within the tire tracks. *Hudsonia* lacks rhizomes and creepers and can reproduce only by seed, a slow process. After four years, seedlings of beach heather and other species had barely begun to invade the bare wheel ruts (Figure 11). Meanwhile, the sand was exposed to the wind, with the potential for a large and spreading blow-out.

Figure 10. Bearberry, Arctostaphylos uva-ursi, *impact site on stabilized dunes near Hatches Harbor, Cape Cod National Seashore. Top photo was taken in 1974 after 50 passes of an ORV. Revegetation of the tracks by 1978, bottom photo, resulted primarily from resprouting of undamaged, woody stems creeping on the ground surface and visible in the top photo. The level of impact was not enough to destroy these stems completely. (1974 photo by John Brodhead)*

---

*Leader, NPS CRU, University of Massachusetts at Amherst.

Figure 11. False beach heather, Hudsonia tomentosa, *impact site on stabilized dunes near Hatches Harbor. Top photo was taken in 1974 after 50 passes of an ORV, bottom photo in 1978. Revegetation of the tracks occurred only by establishment of new seedlings.* Hudsonia *does not spread laterally by means of creeping stems.*

Vehicle impact also severely damaged the hairgrass-lichen community. The tussocky grass was somewhat resistant to tires, but the dry and fragile lichens were simply pulverized. The hairgrass began recovering promptly; within three seasons it had regained preimpact biomass. But even after four years few lichens could be found among the hairgrass clumps. We do not know how long complete recovery will take.

Salt Marshes and Tidal Flats

Under natural conditions, the boundary between a Massachusetts salt marsh and adjacent upland is occupied by a tall form of salt meadow cordgrass (*Spartina patens* var. *monogyna*) that can survive either marsh or dune conditions. This grass serves well to protect the dune edge from wind and wave erosion (and subsequent deposition of sand on the marsh itself). The next zone down is that of the weak-stemmed (decumbent) form of *S. patens*, typical of salt marshes flooded by spring tides. Below this is the low marsh, where salt marsh cordgrass (*Spartina alterniflora*) and glasswort (*Salicornia* spp.) mark the community flooded by every high tide. Beyond the marsh are sand and mud flats with their characteristic faunas.

The Hatches Harbor area near Race Point on Cape Cod is a complex of salt marshes and intertidal flats that contain soft-shelled clams, *Mya arenaria*. When our studies began in 1974, both the flats and the upper boundary of the marsh showed evidence of much driving. In what might have been the salt meadow cordgrass zone of the marsh border, we found a continuous band of bare, rutted sand; the dune was scarped and eroded rather than smoothly sloped (Figure 12). Much of the intertidal flat was covered with tracks and the soil was compacted. To observe the response of these environments to protection from ORVs, John Brodhead set up vehicle exclosures and monitored subsequent biological recovery.

Once the marsh border was protected, beachgrass (*Ammophila*) and salt meadow cordgrass (*S. patens* var. *monogyna*) were able to grow across a 3-meter-wide vehicle track within two years. The previously impacted exclosures in the intertidal flats developed healthy young salt marsh communities within four years (Figure 13). Evidently, ORV use on these flats was preventing the invasion of salt marsh plants by physically destroying seedlings, and also by compacting the surface to such an extent that normal gas exchange and percolation into the sand were prevented. We think that certain large barren areas behind Cape Cod barrier beaches would become marshes if protected from drivers, and that total marsh cover could increase by at least 10 percent in Hatches Harbor.

People do not frequently drive ORVs in the established high and low marshes but might do so more often if the sand flats and marsh borders were closed. Therefore, Brodhead performed controlled-driving experiments in the two marsh zones and used the same procedures as on the beach and dunes.

Figure 12. Eroding dune/tidal marsh border, typical of Hatches Harbor wherever vehicles have traveled around the periphery of the marsh. The barren zone shown here is potentially high salt marsh and would be dominated by salt meadow cordgrass, Spartina patens.

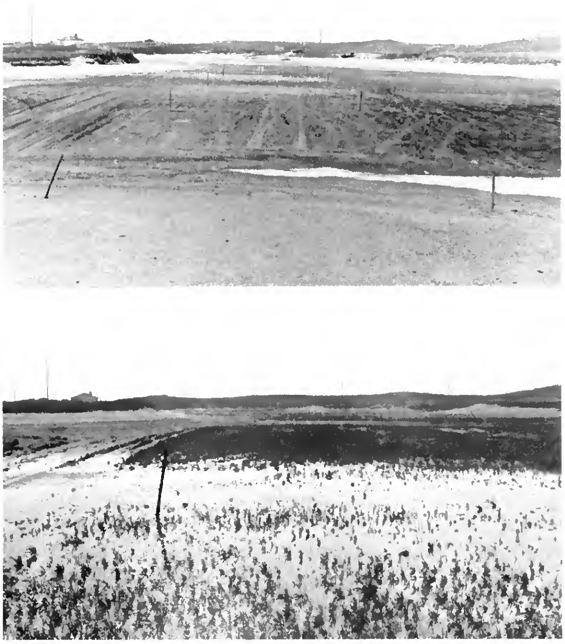


Figure 13. Exclosures set up in Hatches Harbor on barren tide flats heavily traveled on by ORVs. Top photo (1974) shows the exclosure soon after construction. (The Race Point light station is visible on the left horizon.) Vehicles stayed out of the fenced area and marsh plants began to invade quickly. By 1978, bottom photo, the marsh was developing well. Hatches Harbor had been closed to vehicles prior to 1978, allowing vegetation to invade all formerly barren flats.

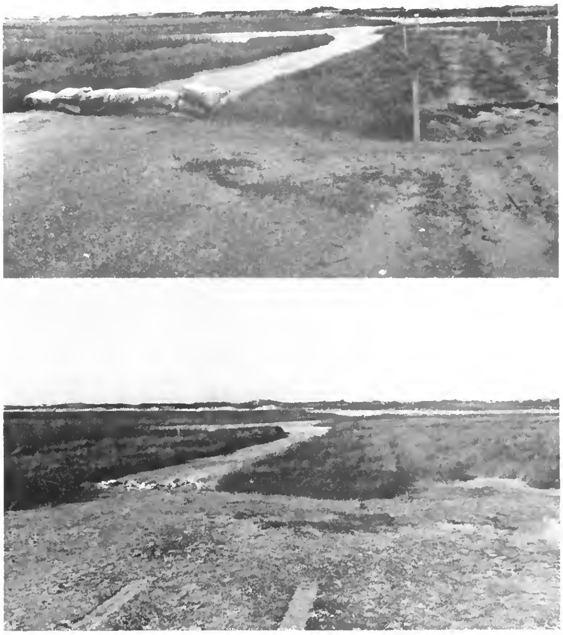


Figure 14. High marsh impact site in Hatches Harbor. On the right in the top photo (1975) is a test track after 200 passes. On the left, a barren channel used by vehicles was closed with sand bags to slow water flow. By 1977, bottom photo, the grasses (mainly Spartina patens*) had been able to revegetate the test track, since the root mat was not completely destroyed; nevertheless, the tracks were still visible and are so today. The bags broke down in the channel, but salt marsh cord grass,* Spartina alterniflora*, can be seen invading the area in front of the channel. With continued protection, the channel should eventually fill with marsh grass.*

In the decumbent *S. patens* zone, 200 passes could occur before the grass was killed. Regrowth in the test tracks was very slow where the mat was severely damaged and bare sand was exposed. Where tracks were eroded by tide water, recolonization was practically nonexistent. In contrast, the grass was able to recover in a few years if some of the original vegetation mat remained (Figure 14).

The soft muck of the low marsh was very easily rutted by a vehicle. Ninety passes through a salt marsh cordgrass (*Spartina alterniflora*) stand were more than enough to obliterate the vegetation. (Brodhead's plan to apply 100 passes was abandoned when the test vehicle got stuck in the resulting quagmire.) Despite the mess created by the test, regrowth began immediately, and after two years the ruts were nearly obscured by new grass. Nevertheless, the ruts themselves remained after four years, collecting saltwater that formed small salt pannes during periods of high evaporation and provided a good habitat for salt marsh mosquito larvae. (Figure 15).

Nancy Wheeler studied the impact of vehicles on sand-flat infauna and found that various animals, particularly amphipods, *Talorchestia*, were much fewer in flats where driving occurred. She also concluded that 50 passes were enough to reduce populations of polychaete worms, *Scolopolos fragilis*, from 240 per square meter to 0. In a series of tests, Wheeler subjected populations of soft-shelled clams, *Mya arenaria*, to vehicle impacts of 50 and 1,000 passes and found that 50 were enough to kill up to a third of her test animals, and that 1,000 killed them all. Although this test did not prove that vehicles caused the decline of clams in Hatches Harbor, it did show that even relatively light traffic can have very damaging effects on the biota of the flats. Hundreds of vehicle passes can easily occur during a summer day on a well-traveled sand-flat route.

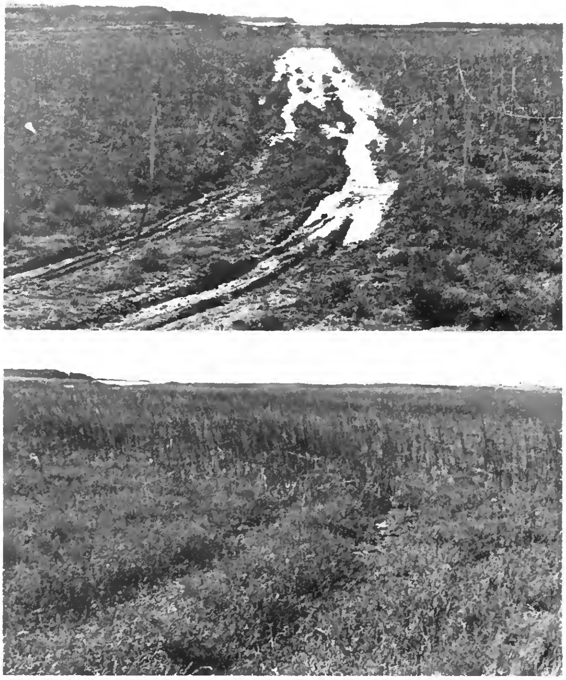


Figure 15. Low marsh impact site in Hatches Harbor. Top photo (1974) shows how 90 ORV passes created a quagmire and depressions in the peat. By 1978, bottom photo, the cordgrass, Spartina alterniflora, *had invaded most of the site, although depressions remained clearly visible. Low vegetation in front of the grass is glasswort,* Salicornia.

From all these studies, it is clear that there is no satisfactory ORV corridor in the intertidal marsh and sand-flat environment; unacceptable damage occurs everywhere. Therefore, such areas should be completely protected.

What Is Being Done?

From these and other studies have come many recommendations to both the coastal land manager and the ORV driver. The use to which these ideas will be put depends on the goals and needs of the decision makers. There can be no doubt that ORVs do environmental damage in just about any ecological setting. The problem is to decide where the least damage will occur, and how much, if any, is acceptable.

The control of ORVs on federal lands was mandated by President Nixon's 1972 Executive Order 11644, subsequently amended by President Carter in 1977 in his EO 11989. In effect, these orders give the power to control ORVs to the "respective agency head" when he determines that ORV use is "causing considerable adverse effects." The burden, of course, is placed on the "agency head" to determine that such control is needed. Today, actions are being implemented that will curb ORV excesses. The National Park Service is preparing an ORV management plan for Cape Cod National Seashore, based largely on the research described here, and designed to meet the needs of both the park and its visitors. The plan would allow some use on designated and acceptable fishing beaches, controlled use in upland areas, and closures in ecologically sensitive sections. Some plans in park areas other than Cape Cod call for the total elimination of privately owned ORVs and for the provision of public transportation systems. Where ORV use is to be continued, dune damage can be reduced by building ramps or other structures that will improve access to the beaches.

For the last several years, a driving ban in Hatches Harbor has produced a noticeable increase of marsh plants on formerly barren flats. The town of Eastham, Massachusetts, voted to close its Nauset (Coast Guard) Beach following the extensive overwashing of 1978. Dunes are now growing on the overwashed sites, and areas that had been damaged by ORVs are healing. If Nauset (Coast Guard) Beach were reopened to ORVs, extensive damage would likely result during this very sensitive phase in the life of the barrier beach. Freedom from vehicles also has greatly increased the enjoyment of thousands of visitors who want to walk on a beach that has no tracks or other disturbances.

Education programs are under way, under the auspices of the National Park Service and other agencies, and also through user clubs, such as the Massachusetts Beach Buggy Association, Cape Cod Four-Wheel Drive Club, and the United Mobile Sportfishermen. The Cape Cod National Seashore has recently instituted a program in which permittees are given a training course and must then sign an affidavit verifying their participation therein. Responsible ORV organizations have instructed members about the need to protect dunes and wildlife, to develop codes of conduct, to assist in both research and planning for ORV management, and to participate in dune planting projects. It is clear that if ORVs are to be tolerated, drivers must be sensitive to the environments they are entering. ORV traffic must be managed, and it is important that all parties realize that cooperation and control are necessary to prevent continuing damage to coastal ecosystems.

Paul J. Godfrey is Associate Professor of Botany at the University of Massachusetts at Amherst, Research Biologist (WAE), National Park Service, and was Leader of the NPS Cooperative Research Unit at the University of Massachusetts at Amherst from 1973 to 1977. Melinda M. Godfrey is his wife and collaborator, and a marine biologist.

All photographs were taken by Paul J. Godfrey unless noted otherwise, and graphics are by Michael J. Stroman.

The opinions presented here are solely those of the authors and do not necessarily reflect official positions of the National Park Service.

Acknowledgments
The research described in this article was supported by National Park Service Contract No. CX-1600-5-0001, North Atlantic Regional Office, Boston, Mass., P. A. Buckley, Chief Scientist. We thank Dr. Buckley for helpful comments on this manuscript. Additional support came from the Office of Science and Technology, National Park Service, Washington, D.C. Research facilities and other assistance were provided by Cape Cod National Seashore and coordinated by James Killian. Completion of the studies was aided by Stephen P. Leatherman. D. Craig Edwards of the University of Massachusetts at Amherst Zoology Department was advisor for the infauna study, and Fred Greeley of the University of Massachusetts at Amherst Department of Forestry and Wildlife was advisor for the tern research.

Selected References

Benedict, M.A. 1978. The preparation of an off-road recreational trail map of the Province Lands, Cape Cod: Procedures, observations, and management suggestions. NPS CRU Report No. 27, University of Massachusetts at Amherst.

Blodget, B.G. 1979. The effect of off-road vehicles on least terns and other shorebirds. NPS CRU Report No. 26, University of Massachusetts at Amherst.

Brodhead, J.M., and P.J. Godfrey. 1977. Off-road vehicle impact in Cape Cod National Seashore: Disruption and recovery of dune vegetation. *Internat. J. Biometeor.* 21: 299-306.

———. 1979. The effects of off-road vehicles on plants of a northern marsh. NPS CRU Report No. 33, University of Massachusetts at Amherst. The effects of off-road vehicles on coastal dune vegetation in the Province Lands. NPS CRU Report No. 32, University of Massachusetts at Amherst.

Godfrey, P.J. 1976. Barrier beaches of the East Coast. *Oceanus* 19(5): 27-40.

Godfrey, P.J., J.M. Brodhead, H. Walker, J. Gilligan, and A. Davis. 1975. Ecological effects of off-road vehicles in Cape Cod National Seashore, Massachusetts. NPS CRU Report No. 6, University of Massachusetts at Amherst.

Godfrey, P.J., S.P. Leatherman, and P.A. Buckley. 1978. Impacts of off-road vehicles on coastal ecosystems. In *Coastal Zone '78; Proceedings – Symposium on Coastal Zone Planning and Management*, pp. 581-600. San Francisco.

———. 1980. ORV's and barrier beach degradation. *Parks* 5(2): 5-11.

Palmer, J.F., and S.P. Leatherman. 1979. Off-road vehicle usage on federally managed coastal parklands. NPS CRU Report No. 46, University of Massachusetts at Amherst.

Steiner, A.J., and S.P. Leatherman. 1979. A preliminary study of the environmental effects of recreational usage on dune and beach ecosystems of Assateague Island. NPS CRU Report No. 44, University of Massachusetts at Amherst.

Wheeler, N.R. 1979. Effects of off-road vehicles on the infauna of Hatches Harbor, Cape Cod National Seashore. NPS CRU Report No. 28, University of Massachusetts at Amherst.

U.S. Department of Interior, National Park Service, 1980. Analysis of management alternatives (including environmental assessment) for off-road vehicle use. Cape Cod National Seashore, North Atlantic Region, Boston, Mass.

Zaremba, R.E., P.J. Godfrey, and S.P. Leatherman. 1978. The ecological effects of off-road vehicles on the beach/backshore drift line zone in Cape Cod National Seashore, Massachusetts. NPS CRU Report No. 29, University of Massachusetts at Amherst.

INDEX

Volume 23 (1980)

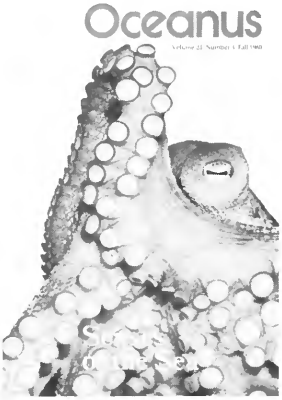
Number 1, Spring, A Decade of Big Ocean Science: Edward Wenk, Jr. *Genesis of a Marine Policy — The IDOE* — Feenan D. Jennings and Lauriston R. King *Bureaucracy and Science: The IDOE in the National Science Foundation* — E. M. Davin and M. G. Gross *Assessing the Seabed* — J. M. Edmond *Geosecs Is Like the Yankees: Everybody Hates It and It Always Wins* — Allan R. Robinson and William Simmons *A New Dimension in Physical Oceanography* — John D. Costlow and Richard Barber *IDOE Biology Programs* — Peter Francis Hooper *Scientists' Attitudes toward Big Ocean Science* — Warren S. Wooster *The Endless Quest.*

Number 2, Summer, General Issue: John H. Steele *Patterns in Plankton* — Michael H. Glantz *El Niño: Lessons for Coastal Fisheries in Africa* — Michael J. Mottl *Submarine Hydrothermal Ore Deposits* — Daniel P. Finn *Georges Bank: The Legal Issues* — Francisco J. Palacio *The Development of Marine Science in Latin America* — Sidney Tamm *Cilia and Ctenophores.*

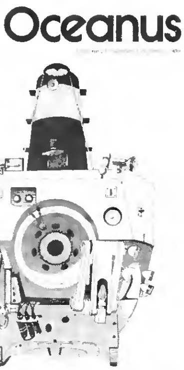
Number 3, Fall, Senses of the Sea: Jelle Atema *Senses of the Sea: An Introduction* — Jelle Atema *Tasting and Smelling Underwater* — Joseph S. Levine *Vision Underwater* — J. H. S. Blaxter *Fish Hearing* — Bernd-Ulrich Budelmann *Equilibrium and Orientation in Cephalopods* — Peter Moller *Electroperception* — Paul R. Ryan *Geomagnetic Guidance Systems in Bacteria, and Sharks, Skates, and Rays* — R. Stimson Wilcox *Ripple Communication* — William E. Evans *Dolphins and Their Mysterious Sixth Sense.*

Number 4, Winter, The Coast: Willard Bascom *Waves and Beaches* — William H. MacLeish *Going to the Beach* — David G. Aubrey *Our Dynamic Coastline* — Robert J. Livingston *The Apalachicola Experiment: Research and Management* — John Clark and Scott McCreary *Prospects for Coastal Resource Conservation in the 1980s* — Robert Dolan and Bruce Hayden *Templates of Change: Storm and Shoreline Hazards* — Orrin H. Pilkey and William J. Neal *Barrier Island Hazard Mapping* — H. Crane Miller *Federal Policies in Barrier Island Development* — Paul J. Godfrey and Melinda M. Godfrey *Ecological Effects of Off-Road Vehicles on Cape Cod.* INDEX

OCEANUS BACK ISSUES



Limited quantities of back issues are available at $4.00 each; a 25% discount is offered on orders of five or more. We accept only prepaid orders. Checks should be made payable to Woods Hole Oceanographic Institution; checks accompanying foreign orders must be payable in U.S. currency and drawn on a U.S. bank. Address orders to: Oceanus Back Issues, 1172 Commonwealth Avenue, Boston, MA 02134.

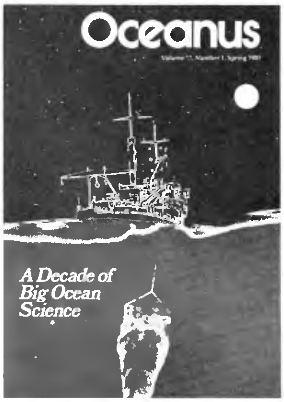


Senses of the Sea, Vol. 23:3, Fall 1980—Marine animals have complex sensory systems. Here we learn that lobsters can taste and smell, bacteria can sense their world magnetically, and some fish can sense electrically. We discover that octopuses have a sophisticated sense of equilibrium, and that some insects use the water surface to communicate. Underwater vision, hearing, and echolocation are also discussed.

General Issue, Vol. 23:2, Summer 1980—A collection of articles on a range of topics, including: the dynamics of plankton distribution; submarine hydrothermal ore deposits; legal issues involved in drilling for oil on Georges Bank; and the study of hair-like cilia in marine organisms.

A Decade of Big Ocean Science, Vol. 23:1, Spring 1980—As it has in other major branches of research, big science has become a powerful force in oceanography. The International Decade of Ocean Exploration is the case study. Eight articles examine scientific advances, management problems, political negotiations, and the attitudes of oceanographers toward the team approach.

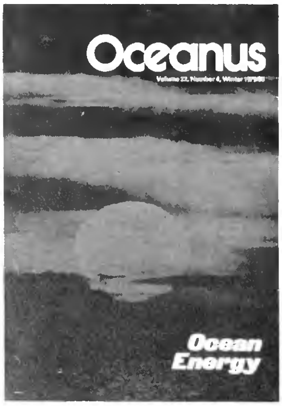
Ocean Energy, Vol. 22:4, Winter 1979/80—How much new energy can the oceans supply as conventional resources diminish? The authors in this issue say a great deal, but that most options—thermal and salinity gradients, currents, wind, waves, biomass, and tides—are long-term prospects with important social ramifications.

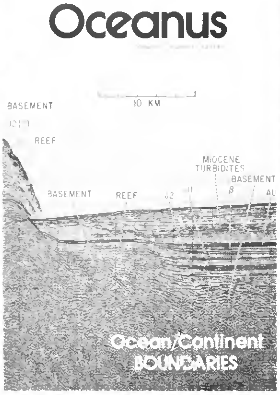


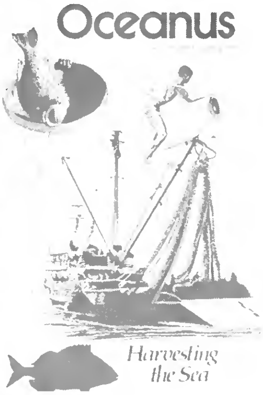
Ocean/Continent Boundaries, Vol. 22:3, Fall 1979—Continental margins are no longer being studied for plate tectonics data alone, but are being analyzed in terms of oil and gas prospects. Articles deal with present hydrocarbon assessments, ancient sea-level changes that bear on petroleum formations, and a close-up of the geology of the North Atlantic, a current frontier of hydrocarbon exploration. Other topics include ophiolites, subduction zones, earthquakes, and the formation of a new ocean, the Red Sea.

General Issue, Vol. 22:2, Summer 1979—This issue features a report by a group of eminent marine biologists on their recent deep-sea discoveries of hitherto unknown forms of life in the Galápagos Rift area. Another article discusses how scuba diving is revolutionizing the world of plankton biology. Also included are pieces on fish schooling, coastal mixing processes, chlorine in the marine environment, drugs from the sea, and Mexico's shrimp industry.

Harvesting The Sea, Vol. 22:1, Spring 1979—Although there will be two billion more mouths to feed in the year 2000, it is doubtful that the global fish harvest will increase much beyond present yields. Nevertheless, third world countries are looking to more accessible vessel and fishery technology to meet their protein needs. These topics and others—the effects of the new law of the sea regime, postharvest fish losses, long-range fisheries, and krill harvesting—are discussed in this issue. Also included are articles on aquaculture in China, the dangers of introducing exotic species into aquatic ecosystems, and cultural deterrents to eating fish.







expand your own world and share it with someone else

Oceanus

[illegible]

Oceanus

The Illustrated Magazine
of Marine Science
Published by Woods Hole
Oceanographic Institution

subscription order form

Please make checks payable to Woods Hole Oceanographic Institution.
Checks accompanying foreign orders must be payable in U.S. currency and
drawn on a U.S. bank.
[illegible]

Please enter my subscription to OCEANUS for:

☐ one year at $15.00 ☐ payment enclosed

☐ please renew my subscription for one year ☐ bill me

Please send MY Subscription to:

Name (please print)

Street Address

City State Zip

Please send a GIFT Subscription to:

Name (please print)

Street Address

City State Zip

Donor's Name

Address

Oceanus

The Illustrated Magazine
of Marine Science
Published by Woods Hole
Oceanographic Institution

subscription order form

Please make checks payable to Woods Hole Oceanographic Institution.
Checks accompanying foreign orders must be payable in U.S. currency and
drawn on a U.S. bank.
[illegible]

Please enter my subscription to OCEANUS for:

☐ one year at $15.00 ☐ payment enclosed

☐ please renew my subscription for one year ☐ bill me

Please send MY Subscription to:

Name (please print)

Street Address

City State Zip

Please send a GIFT Subscription to:

Name (please print)

Street Address

City State Zip

Donor's Name

Address

HAVE THE
SUBSCRIPTION
COUPONS
BEEN DETACHED?

If someone else has
made use of the
coupons attached to
this card, you can still
subscribe. Just send a
check — $15 for one year
($17 overseas)
— to this address . . .

Oceanus

Woods Hole Oceanographic Institution
Woods Hole, Mass. 02543

PLACE
STAMP
HERE

Please make check
payable to:
Woods Hole
Oceanographic
Institution

[illegible]
Woods Hole Oceanographic Institution
Woods Hole, Mass. 02543

Remember —
You can make
your Marine
Science Library
complete with
back issues!

PLACE
STAMP
HERE

See inside
back cover

[illegible]
Woods Hole Oceanographic Institution
Woods Hole, Mass. 02543

1930 - 1980

A Valuable Addition to any Marine Science Library

Oceans and Climate, Vol. 21:4, Fall 1978—This issue examines how the oceans interact with the atmosphere to affect our climate. Articles deal with the numerous problems involved in climate research, the El Niño phenomenon, past ice ages, how the ocean heat balance is determined, and the roles of carbon dioxide, ocean temperatures, and sea ice.

General Issue, Vol. 21:3, Summer 1978—The lead article looks at the future of deep-ocean drilling, which is at a critical juncture in its development. Another piece—heavily illustrated with sharp, clear micrographs—describes the role of the scanning electron microscope in marine science. Rounding out the issue are articles on helium isotopes, seagrasses, red tide and paralytic shellfish poisoning, and the green sea turtle of the Cayman Islands.

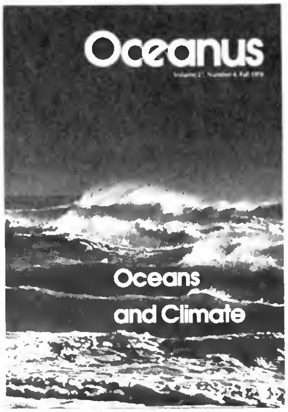
Marine Mammals, Vol. 21:2, Spring 1978—Attitudes toward marine mammals are changing worldwide. This phenomenon is appraised in the issue along with articles on the bowhead whale, the sea otter's interaction with man, behavioral aspects of the tuna/porpoise problem, strandings, a radio tag for big whales, and strategies for protecting habitats.

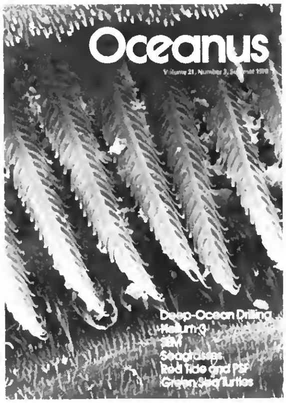
The Deep Sea, Vol. 21:1, Winter 1978—Over the last decade, scientists have become increasingly interested in the deep waters and sediments of the abyss. Articles in this issue discuss manganese nodules, the rain of particles from surface waters, sediment transport, population dynamics, mixing of sediments by organisms, deep-sea microbiology—and the possible threat to freedom of this kind of research posed by international negotiations.

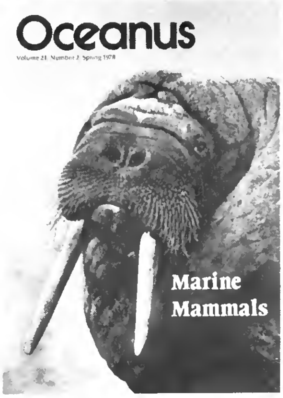
General Issue, Vol. 20:3, Summer 1977—The controversial 200-mile limit constitutes a mini-theme in this issue, including its effect on U.S. fisheries, management plans within regional councils, and the complex boundary disputes between the U.S. and Canada. Other articles deal with the electric and magnetic sense of sharks, the effects of tritium on ocean dynamics, nitrogen fixation in salt marshes, and the discovery during a recent Galápagos Rift expedition of marine animal colonies existing on what was thought to be a barren ocean floor.

Sound In The Sea, Vol. 20:2, Spring 1977—Beginning with a chronicle of man's use of ocean acoustics, this issue covers the use of acoustics in navigation, probing the ocean, penetrating the bottom, studying the behavior of whales, and in marine fisheries. In addition, there is an article on the military uses of acoustics in the era of nuclear submarines.

Estuaries, Vol. 19:5, Fall 1976—Of great societal importance, estuaries are complex environments increasingly subject to stress. The issue deals with their hydrodynamics, nutrient flows, and pollution patterns, as well as plant and animal life—and the constitutional issues posed by estuarine management.

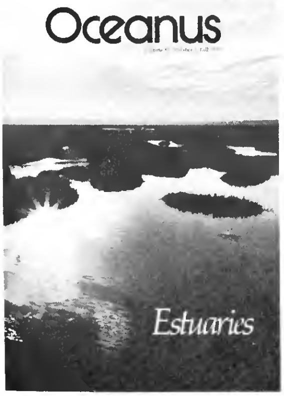


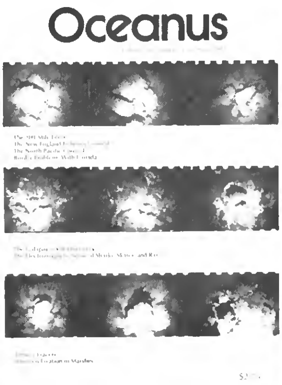


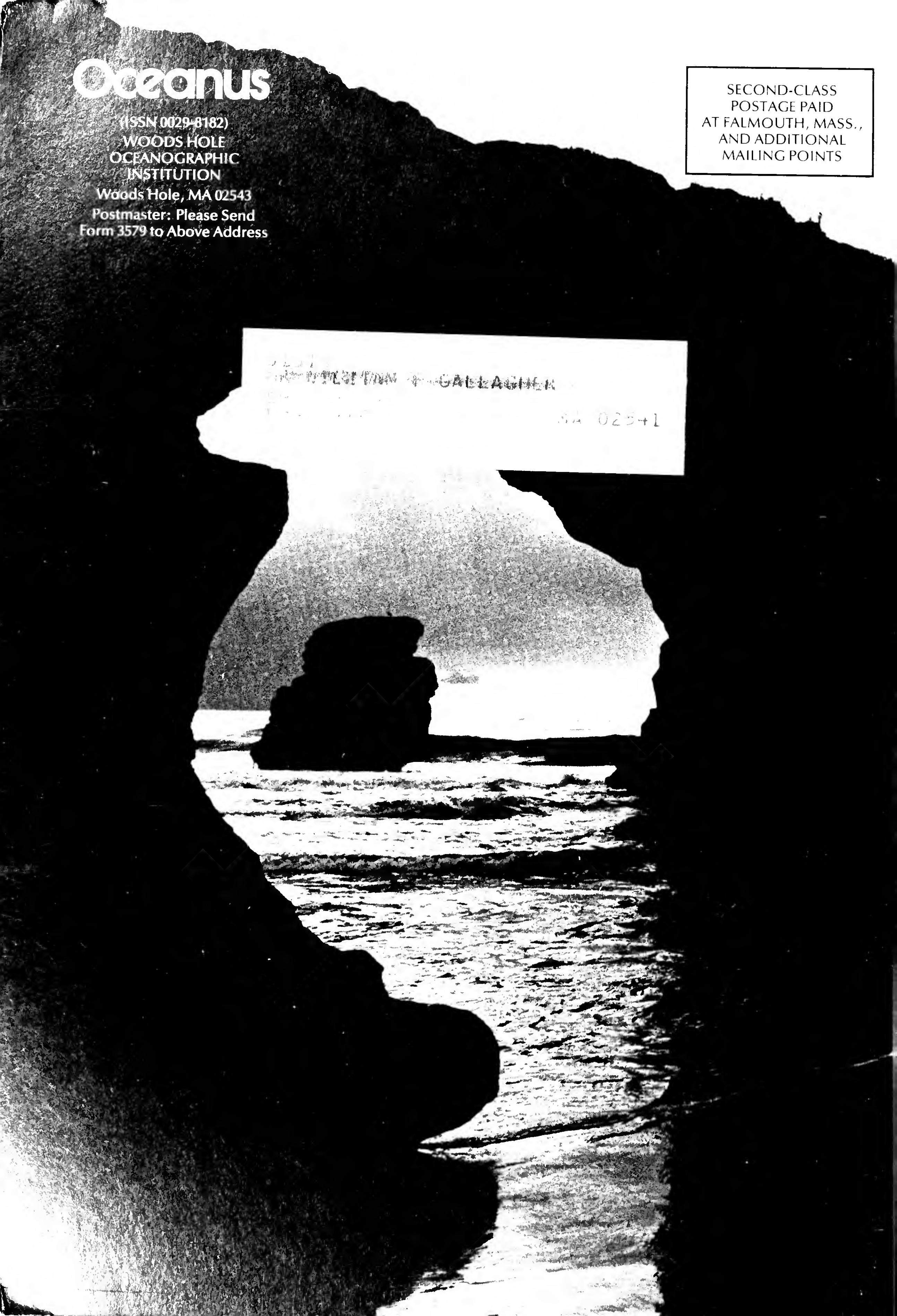


ISSUES OUT OF PRINT: Sea-Floor Spreading, Vol. 17:3, Winter 1974 **Air-Sea Interaction,** Vol. 17:4, Spring 1974 **Energy And The Sea,** Vol. 17:5, Summer 1974 **Marine Pollution,** Vol. 18:1, Fall 1974 **Food From The Sea,** Vol. 18:2, Winter 1975 **Deep-Sea Photography,** Vol. 18:3, Spring 1975 **The Southern Ocean,** Vol. 18:4, Summer 1975 **Seaward Expansion,** Vol. 19:1, Fall 1975 **Marine Biomedicine,** Vol. 19:2, Winter 1976 **Ocean Eddies,** Vol. 19:3, Spring 1976 **General Issue,** Vol. 19:4, Summer 1976 **High-Level Nuclear Wastes In The Seabed?** Vol. 20:1, Winter 1977 **Oil In Coastal Waters,** Vol. 20:4, Fall 1977

Out-of-print issues and those published prior to Winter 1974 are available on microfilm through University Microfilm International, 300 North Zeeb Road, Ann Arbor, Michigan 48106.







Oceanus
(ISSN 0029-8182)
WOODS HOLE
OCEANOGRAPHIC
INSTITUTION
Woods Hole, MA 02543
Postmaster: Please Send
Form 3579 to Above Address

SECOND-CLASS
POSTAGE PAID
AT FALMOUTH, MASS.,
AND ADDITIONAL
MAILING POINTS

[illegible] GALLAGHER
[illegible] 025+1